APPENDIX D—CONTROL STATION LITERATURE REVIEW

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EXECUTIVE SUMMARY

The objective of the research was to review sources that could inform minimum information requirements and design guidance for Unmanned Aircraft System (UAS) control stations. Sources consulted included the research literature; federal regulations; operational control stations; UAS incident and accident reports, and meta analyses. Information requirements were identified from the sources to support recommendations for potential minimum information requirements for UAS operation in an integrated National Airspace System (NAS).

For the research literature review, search terms and databases containing UAS human factors literature were identified. A taxonomy was developed to categorize the relevant literature. In total, 214 documents were deemed potentially relevant based on title and abstract review; of those documents, 44 were identified as relevant for the project A7 scope and objective. The results revealed that few manuscripts address minimum UAS control station information requirements, with the literature focused more on detect-and-avoid functions than aviate, navigate, communicate, and systems management functions. For applicable documents, information content and format were identified.

Nine federal regulation parts were reviewed to identify any manned aviation regulations that were also relevant for UAS operation in the NAS: aircraft-type-specific Parts 23-33, 121, and 125, and Part 91 containing regulations for all aircraft operation in the NAS. Parts 23, 25, and 91 were identified as the most relevant for developing minimum information requirements for UAS control stations, as they regulate general aviation aircraft (Part 23), transport category aircraft (Part 25), and all NAS operations (Part 91). Parts 23, 25, and 91 cover a majority of the regulations applicable for UAS operation in the NAS, but gaps resulting from differences between manned and unmanned operations still need to be identified and addressed. The full set of FARs reviewed is contained in Appendix D8.

Five operational control stations were reviewed to identify information content, design guidance, and design philosophies. The focus of the operational control station review was on aviating the aircraft, and recommendations were created based on the review of each control station. The recommendations were divided into four categories, including information requirements, design guidance, automation, and procedures.

National Transportation Safety Board (NTSB), Aviation Safety Reporting System (ASRS), and Federal Aviation Administration (FAA) databases with accident and incident data were also reviewed. The searches of the NTSB database returned 68 accidents involving UAS, of which 12 were identified as relevant for the research; the ASRS search returned 229 incidents, of which 79 were relevant; and the FAA search returned 2,617 events, a vast majority of which were unmanned aircraft sightings from manned pilots. Relevant incidents and accidents were reviewed and categorized via the Human Factors Analysis and Classification System, and recommendations for control station design were developed based on the analysis.

A review of existing UAS incident and accident meta analyses was also conducted; eleven documents were identified and a list of recommendations spanning the existing meta analyses was created.

1. INTRODUCTION

This Unmanned Aircraft System (UAS) control station literature review has been conducted to inform minimum information requirements and control station design guidelines for aviating fixed-wing unmanned aircraft (UA) greater than 55 lb.

The next section describes the methodology for the literature review. The Results Section contains a taxonomy of UAS control station research, categorizations mapping the literature to the taxonomy, an overview of operational control stations, a FAR review, a UAS incident/accident analysis, and review of incident/accident meta analyses. The concluding sections contain key points derived from the review and highlight limitations in the research to date. Other details of the research are contained in the appendices.

2. METHODOLOGY

The following sources were considered in this work:

1. research literature focusing on UA control station human factors,
2. federal regulations,
3. operational control stations,
4. a UAS incident/accident analysis, and
5. review of relevant incident/accident meta analyses.

2.1 REVIEW OF RESEARCH LITERATURE

The human factors design standard HF-STD-001B (Federal Aviation Administration, 2016) was consulted, where necessary, since it is an easy-to-use source of human factors design criteria oriented to the needs of the Federal Aviation Administration (FAA) mission and systems. As it is not a flight deck design standard, it was used to supplement and reinforce the findings from the reviews conducted as part of this ASSURE A7 work. Specific sections relevant to the work include:

- Section 4 General Design Requirements (except for Section 4.8 Maintenance),
- Section 5.1 Specific Design Requirements for Automation (except for Section 5.1.10 Training),
- Section 5.3 Specific Design Requirements for Displays and Printers (except for Sections 5.3.4 Special Conditions and 5.3.5 Printers),
- Section 5.4 Specific Design Requirements for Controls and Visual Indicators (except for Section 5.4.4 Accommodating People with Disabilities),
- Section 5.5 Specific Design Requirements for Alarms, Audio, and Voice Communications,
- Section 5.6 Specific Design Requirements for the Computer-Human Interface (except for Section 5.6.18 Accommodating People with Disabilities), and
- Section 5.7 Specific Design Requirements for Keyboards and Input Devices (except for Section 5.7.6 Accommodating People with Disabilities).

All UAS control station designers should refer to HF-STD-001B as a source for sound human factors design guidance and principles.

2.1.1 Literature Identification

Table 1 lists the online databases that were searched. The databases are broken down into four main categories, including:

1. generic science and engineering,
2. aviation-specific,
3. journals and conference proceedings, and
4. Code of Federal Regulations (CFR) for manned aircraft.

For the first three types of databases, the search was conducted in December 2016. Additional literature was added based on references in the selected manuscripts.

Table 1. Databases searched for relevant UAS literature.

Generic Science and Engineering	Aviation-Specific	Journals and Conference Proceedings
ACM Digital Library Defense Technical Information Center Engineering Village Google Scholar IEEE Xplore ScienceDirect Taylor and Francis Web of Science	FAA Technical Library NASA Technical Reports Server	Human Factors Human Factors and Ergonomics Society Annual Meeting Proceedings

A set of terms (Table 2) was developed to search for literature related to UAS control station design and information requirements. All the terms in the *Terms Related to UAS* column were crossed with the terms in the *Terms Related to Control Station Design* column in the searches of the identified databases.

Table 2. Search terms developed to search for relevant UAS literature.

Terms Related to UAS	Terms Related to Control Station Design
Unmanned Aircraft System Control Station Unmanned Aerial System Control Station Unmanned Aerial Vehicle Control Station Remotely Piloted Aircraft Control Station	Design Hardware Display Control Alert Information Requirements

The titles and abstracts of the documents returned from the searches were reviewed for relevance to the research goals, including inputs from any of the following:

- fielded systems,
- systems under development,
- research studies,
- published reviews of incidents and accidents,
- pilot observations,
- discussion forums, and
- existing regulatory gap analyses.

In general, any document providing UAS control station design guidance or information presentation to the remote pilot in command (RPIC) could be designated as relevant for addressing the research goals. However certain findings are beyond the scope of the intentions of A7. While multiple UA controlled by a single operator is beyond the A7 project scope, results were included that addressed workstation information requirements or design guidance that was relevant to single UA operation (multi-UA documents are explicitly labeled as such, where necessary). The A7 project focuses on information requirements for UAS weighing more than 55 lb. However, small UAS (sUAS) research contains relevant implications for the design of control stations for UAS larger than 55 lb. The A7 project does not focus on mission-specific or aerial-work-specific information or display designs; therefore, all literature reviewed is for mission-agnostic information requirements and display design guidance.

2.1.2 Taxonomy Development

For this review, we developed a taxonomy focusing on three main categories: control station design, measures, and context. The control station design portion of the taxonomy conveys the control station structure, control interface, and information provided to the RPIC. The measures portion of the taxonomy was used to specify the variables that exist for empirically evaluating the various control station designs and information presented to the RPIC in terms of human performance and human-automation interaction. Literature both within and outside of the UAS domain, including human factors engineering and cognitive systems engineering sources, were consulted to populate the list of measures. The research context includes air-transportation-relevant variables such as environment conditions, vehicle type, task, crew, and airspace. The context also includes the approach taken by the research (e.g., literature review, human in the loop simulation, and usability study). Whenever a document featured an attribute that was not part of the taxonomy, the attribute was added to the taxonomy. Therefore, taxonomy development continued throughout the literature review process.

2.1.3 Support Tool Development

The relevant literature was organized using the EndNote X7 reference management software (Thomson Reuters Corporation, New York, NY). EndNote X7 includes a plug-in for Word 2013 (Microsoft Corporation, Redmond, WA), automating in-text citations, reference list population, and formatting during document writing.

To facilitate categorization of the literature with the taxonomy, a custom database and associated user interface (Figure 1) was created with Access 2013 (Microsoft Corporation, Redmond, WA). The top of the screen features literature search and selection functionality. The user is able to search by author or title and select any of the documents designated as relevant for the review. The tabbed interface below the literature search functionality reflects the three general taxonomy categories, including research context, control station design, and measures. The user selects any part of the taxonomy in the list box next to the *Taxonomy* label, or can search the taxonomy using the search box next to the *Search Control Station* label. After selecting a taxonomy entry, clicking the *Add to Database* function adds the source and taxonomy to the database. Finally, when a document is selected at the top of the screen, the information next to the *Authors*, *Title*, *Year*, and *Control Station Summary* populates, showing the user which categorizations have already been entered for the selected document.

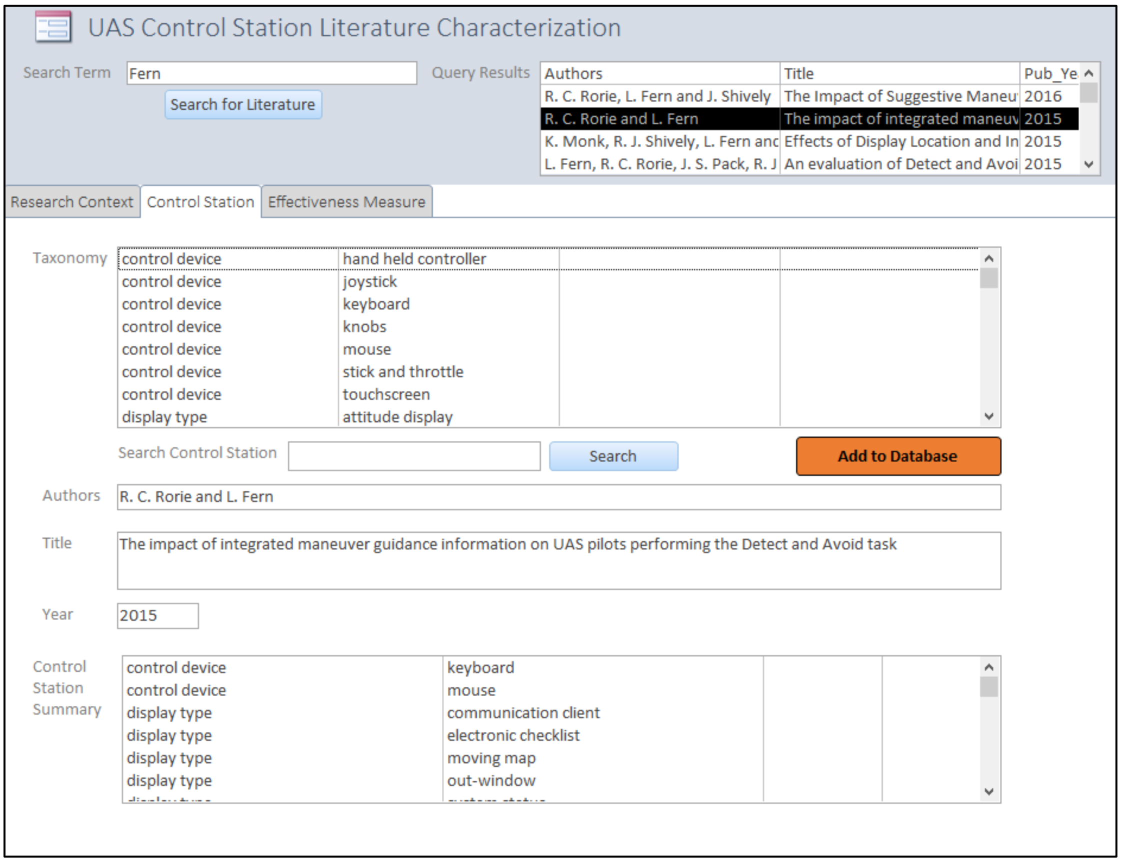

Figure 1. Screenshot of the custom database interface used to categorize literature.

2.1.4 Literature Categorization

All relevant literature was mapped to the taxonomy and categorized using the Access database.

2.2 REVIEW OF FEDERAL REGULATIONS

The CFRs in Tables 3-11 were reviewed. The objective of the CFR review was to identify any instruments and indicators required for manned operation that were also relevant for unmanned operation. CFR Parts 23-33, 121, and 125 were reviewed because they are requirements for specific aircraft types. Similarly, Part 91 was also reviewed because the requirements in Part 91 are applicable to all aircraft flying in the NAS. Part 23 was updated while the work in this document was being performed, so this report references the earlier Part 23. An account of the regulations reviewed is in Appendix D8.

Table 3. 14 CFR 23—Airworthiness standards: Normal, utility, acrobatic, and commuter category airplanes.

Subpart B—Flight	
§23.207	Stall warning.
Subpart D—Design and Construction	
§23.677	Trim systems.
§23.691	Artificial stall barrier system.
§23.699	Wing flap position indicator.
§23.703	Takeoff warning system.
§23.729	Landing gear extension and retraction system.
Subpart E—Powerplant	
§23.1091	Air induction system.
§23.1141	Powerplant controls: General.
Subpart F—Equipment	
§23.1303	Flight and navigation instruments.
§23.1305	Powerplant instruments.
§23.1321	Arrangement and visibility.
§23.1323	Airspeed indicating system.
§23.1326	Pitot heat indication systems.
§23.1329	Automatic pilot system.
§23.1331	Instruments using a power source.
§23.1335	Flight director systems.
§23.1337	Powerplant instruments installation.
§23.1351	General.
§23.1353	Storage battery design and installation.
§23.1435	Hydraulic systems.
§23.1457	Cockpit voice recorders.
§23.1459	Flight data recorders.
Subpart G—Operating Limitations and Information	
§23.1545	Airspeed indicator.
§23.1547	Magnetic direction indicator.

§23.1549	Powerplant and auxiliary power unit instruments.
§23.1551	Oil quantity indicator.
§23.1553	Fuel quantity indicator.
§23.1555	Control markings.
§23.1563	Airspeed placards.

Table 4. 14 CFR 25—Airworthiness standards: Transport category airplanes.

Subpart B—Flight	
§25.207	Stall warning.
Subpart D—Design and Construction	
§25.677	Trim systems.
§25.703	Takeoff warning system.
§25.729	Retracting mechanism.
Subpart E—Powerplant	
§25.1141	Powerplant controls: general.
Subpart F—Equipment	
§25.1303	Flight and navigation instruments.
§25.1305	Powerplant instruments.
§25.1307	Miscellaneous equipment.
§25.1323	Airspeed indicating system.
§25.1325	Static pressure systems.
§25.1326	Pitot heat indication systems.
§25.1329	Flight guidance system.
§25.1331	Instruments using a power supply.
§25.1337	Powerplant instruments.
§25.1353	Electrical equipment and installations.
§25.1383	Landing lights.
§25.1419	Ice protection.
§25.1420	Supercooled large drop icing conditions.
§25.1435	Hydraulic systems.
§25.1457	Cockpit voice recorders.
§25.1459	Flight data recorders.
Subpart G—Operating Limitations and Information	
§25.1547	Magnetic direction indicator.
§25.1549	Powerplant and auxiliary power unit instruments.
§25.1551	Oil quantity indication.
§25.1553	Fuel quantity indicator.
§27.1555	Control markings
§25.1563	Airspeed placard.

Table 5. 14 CFR 27—Airworthiness standards: Normal category rotorcraft.

Subpart D—Design and Construction	
§27.729	Retracting mechanism.
Subpart E—Powerplant	
§27.1141	Powerplant controls: general.
Subpart F—Equipment	
§27.1303	Flight and navigation instruments.
§27.1305	Powerplant instruments.
§27.1323	Airspeed indicating system.
§27.1329	Automatic pilot system.
§27.1335	Flight director systems.
§27.1337	Powerplant instruments.
§27.1351	General.
§27.1353	Storage battery design and installation.
§27.1419	Ice protection.
§27.1457	Cockpit voice recorders.
§27.1459	Flight data recorders.
Subpart G—Operating Limitations and Information	
§27.1545	Airspeed indicator.
§27.1547	Magnetic direction indicator.
§27.1551	Oil quantity indicator.
§27.1553	Fuel quantity indicator.
§27.1555	Control markings.

Table 6. 14 CFR 29—Airworthiness standards: Transport category rotorcraft.

Subpart D—Design and Construction	
§29.729	Retracting mechanism.
Subpart E—Powerplant	
§29.1141	Powerplant controls: general.
Subpart F—Equipment	
§29.1303	Flight and navigation instruments.
§29.1305	Powerplant instruments.
§29.1307	Miscellaneous equipment.
§29.1329	Automatic pilot system.
§29.1331	Instruments using a power supply.
§29.1335	Flight director systems.
§29.1337	Powerplant instruments.
§29.1351	General.
§29.1353	Electrical equipment and installations.
§29.1435	Hydraulic systems.
§29.1457	Cockpit voice recorders.
§29.1459	Flight data recorders.
Subpart G—Operating Limitations and Information	
§29.1545	Airspeed indicator.
§29.1547	Magnetic direction indicator.
§29.1549	Powerplant instruments.
§29.1553	Fuel quantity indicator.
§29.1555	Control markings.

Table 7. 14 CFR 31—Airworthiness standards: Manned free balloons.

Subpart D—Design Construction	
§31.49	Control systems.
Subpart F—Operating Limitations and Information	
§31.85	Required basic equipment.

Table 8. 14 CFR 33—Airworthiness standards: Aircraft engines.

Subpart B—Design and Construction; General	
§33.29	Instrument connection.
Subpart E—Design and Construction; Turbine Aircraft Engines	
§33.71	Lubrication system.

Table 9. 14 CFR 91—General operating and flight rules.

Subpart C—Equipment, Instrument, and Certificate Requirements	
§91.205	Powered civil aircraft with standard category U.S. airworthiness certificates: Instrument and equipment requirements.
§91.215	ATC transponder and altitude reporting equipment and use.
§91.219	Altitude alerting system or device: Turbojet-powered civil airplanes.
§91.225	Automatic Dependent Surveillance-Broadcast (ADS-B) Out equipment and use.
§91.227	Automatic Dependent Surveillance-Broadcast (ADS-B) Out equipment performance requirements.

Table 10. 14 CFR 121—Operational requirements for domestic, flag, and supplemental operations.

Subpart K—Instrument and Equipment Requirements	
§121.305	Flight and navigational equipment.
§121.307	Engine instruments.
§121.313	Miscellaneous equipment.
§121.321	Operations in icing.
§121.325	Instruments and equipment for operations under IFR or over-the-top.
§121.343	Flight data recorders.
§121.344	Digital flight data recorders for transport category airplanes.
§121.347	Communication and navigation equipment for operations under VFR over routes navigated by pilotage.
§121.349	Communication and navigation equipment for operations under VFR over routes not navigated by pilotage or for operations under IFR or over the top.
§121.354	Terrain awareness and warning system.
§121.356	Collision avoidance system.
§121.357	Airborne weather radar equipment requirements.
§121.358	Low-altitude windshear system equipment requirements.
§121.359	Cockpit voice recorders.

Table 11. 14 CFR 125—Certification and operations: Airplanes having a seating capacity of 20 or more passengers or a maximum payload capacity of 6,000 pounds or more; and rules governing persons on board such aircraft.

Subpart F—Instrument and Equipment Requirements	
§125.203	Communication and navigation equipment.
§125.205	Equipment requirements: Airplanes under IFR.
§125.206	Pitot heat indication systems.
§125.213	Miscellaneous equipment.
§125.224	Collision avoidance system.
§125.225	Flight data recorders.
§125.226	Digital flight data recorders.
§125.227	Cockpit voice recorders.

2.3 REVIEW OF OPERATIONAL UAS CONTROL STATIONS

A form was developed to guide the interview, which is contained in Appendix D9. Some reviews were conducted in person, and others were conducted via video conferencing. The reviews of operational control stations aimed to answer the following questions:

- What information is provided to the RPIC?
- How is the information conveyed?
- How does the RPIC use the control station to aviate the UA?
- What "lessons learned" about the control station can potentially be used to inform minimum automation and information requirements?

2.4 UAS INCIDENT AND ACCIDENT ANALYSIS

Multiple sources were used in the review, and incidents and accidents were characterized using the Human Factors Analysis and Classification System (HFACS) (Wiegmann & Shappell, 2003).

2.4.1 Sources

Several sources were used in the review. One category of sources was published UAS incident and accident reports from the NTSB. The database at https://www.ntsb.gov/layouts/ntsb.aviation/index.aspx was searched with the term "unmanned" in the event details word string.

One category of sources included information from ASRS reports. A query of the ASRS database was conducted by entering "UAS or UAV or unmanned" into the search text of the ASRS narratives.

One category of sources included information from FAA sources. The FAA maintains a web site at https://www.faa.gov/uas/resources/uas_sightings_report/ called the UAS Sightings Report. On that web site as of March 2017, there were reports of UAS sightings between November 2014 and September 2016.

One category of sources was published literature on UAS accidents: meta analyses and analyses of UAS accidents and incidents in the literature. These papers were identified in the search for research literature, as well as any relevant UAS accident/incident analyses referenced in the reviewed literature.

2.4.2 Classification Scheme

For the accident and incident information, the Human Factors Analysis and Classification System (HFACS) (Wiegmann & Shappell, 2003), an error framework that has been successfully used to analyze human factors aspects of aviation, was used. The taxonomy is as follows:

- Unsafe acts
  - Skill-based errors: errors occurring without significant conscious thought
  - Judgment and decision-making errors: intentional behavior that proceeds as intended, yet the plan proves inadequate or inappropriate for the situation
  - Perceptual errors: errors occurring when sensory input is degraded
  - Routine violations: willful disregard for rules/regulations that are habitual by nature and often tolerated by governing authority
  - Exceptional violations: isolated departures from authority, atypical of an individual's behavior pattern and not condoned by management
- Preconditions for unsafe acts
  - Adverse mental states: mental conditions that affect performance (e.g., loss of situation awareness, task fixation, distraction, and mental fatigue)
  - Adverse physiological states: medical or physiological conditions that preclude safe operation
  - Physical/mental limitations: instances in which task requirements exceed the capabilities of the individual at the controls
  - Crew resource management: occurrence of poor coordination among personnel
  - Personal readiness: failure to prepare physically or mentally for duty
  - Physical environment: adverse impact of the operational environment and/or ambient environment
  - Technological environment: encompasses issues such as the design of equipment and controls, display/interface characteristics, checklist layouts, task factors, and automation
- Unsafe supervision
  - Inadequate supervision: lack of guidance and/or oversight
  - Planned inappropriate operation: a situation occurring during normal operations that puts the individual or crew in danger

  - Failure to correct known problem: deficiencies among individuals, equipment, training, or other related safety areas are known to the supervisor, but are allowed to continue unabated
  - Supervisory violations: instances when existing rules and regulations are willfully disregarded by supervisors
- Organizational influences
  - Resource management: corporate-level decision making regarding the allocation and maintenance of organizational assets such as human resources, monetary assets, and equipment/facilities
  - Organizational climate: the working atmosphere within the organization
  - Organizational process: corporate decisions and rules that govern the everyday activities within an organization

The analysis herein applies HFACS to inform information requirements. Thus, the subset of the taxonomy for the focus of this research includes:

- Skill-based errors are one area that can inform information requirements as the RPIC may need feedback to help with knowing that he or she completed a task that may lead to a problem.
- Judgment and decision-making errors may lead to the identification of situations where information analysis automation could provide support.
- Perceptual errors may lead to the identification of situations where information acquisition and analysis automation could provide support.
- Adverse mental states may lead to the identification of situations where information acquisition and analysis automation could provide support.
- Physical/mental limitations may lead to the identification of situations where all types of automation could provide support.
- Issues from the physical environment may lead to the identification of situations where all types of automation could provide support.
- Issues related to the technical environment may lead to the identification of situations where all types of automation could provide support.

3. RESULTS

3.1 REVIEW OF RESEARCH LITERATURE

In total, 2,711 documents were identified using the search terms. Of these, 214 documents were designated as potentially relevant based on title and abstract review. Of the 214 documents, forty-four (44) contained information relevant to the project A7 scope. The set of 214 documents reviewed is listed in Appendix D1.

3.1.1 Taxonomy

The developed taxonomy (Appendix D2) was divided into three main categories: control station, the context of the research, and the measures used to evaluate the effectiveness of the control station design. As the focus of this report is on control stations, we focus on the control station portion of the taxonomy that addresses the information about the control station used to operate the UAS, including hardware, control device, display type, and displayed information.

3.1.1.1 Hardware

Four hardware components were identified, including laptop computer, tablet computer, desktop computer, and control station suite. A desktop computer hardware setup was defined as any system utilizing one monitor in an office setting, while a control station suite included multiple displays either in an office setting or in a dedicated control station. A study can include more than one hardware component. For example, a setup can include a desktop setup in addition to a laptop computer to control a real or simulated UAS.

3.1.1.2 Control Device

The list of control devices was populated based on the control station simulators and prototypes used in the literature reviewed as part of the A7 function allocation review, the UAS control device inventory by Williams (2007), and Scheff's (2014) UAS inventory. Scheff's inventory included 107 control stations (Appendix D4). The final set of control device options are listed below:

- Hand held controller
- Joystick
- Keyboard
- Knobs
- Mouse
- Slider control
- Stick and throttle
- Touchpad
- Touchscreen
- Trackball

3.1.1.3 Information Interface

A control station operator interface presents relevant information, supports command and control, or both. With respect to the display of information, the literature mentions a range of interface types: ways that the displayed elements can be grouped. An information display can be dedicated to an entire device screen, such as with the Control Display Unit of a Flight Management System. In other cases, a set of information elements can be integrated into a display that may be displayed across an entire device screen with or without other information. For example, a traffic situation display may be displayed across an entire device screen but the pilot may be able to overlay weather information. In other cases, a display may be composed of a set of related displayed elements such as with a Primary Flight Display (PFD) that is composed of an attitude indicator, an airspeed indicator, an altitude indicator, a vertical speed indicator, a heading display, navigational marker information, autopilot control “bugs”, ILS glideslope indicators, course deviation indicators, altitude indicator QFE settings, and so forth. These components can also be made up of grouped information such as an airspeed indicator with indicated airspeed and data such as the maximum operating limit.

Reported below is the list of interface types based on simulators and systems used in the literature, a review of current manned aircraft standards (e.g., 14 CFR 91 Subpart C- Equipment, Instrument, and Certificate Requirements), and operational unmanned systems. Related items are grouped.

- Clock
- Communication
    - Communication client
    - Radio (voice) communication
- Electronic checklist
- Landing gear position (if relevant)
- Navigation display
    - Horizontal situation indicator (HSI)
    - Moving map
    - Weather information (as an overlay)
- Out-the-window view
- Payload status
- Pitot heat indicator
- Powerplant
    - Engine status and related information (e.g. air intake door position, coolant, fuel pump, manifold pressure, oil pressure, tachometer. temperature if relevant)
    - Power/fuel status
    - Thrust indicator
    - Thrust reverser status
- Primary flight display
    - Airspeed indicator
        - Speed warnings
    - Altitude indicator
    - Attitude indicator/pitch ladder
    - Control mode display
    - Heading indicator/magnetic direction indicator
        - Turn bank indicator/turn coordinator, Slip/Skid indicator
- System status
- Traffic Collision Avoidance System (TCAS) display
    - Traffic information
- Vertical situation display

- Wing flap position indicator

3.1.1.4 Displayed Information

Displays often differ in terms of the information presented on them. For example, the out-the-window view of one UAS could overlay the video feed with a "highway in the sky" tunnel reflecting the projected future trajectory of the UA, while another UAS may present the video feed alone. These could both be labeled as "out-the-window view" displays, despite the differing information content. Since control stations can differ in terms of what specific information is being presented and how it is being presented, the displayed information portion of the taxonomy contains information presented to the RPIC via the control station interfaces (listed below). The information was initially populated using the results from the A7 function allocation review (Pankok & Bass, 2016), information presented by Kamine and Bendrick (2009), and review of manned aircraft standards (see Appendix D8 for the information elements retrieved from the standards); information elements were added as needed during the literature review process. Information is grouped into categories, including communication, environmental conditions, National Airspace System, navigation, out-the-window, ownship, terrain, time, and traffic.

- Communication
    - Data communication
    - Frequency in use
    - Radio in use
    - Radio settings
    - Radio signal reception strength
- Environmental conditions
    - Air temperature
    - Cloud coverage
    - Cloud height
    - Ice
    - Precipitation
    - Pressure
    - Storm cell location
    - Turbulence
    - Visibility
    - Wind direction
    - Wind speed
- National Airspace System
    - Airport (including locations of traffic on the surface; outlining runways on a situation indicator display or map to indicate status).
        - Runway and taxiway layout
        - Runway status
        - Surface traffic
        - Taxiway status
    - Airspace

        - Alert area location(s)
        - Controlled firing area location(s)
        - Military operations area location(s)
        - National security area location(s)
        - Prohibited area location(s)
        - Restricted area location(s)
        - Sector boundaries
        - Warning area location(s)
- Navigation
    - Distance to destination
    - Distance to next waypoint
    - Flight plan cleared route
    - Past re-planning tasks
    - Pending re-planning tasks
    - Taxi route
    - Time to destination
    - Time to next waypoint
    - Waypoint location
- Out-the-window
    - Enhanced vision
    - Highway-in-the-sky
    - Night vision
    - Out-the-window video feed
    - Synthetic vision
- Ownship
    - Air intake door status
    - Airspeed
    - Aircraft maximum flaps extended speed (V_{FE})
    - Aircraft maximum landing gear operating speed (V_{LO})
    - Aircraft maximum speed for normal operations (V_{NO})
    - Aircraft maximum operating limit speed (V_{MO})
    - Aircraft maximum operating maneuvering speed (V_{O})
    - Aircraft minimum control speed (V_{MC})
    - Aircraft never exceed speed (V_{NE})
    - Aircraft stall speed (V_{S})
    - Aircraft stall speed in landing configuration for which the aircraft is still controllable (V_{S1})
    - Aircraft stall speed in landing configuration (V_{S0})
    - Aircraft type
    - Altitude
    - Attitude
    - Bank angle

- Battery temperature
- Carburetor air temperature
- Command sent status
- Control link status
- Control mode
- Current lost link procedure
- Cylinder head temperature
- Distance ring
- Electric power system quantity (voltage, current)
- Engine rotor speed (RPM)
- Engine rotor speed limit (RPM)
- Fuel flow
- Fuel level
- Fuel pressure
- Fuel pump status
- Fuel strainer contamination level
- Fuel system heater status
- Fuel temperature
- Generator/alternator status
- Ground speed
- Ice protection system status
- Heading
- History trail
- Hydraulic system pressure
- Landing gear position (if relevant)
- Location
- Manifold pressure
- Oil pressure
- Oil quantity
- Oil strainer contamination level
- Oil temperature
- Pilot identification data
- Pitot heating system status
- Powerplant status
- Powerplant valve position
- Rate of climb
- Rate of turn
- Slip/skid status
- Telemetry data
- Thrust level
- Thrust reverser status
- Trajectory

    - Transponder status
    - Trim device position
    - Usable fuel quantity
    - Usable oil quantity
    - Vertical trend
    - Vertical velocity
    - Wing flap position
- Terrain
    - Elevation
    - Location
- Time
    - Time of day
    - Time of day (origin)
    - Time of day (destination)
    - Elapsed flight time
- Traffic
    - Intruder
        - Absolute altitude
        - Aircraft ID
        - Aircraft length
        - Aircraft width
        - Airspeed
        - Bearing
        - Climb/descent direction
        - Climb/decent rate
        - Ground speed
        - Heading
        - Heading predictor
        - History trail
        - Location
        - Manned/unmanned
        - Onboard equipment (e.g., TCAS II and ability to generate resolution advisory alerts)
        - Range
        - Relative altitude
        - Threat level
        - Vector line
        - Vertical trend
        - Vertical velocity
    - Conflict detection (information used to convey conflict geometry)
        - Closest point of approach (CPA) location
        - Distance to CPA

        - Time to CPA
    - Conflict resolution
        - Suggested maneuver
        - Maneuver success (i.e., whether the RPIC's planned maneuver successfully meets an objective, such as resolving a conflict)

3.1.2 Taxonomy Categorization Summary

The number of documents generated for each element of the taxonomy was based on the literature returned from the searches of generic science and engineering databases, aviation-specific databases, and relevant journals and conference proceedings. The queries used to generate literature counts are listed in Appendix D5, and tables containing the number of documents mapped to each taxonomy element are contained in Appendix D6. Regarding the control station portion of the taxonomy, most of the existing literature utilizes a control station suite, with mouse and keyboard as the most common control devices. A majority of the control stations reviewed contain one or more of the following displays:

- an out-the-window view (or payload camera),
- a navigation display, and/or
- a system health and status display.

A wide range of information is presented to RPICs across control stations, but almost all present ownship and route information to the RPIC. There is little work assessing laptop computer control stations, UASs controlled by physical knobs or touchscreen interfaces, or control stations including a weather information display or a communication display.

Regarding the measures portion of the taxonomy, research on control station design and information requirements tends to use human-computer interaction measures, control measures, mission performance measures, and RPIC state measures to test the differences between varying levels of information or different designs. Much less work has used attention allocation or detection and assessment measures (refer to Appendix D3).

Regarding the context portion of the taxonomy, a majority of the research utilizes human in the loop experimentation in the en route and aerial work/mission phases of flight, requiring the RPIC to perform aviate, navigate, and system management tasks. Communication tasks have not been assessed to a great degree in the literature. The literature also lacks in the takeoff, departure, approach, and arrival phases of flight. Little research assesses the role of visual observers in communicating with the RPIC and ensuring separation with aircraft, terrain, and foreign object debris.

3.1.3 Summary of the Research Literature

The literature reviewed from the generic science and engineering databases, aviation-specific databases, and relevant journals and conference proceedings focuses on interfaces designed for UAS aviating tasks; a review of control stations for other tasks (e.g., detect and avoid, navigation, and communication) is contained in Appendix D7. Since the focus of the review is on aviating tasks, the review is partitioned by the method(s) the control station uses to aviate the UA, including manual control, target parameter control (such as heading, speed, and altitude holds), waypoint manipulation control, and control stations that utilize multiple control strategies. The final subsection of the review contains an overview of research that is control station agnostic.

While the focus of this A7 control station research is to develop recommendations for *minimum* information requirements and design guidelines for safe UAS operation in the National Airspace System (NAS), the existing UAS control station literature seeks information levels and design that *optimize* UAS human-machine performance. In other words, human factors researchers and practitioners typically have a goal of enhancing system performance, which is different from our goal of identifying minimum requirements. This difference in objectives needs to be considered when interpreting the results in the existing literature. What needs to be considered is the objective of the study: was there an unsafe situation that the researchers were trying to address? What safety nets exist with or without the result from the literature? A limited number of resources reviewed focus on information and control station designs supporting self-separation and adaptable control paradigms; these topics are not in the scope of the A7 research but are included to inform gaps.

3.1.3.1 Manual Control

Trujillo et al. (2015) assessed the effects of providing a primary flight display (PFD) and moving map to sUAS operators in a simulation of sUAS control in visual line of sight (VLOS) conditions. Participants conducted simulated search-and-rescue and nuclear plant inspection missions under three conditions: (a) VLOS, (b) VLOS and PFD, and (c) VLOS, PFD, and moving map. Providing RPICs with both the PFD and moving map led to smaller altitude error, fewer collisions, better preference ratings, and better perceived ability to avoid manned aircraft than the VLOS condition. However, awareness of other traffic in the area was decreased in the PFD and moving map condition (traffic was not displayed on the moving map). Regarding RPIC information requirements, the results suggest that audio alerting and depiction of traffic information on the moving map (i.e., not relying on RPIC visual detection of traffic) may be necessary for safe UAS operation.

Rodes and Gugerty (2012) conducted a human in the loop experiment to assess the relative effects of north-up and track-up maps in UAS operation. The control station simulation used a single monitor to display an electronic map and an out-the-window view, controlled via joystick and keyboard inputs. The map display either remained fixed in a north-up condition, or was presented in a track-up condition with a compass displayed on the upper-right corner of the map. Each experimental trial required participants to follow a predefined path to eight targets and make either a cardinal direction judgment or a direction-of-turn judgment at each target. NASA TLX measures revealed that the workload associated with the north-up map was significantly greater than for the track-up map. Similarly, accuracy and response time (RT) to the queries revealed the benefits of a track-up map; since the out-the-window view is always track-up, the inconsistency between the north-up map and the out-the-window view made it difficult for RPICs to make directional judgments, since the queries required integrating information across both displays. However, participants were more accurate in post-trial map reconstruction with the north-up map than with the track-up map, due to the fixed frame of reference provided by the north-up map. Regarding implications for control station display design, the benefits of track-up vs. north-up map displays are dependent on the context of the operation; however, the default mode should be track up to promote consistency with an out-the-window view, when one is provided.

The United States Air Force Research Laboratory's (AFRL) Predator-like control station is called the *Air Vehicle Operator Workstation*. The workstation consists of two larger displays, one above the other, at and above RPIC eye level. Below eye level were two smaller head-down displays situated next to each other (Figure 2). The two larger displays contained a map view (identifying current UA location, mission waypoints, and current sensor footprint) and video imagery from an onboard camera with symbology overlaid on the picture. The two smaller displays presented subsystem and communication information. The control station also had control inputs via joystick or keyboard and trackball. A majority of the research using the control station, described next, assessed tactile interfaces during UAS operation.

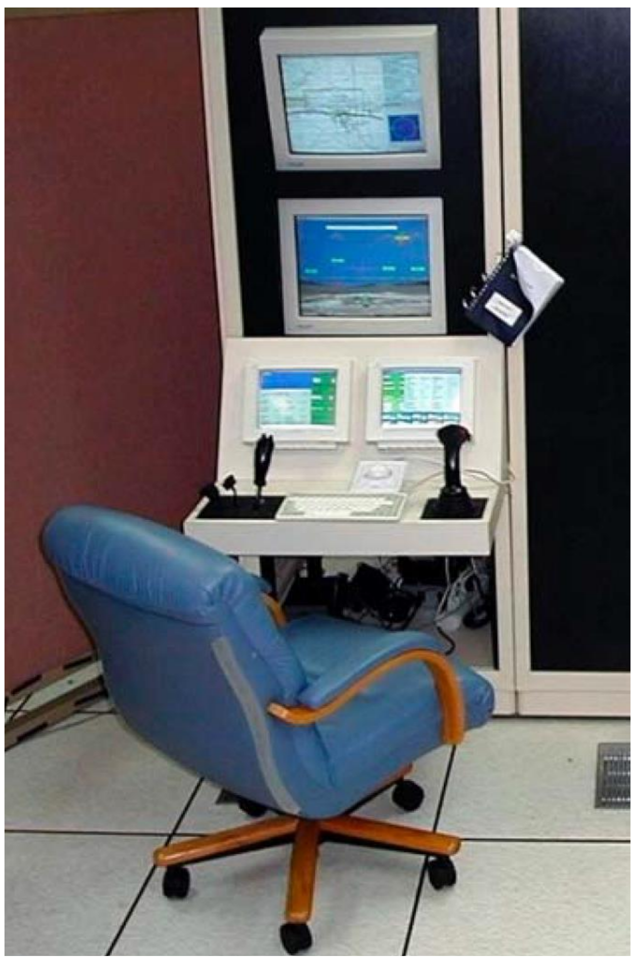

Figure 2. Air vehicle operator workstation (Williamson, Draper, Calhoun, & Barry, 2005).

In a human in the loop experiment using the *Air Vehicle Operator Workstation*, Williamson et al. (2005) assessed the effect of manual vs. speech data entry while simultaneously operating a UAS.

During the simulated flight, participants were asked to perform data entry tasks, either manually or with speech input. Speech input yielded faster completion times, higher task accuracy, lower flight path error, and higher subjective ratings than the manual input. Although the experiment provides no direct insight into minimum information requirements, the results have implications for control station design. Control of a UAS can yield high utilization rates of the RPIC's manual resources, so offloading secondary tasks to speech input methods may lower RPIC workload.

Ruff, Draper, Lu, Poole, and Repperger (2000) used the *Air Vehicle Operator Workstation* with a force-feedback joystick to conduct a series of simulated UA landings. The delivery of force feedback cues was manipulated (on vs. off) to convey turbulence information. In the force-feedback conditions, the following information was conveyed to the RPIC: turbulence strength (mild vs. severe), turbulence axis (horizontal vs. vertical), and proximity to the runway (near vs. far) through the magnitude of the force-feedback, direction of the force-feedback, and timing of the force-feedback, respectively. The inclusion of tactile feedback yielded higher SA ratings and lower landing difficulty ratings, but participant comments suggested that the delivery of the cues to the joystick impeded RPIC control of the vehicle in some cases, resulting in higher difficulty landings, particularly when there was turbulence close to the runway. The results also exhibited a concerning trend that with more experience using the system, participants became less able to accurately identify the direction of the turbulence (horizontal vs. vertical) and severity. Regarding design and information recommendations, RPICs would benefit from turbulence information, but joystick force-feedback may not be the optimal modality for information delivery, as it can impede RPIC control of the vehicle (a similar conclusion was reached by Lam, Mulder, and van Paassen (2007) for collision avoidance cueing, highlighting the potential disruptiveness of joystick force-feedback to UAS control).

Focusing on the use of haptic displays during UAS operation, Calhoun, Draper, Ruff, Fontejon, and Guilfoos (2003) manipulated the modality of alerts delivered to participants in the *Air Vehicle Operator Workstation* as tactile on vs. tactile off (visual and auditory alerts were presented in both conditions). Two tactile sensors were fixed to each participant's forearms for delivery of tactile alerts, indicating that the RPIC needed to perform one or more checklist tasks. The addition of haptic cues did not have a significant effect on RT to alerts, number of missed alerts, or flight technical error. Subjective responses revealed favorable perceptions of the haptic system. The authors suggest that the lack of significant performance effects may be related to the tactile interface was a redundant cue, rather than a standalone alert. The results suggest that auditory alerting may be superior to tactile alerting during UAS operation.

Calhoun, Fontejon, Draper, Ruff, and Guilfoos (2004) conducted a follow-on experiment (again using the *Air Vehicle Operator Workstation*) assessing whether tactile alerts could substitute for auditory alerts rather than provide alert redundancy. Three alert conditions were manipulated for two levels of alerting: caution and "critical". The experiment modality manipulations included a visual-only condition, a visual and auditory condition, and a visual, auditory, and tactile condition in which the critical level alert was visual and tactile only. Two auditory loading conditions (low and high) were crossed with the modality alerting condition. Results revealed the two multimodal conditions to have significantly shorter RT than the visual-only condition, with no significant difference between the two multimodal conditions. This result motivated a second experiment using three alerting conditions: visual only, visual and auditory, and visual and tactile. RT results were the same (in terms of significance) as the first experiment. Regarding implications for control station design, the results of both experiments reinforce the potential utility of redundant cueing (in the form of auditory or haptic cues added to a visual alert). However, there is no evidence suggesting that the tactile modality is more effective for alert cue delivery than the auditory modality, or vice versa.

In another follow-on effort using the *Air Vehicle Operator Workstation*, Calhoun, Draper, Guilfoos, and Ruff (2005) assessed the use of auditory and tactile alerting as redundant cues for periods of vigilance. Performance was also evaluated in low vs. high auditory alerting, manipulated by the number of radio calls to the RPIC while performing the task. Trials lasted 30 minutes in the experiment, as opposed to the previous experiments in which trials lasted approximately 12 minutes. As with the prior experiments, the redundant conditions yielded smaller RT than the visual-only condition, but there was no statistical difference between the auditory and tactile displays (across auditory loading conditions). However, workload ratings revealed tactile displays to impose the least workload, followed by the auditory displays, then followed by the visual-only displays. Corroborating the previous experiments, the results suggest that tactile and auditory redundant cueing are both sufficient from a RT perspective, but tactile alerting may be associated with lower cognitive workload than auditory cueing.

3.1.3.2 Target Parameter Control

Haber and Chung (2016) developed a novel control station concept that integrated multi-touch gesture inputs and user configurability with the hypothesis that these features would enhance RPIC effectiveness. The workstation includes drag-and drop functionality, allowing the RPIC to place flight instrument windows in any place on the screen (Figure 3). The user interface also features a tab-based system, where different tabs can be created and displays moved to the user’s desired tab. The authors specify five key features of the interface, including: (1) multi-touch gesture input functionality; (2) user interface configurability; (3) tab-based interface; (4) instrument side tab; and (5) alert/notification system. The instrument side tab includes the following display options: vehicle health and status, angle of attack gauge, autopilot controller, engine monitor, flap controller, fuel gauge, gesture map, non-gesture map, payload controller, primary flight display, and throttle/gear control. To assess the utility of the multi-touch gesture feature, a human in the loop experiment was conducted comparing a mouse-and-keyboard control interface with the multi-touch interface. NASA TLX ratings were statistically lower by 38% with the multi-touch gesture interface compared to the mouse-and-keyboard interface. However, participant comments revealed the difficulty of using the multi-touch gesture interface without any form of haptic feedback. Regarding control station design, touchscreen gestures may be better for some interfaces and functions, such as map zoom functionality, than more traditional mouse-and-keyboard control.

Figure 3. Instrument panels available to RPICs in Haber and Chung's (2016) simulator.
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3.1.3.3 Waypoint Manipulation Control

Cook, Smallman, Lacson, and Manes (2009) conducted an experiment assessing the ability of RPICs to perform a re-routing task in flat and mountainous terrain using a two-dimensional (2D) top-down display (Figure 4). The experiment also featured restricted airspace as a constraint to consider when re-routing the vehicle. The 2D top-down display, which contained color-coded terrain information and airspace restriction information, was accompanied with a vertical situation display containing waypoints, flight path, and terrain information. Results revealed re-routing to be slower and more effortful (i.e., increased number of waypoint movements) in mountainous terrain. Terrain type also interacted with airspace restrictions such that there was an additive effect of mountainous terrain and airspace restriction on RT and number of waypoint movements per trial. The results highlight the difficulty in dynamic, real-time re-routing tasks. Regarding implications for control station design recommendations and information requirements, RPICs require sufficient terrain and airspace information in order to successfully perform the re-routing task.

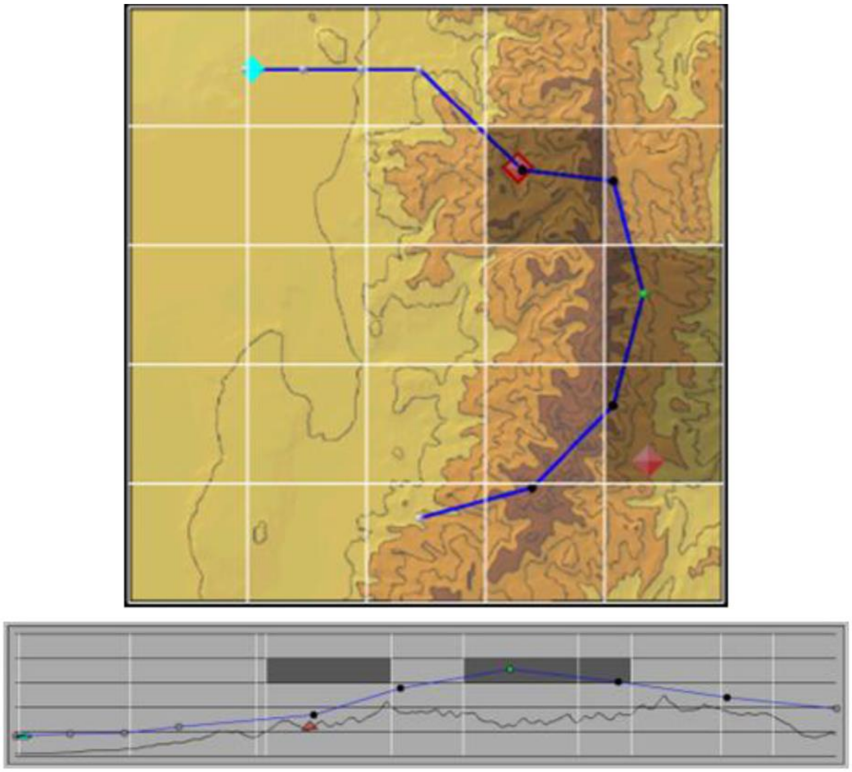


Figure 4. Top-down view (top) and profile view (bottom) used in Cook et al.'s (2009) experiment.
Reproduced from the Proceedings of the Human Factors and Ergonomics Society Annual Meeting, Vol. 53, No. 4, 2009.

In a follow-on study, Cook, Smallman, Lacson, and Manes (2010) used a UAS simulator containing a display presenting terrain, airspace information, target location, and route information to RPICs. They assessed three formats of the display to assess which facilitated route re-planning while flying to a target. The three display types included (1) a baseline 2D display which showed the scene in a top-down view, presenting higher terrain altitude as progressively darker color bands (Figure 4); (2) an augmented 2D display, which presented shape information about the targets and conveyed terrain altitude information achromatically with a grey matte texture draping (i.e., shaded as if a light was being shone on the terrain from one direction; Figure 5); and (3) a perspective 3D display, which rendered the augmented 2D scene view from a 45-degree viewing angle (Figure 5). Route re-planning time and accuracy were improved with the augmented 2D display and perspective 3D display (with no statistical difference between the augmented 2D and perspective 3D displays), but error severity was significantly highest in the baseline display, followed by the perspective 3D display, followed by the augmented 2D display. Regarding subjective preference ratings, participants generally preferred the perspective 3D display over the augmented 2D display, with the baseline display receiving the lowest preference ratings. The results generally suggest that the augmented 2D display is superior to the baseline 2D and perspective 3D displays, reinforcing the utility of 2D displays for tasks requiring precise position judgments.

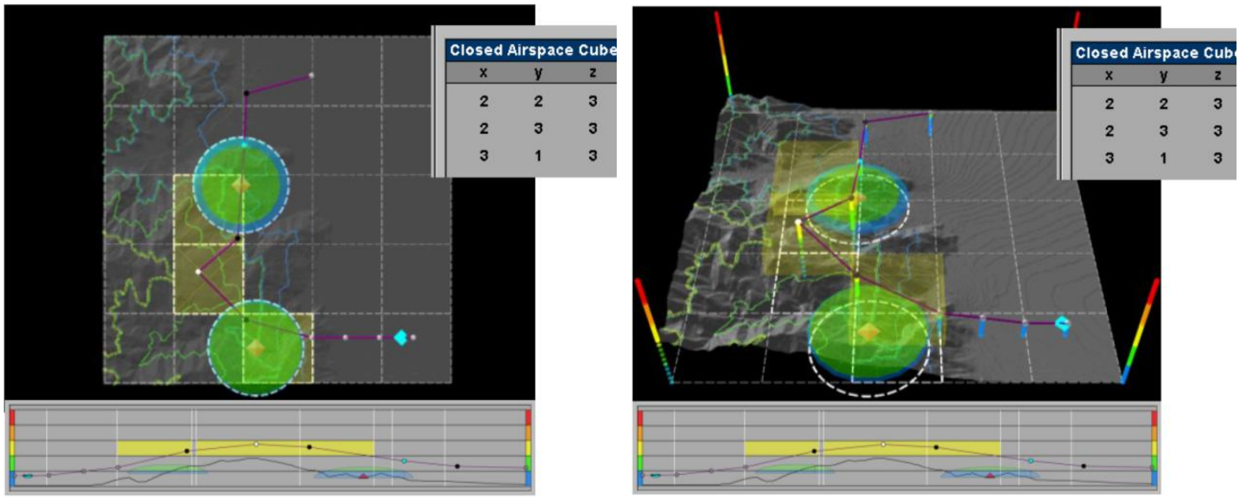


Figure 5. Augmented 2D display (left) and Perspective 3D display (right) used in Cook et al.'s (2010) experiment.
Reproduced from the Proceedings of the Human Factors and Ergonomics Society Annual Meeting, Vol. 54, No. 4, 2010. Copyright 2010 by the Human Factors and Ergonomics Society.

Arrabito et al. (2013) conducted an experiment in which participants operated a UAS while exposed to alerts presented in multiple modalities to assess the efficacy of offloading visual information to the auditory and haptic modalities. Their control station consisted of two monitors, with one presenting a map display, UA status window (displaying flight status and health information), warning panel, and autoland panel; and the other presenting the feed from the onboard camera. The UA was controlled via a waypoint editing interface. During the cruise phase of the simulated flight, participants were required to monitor for engine problems (low and high RPM warnings) and in the landing phase, windshear or turbulence could occur at different levels of severity. RPICs were exposed to two configurations of the warnings: visual only and multimodal, in which engine RPM was mapped to an auditory sonification, and attitude was mapped to a tactile display to provide information on wind and turbulence parameters. There was no effect of display type on RT to abort the landing, but there was a significant effect of display type on RT to a critical event (participants were asked to press a button when they perceived a critical event) such that faster RTs occurred for the visual and auditory condition for engine RPM warnings than for the visual-only conditions. There was also no significant effect of display type on NASA TLX workload ratings. The haptic warnings were not significantly different from the other two conditions for any of the responses. These results corroborate a literature review on the effectiveness of tactile displays that concluded that the use of tactile cues alone (i.e., not redundant with visual or auditory cues) yielded large variability in effectiveness (Elliott et al., 2009). The results of the study are mostly applicable to control station design, suggesting that auditory sonifications can improve monitoring performance (in terms of RT) compared to visual alerts, but the use of a tactile display does not significantly improve RPIC monitoring performance.

Donmez, Graham, and Cummings (2008) conducted a human in the loop experiment assessing performance using haptic alerting in a multi-UA supervisory control task. The control station, which was used to monitor a four-UA scenario, contained a map display (containing UA routes and waypoints overlaid on a map) and a timeline display (containing projected events on a timeline for each UA, such as waypoint arrivals and fuel levels), as shown in Figure 6. The timeline display also contained mission status information, a chat client, and vehicle health and status updates. Participants were exposed to continuous or discrete haptic alerts reflecting UA course deviations (through a wristband) or late target arrivals (through a haptic vest) while performing an auditory secondary task. In the continuous conditions, the haptic feedback was constantly presented to participants, but the frequency and depth of the tactile alert changed commensurate with the degree of flight path deviation or lateness. The discrete alerts, however, were triggered when the UA crossed a flight path error threshold. Continuous haptic feedback yielded reduced RT to course deviations, but increased RT to late arrivals; there was no difference in NASA TLX ratings between the two conditions. In another experiment using the same simulated control station, the effects of continuous and discrete auditory alerts of UA course deviations and late targets, as well as single vs. four-UA operation, were assessed (Donmez, Cummings, & Graham, 2009; Graham & Cummings, 2007). The auditory condition had a significant effect on RT to both course deviation and late arrivals such that continuous sonification for both alert types yielded the smallest RTs, with no significant effect on error rate or NASA TLX ratings. However, the presentation of a continuous sonification simultaneously with a discrete alert led to the longest RTs. Overall, the results of the two studies suggest that alerting of UA path deviation is important, and that continuous feedback may yield smaller RT than discrete feedback. Furthermore, alerting using the haptic or auditory channels may reduce the visual resources necessary to track the UA along its path. Finally, there are also implications for alert design; the performance degradations associated with the combination continuous and discrete auditory alerts needs to be considered, as overloading the RPIC's auditory perceptual resources needs to be avoided.

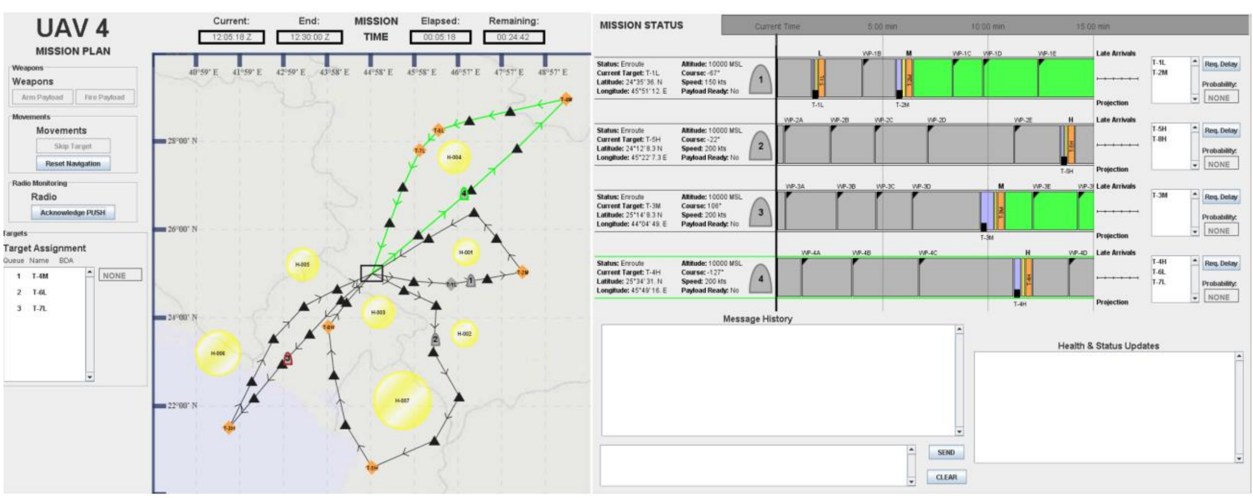


Figure 6. Map display (left) and timeline display (right) used in the Donmez et al. (2008) multi-UAS simulator.

3.1.3.4 Multiple Control Strategies

To test an adaptable control automation paradigm, Calhoun et al. (2013) designed a custom multiple-UAS control station containing two displays: a tactical situation display containing a moving map, route information, and vehicle information; and an activity window showing the UAS status and mode of control. Using an adaptable paradigm, the RPIC could freely switch between four control interfaces:

- manual stick-and-throttle control;
- noodle, which used stick-and-throttle controls used to establish a precise near future path of a particular UAS, with specific heading and altitude changes;
- maneuver, in which one or more UAs could be quickly tasked to make a short, well-defined change in flight path; and
- play, in which higher-level commands were given to the UAS, yielding control of the vehicle paths to automation.

Participants were guided through six scenario-based vignettes during which a moderator administered scripted questions and recorded RPIC comments. Questionnaire data revealed participants to generally favor the adaptable paradigm, suggesting that control stations could benefit from two or more control interfaces that allow the RPIC to freely choose the interface that is best tailored to the RPIC’s task.

Wickens, Dixon, and colleagues (2005; 2002; 2003) used a single-monitor interface to conduct simulator experiments on information and automation used by RPICs in conducting a target search mission (Figure 7). The display was separated into four subsystems, including a 3D ego-centric image view of the terrain below the UA, a 2D top-down map, a message box containing mission instructions, and a display containing four system failure gauges. Across their experiments, participants operated one- or two-UA scenarios under three automation conditions: (1) a baseline condition in which participants were required to continuously navigate via joystick while all other aviating activities were automated (e.g., pitch, bank, airspeed, and altitude); (2) an autoalert condition, which provided auditory alerts when system failures occurred and auditory presentation of mission instructions; and (3) an autopilot condition in which RPICs entered coordinates on a keypad, enabling the computer to guide the UA in a straight-line path to the next command target (autoalert functions were not active in this condition). Over their two experiments, auditory presentation of system failures and waypoints (i.e., offloading visual information to the auditory modality) had no statistical effect on root mean squared (RMS) tracking error, but did facilitate memory of future waypoint location (indicated by fewer repeat requests for information) and decreased system failure detection time. Use of autopilot facilitated memory of future waypoint location and detection of targets of opportunity, suggesting that the reduction in tracking workload allowed pilots to reallocate their perceptual resources to the payload display monitoring task. Generally, while the auditory cueing of system failures did not translate into enhanced vehicle control, the results suggest the importance of providing system failure alerting to RPICs, particularly in the auditory modality.

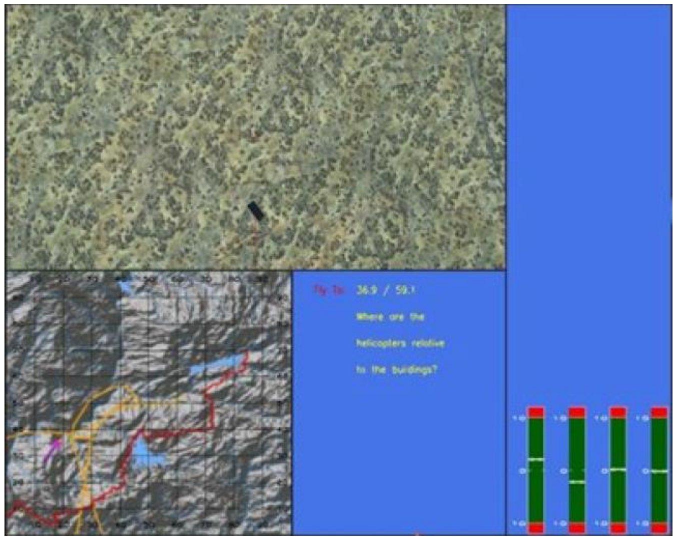


Figure 7. Information interface used by Wickens and colleagues (2002, 2003, 2005). Reproduced from Human Factors, Vol. 47, No. 3, 2005.

Williams (2012) used a generic, single-monitor control station simulator that consisted of a moving map display (depicting ownship, flight waypoints and segments, and traffic) as well as several boxes containing radio settings, datalink status, and point-and-click command buttons to change aircraft heading and altitude (Figure 8). The experiment manipulated the control mode (vector control vs. waypoint control) and modality of health and status information delivery (visual vs. visual and auditory). In the vector control condition, the participant used the mouse to manipulate on-screen buttons for changing the altitude and heading of the aircraft, while the waypoint control condition required the RPIC to enter waypoints on the moving map display and establish the altitude for each leg of the flight. In the visual alerting condition, the aircraft parameter (engine failure or heading control failure) readout turned red, while the visual and auditory condition presented the red-colored readout as well as an auditory alert. Waypoint control yielded lower subjective workload ratings and smaller flight technical error than vector control, but there was no effect of control interface on responses to an engine failure. The addition of auditory alerting increased the proportion of participants who responded to the alarm within five seconds. The results suggest that waypoint control may be beneficial for decreasing RPIC workload while also decreasing flight technical error; however, there were no instances requiring participants to quickly re-route the aircraft (e.g., due to an impending collision). Regarding alerting, auditory cues were superior to visual-only alerts, likely because the visual system is already subjected to a large amount of visual information. In other words, offloading alerting to the auditory modality may be beneficial when possible.

Figure 8. UAS workstation used in the Williams (2012) experiment.

Using an ecological interface design process, Fuchs, Borst, de Croon, van Paassen, and Mulder (2014) designed a multi-UA control station including various features to help RPICs perform a survey mission. Included in the display interface was a mission view, a fleet overview, and a flight control system status window; aircraft were controlled via a point-and-click waypoint editing interface. The mission view contained aircraft routes overlaid on a top-down map with textboxes allowing for altitude, heading, and speed control as well as functionality to upload and change waypoints. The fleet overview presented the RPIC with attitude displays for the aircraft, and the flight control status view presented system health and status. In a human in the loop simulation, participants were asked to survey as much of a town as possible while monitoring for UAS battery failures and wind conditions. After the simulations, participants rated (on a scale from 0 to 10) the usefulness of 11 features (Table 12) included on the display. Generally, participants found color coding reflecting battery life very useful, but the textual presentation of the information (e.g., range at future waypoints) less useful, possibly due to the added cognitive processing required for the numerical presentation and projection of the implications of the information on route planning. Although the experiment focused on multi-UA supervisory control, the results regarding information and design can be considered relevant for monitoring battery/fuel levels and the associated range in single UA operation.

Table 12. Features and mean subjective ratings of features for display (Fuchs et al., 2014).

Feature	Rating (out of 10)
Predicted coverage (predicted proportion of the city that can be searched given the current battery level)	Very useful (ratings between 7 and 10)
Coloring of waypoints (conveying if there is sufficient battery remaining to reach the waypoint and return to base)	
Coloring of lines between waypoints (conveying battery level along path)	
Current battery level	Somewhat useful (ratings between 4 and 6)
Expected battery level at future waypoints	
Actual coverage (proportion of the city searched)	Not useful (ratings between 0 and 3)
Battery level required to return to base	
Current power consumption	
Current range	
Range at future waypoints	
Windsock	

In an investigation of a hand-held control interface for operating a small UA, Hou, Ho, Arrabito, Young, and Yin (2013) evaluated two display layouts and two control input methods. Two display configurations were presented on a tablet computer interface: (1) a map view and out-the-window view on the screen simultaneously, or (2) a map view and out-the-window view on different screens requiring navigation between the two screens. The two display configurations were crossed with two control input methods, requiring participants to control the UA using the touchscreen interface versus the use of a joystick with an *ok* button; in the former condition, participants could directly interact with the displays and the menus while in the latter condition, the joystick was used to move a cursor and the "ok" button was used to make on-screen selections. Across all experiment manipulations, RPICs could freely change between a manual control mode, which required heading and altitude commands, and an automatic mode, which was a waypoint-editing mode. In a simulated reconnaissance task, results revealed significantly shorter training time (to satisfy a performance criterion), faster task completion time, larger trajectory error, and lower mental workload for the touchscreen condition compared to the joystick condition. As expected, there were significantly less switches between displays in the simultaneous presentation condition than in the condition requiring navigation between the two displays. The results corroborate previous findings that the added clutter on a display is worth the tradeoff of not requiring the user to navigate between multiple displays, a conclusion also reached by Fern, Rorie, Pack, Shively, and Draper (2015), Monk, Shively, Fern, and Rorie (2015), and Santiago and Mueller (2015) in their UAS DAA research.

The Vigilant Spirit Control Station (VSCS) was developed by the United States AFRL to be a flexible system for operating one or more vehicles, presenting information on a variety of display configurations, and customizing information needs dependent on the operation context (Feitshans, Rowe, Davis, Holland, & Berger, 2008). NASA has utilized the system to conduct DAA research for integrating UAS into the NAS (discussed below and presented in Figure 9). The NASA research typically employs a four-display suite, containing (1) a cockpit situation display (CSD), (2) an out-the-window view, (3) a tactical situation display (TSD), and (4) a communication, health, and status display. The TSD serves as the RPIC's primary display, providing ownship and route information, a moving map, and navigation and control interfaces. The CSD, when used, contains all of the DAA functionality developed by NASA; the results reported by Fern et al. (2015) provided support for combining the CSD information with the TSD, so follow-on experiments utilized two communication, health, and status displays rather than both a CSD and TSD. The VSCS is typically controlled using mouse and keyboard inputs. The following description includes experiments conducted using the VSCS for facilitating UAS integration into the NAS.

Figure 9. VSCS setup for NASA DAA research (Rorie, Fern, & Shively, 2016).

In a human in the loop experiment, Rorie and Fern (2014) compared three control interfaces in the VSCS using *Measured Response* times, which are the RTs reflecting the time it takes to implement a route change in the control station and coordinate that change with ATC. Participants were asked to fly a gridded pattern, coordinating all maneuvers with ATC (a confederate ATC was responsible for separation). The three control interfaces were stick-and-throttle, waypoint-to-waypoint, and auto-pilot. In the stick-and-throttle condition, lateral maneuvers were achievable through waypoint editing or joystick movements, and vertical maneuvers were achievable through waypoint edits, an altitude override function, or joystick movements. In the waypoint-to-waypoint condition, lateral maneuvers were achievable only by editing the waypoint; vertical maneuvers could be made via waypoint edits or through the altitude override option. In the auto-pilot control mode, RPICs were provided with an additional navigation interface capable of altitude, heading, and speed holds; lateral and vertical maneuvers could be achieved through waypoint edits or hold functions. The measured response times revealed that initial response to ATC was significantly shorter in the auto-pilot condition than in the waypoint-to-waypoint interface, while the stick-and-throttle interface was not significantly different from either interface. The stick-and-throttle interface yielded significantly shorter total edit time than the auto-pilot, which was significantly shorter than the waypoint-to-waypoint interface. The auto-pilot interface facilitated the RPIC to quickly take over control when necessary, while the stick-and-throttle interface supported more immediate maneuvering. The waypoint-to-waypoint interface required several steps to upload waypoint changes to the aircraft, and no ability to enter simple heading holds, suggesting that this other control modes supporting quick route changes (such as manual control or ability to upload altitude, speed, or heading holds) should be available to allow the RPIC to override the waypoint-to-waypoint mode when necessary. The VSCS interface used in the experiment is shown in Figure 10.

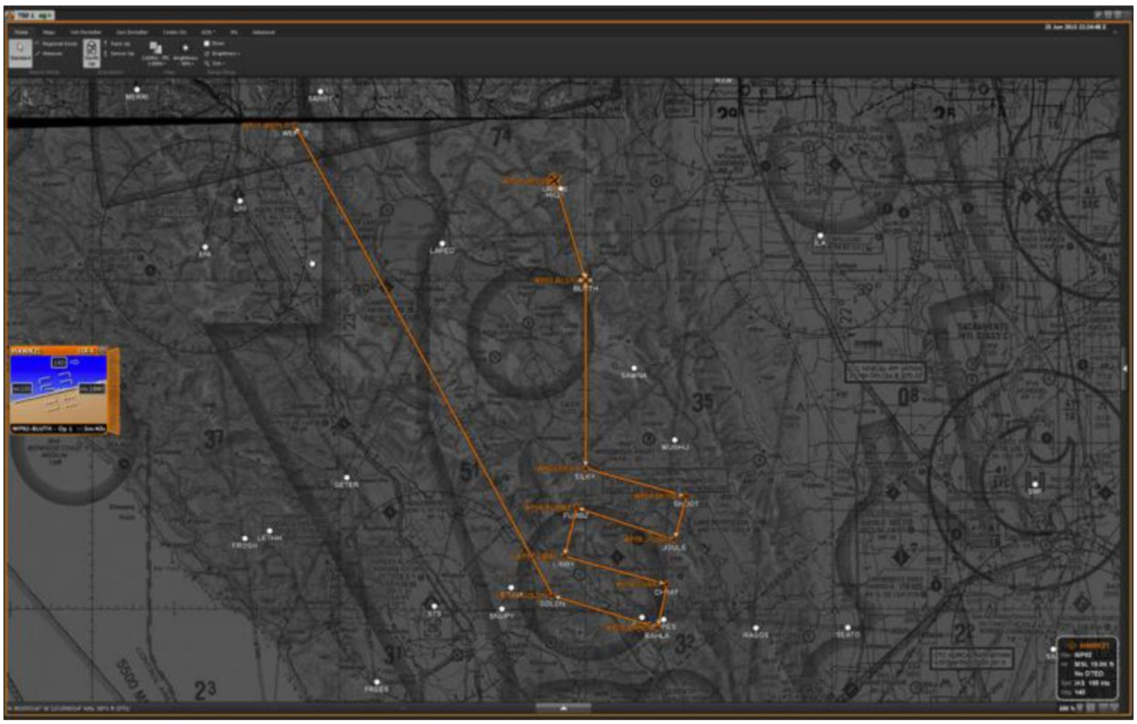


Figure 10. VSCS interface used in the Rorie and Fern (2014) control device experiment. Reproduced from the Proceedings of the Human Factors and Ergonomics Society Annual Meeting, Vol. 58, No. 1, 2014. Copyright 2014 by the Human Factors and Ergonomics Society.

3.1.3.5 Control Station Agnostic Research

In a review of the literature on multi-UA control, Hocraffer and Nam (2017) sought to explore the types of human-system interface testing and research that have been performed, and to use the research to form general guidelines for creating human-system interfaces for managing UA swarms. The authors reviewed 27 articles fitting their search criteria. Although they focused on multi-UA supervisory control, some of the recommendations are relevant for single-UA control. They found that multi-modal control (e.g., via a combination of touch screen and voice commands) has been reported to reduce cognitive load in high-stress situations, suggesting UAS designers may want to utilize multiple modalities since RPICs are typically subject to high levels of visual information. They reported that the addition of multiple types (modalities) of feedback also contributed to reduced cognitive workload, improved SA, and reduction in navigation errors. Another trend across the multi-UA control literature suggests that high levels of task switching and distributed attention across multiple displays reduced RPIC task knowledge. Therefore, control stations should be designed to integrate as much information as possible without overly cluttering the display. Hocraffer and Nam suggest that future human-system interfaces must allow customization based on the user's preferred control and observation mode.

Macbeth, Cummings, Bertuccelli, and Surana (2012) used a hybrid cognitive task analysis, which is used to design displays for envisioned future systems, to design a multi-UA control display interface. The hybrid cognitive task analysis consists of four steps: (1) generate a scenario task overview, (2) generate an event flow diagram, (3) create decision ladders for critical decisions (Rasmussen, 1983), and (4) generate SA requirements. The result of the work was a two-display workstation prototype, containing a situation awareness display and a health and status display. The situation awareness display contained information about the mission phase, a map containing vehicle routes and landing sites, pre-loaded command buttons (e.g., return to base), and windows for comparing settings among the vehicles. The health and status display contained a mission timeline, vehicle health and status information, and a chat communication window. Many of the information requirements are the same as for single-UA operations.

Tasked with addressing functional requirements for UAS human system interfaces, Access 5 (2006) conducted a functional analysis of future UAS operation in the NAS. They had two basic assumptions in formulating their recommendations, including (1) the UAS has very little to no autonomy and (2) there is a 1:1 operator-to-UA ratio. The analysis yielded information and control requirements across four general functional categories, including aviate, navigate, communicate, and avoid hazards. Their information requirements, which are relevant for the A7 minimum information recommendations, are reported in Table 13.

Table 13. Information requirements for aviating tasks reported by Access 5 (2006).

Information Requirement
Convey information to the RPIC to monitor maneuvers
Convey spatial information to the RPIC
Convey aviate systems to the RPIC

Hobbs and Lyall (2015) compiled UAS human factors guidelines and recommendations for information content of displays, control inputs, properties of the interface, and other general UAS design recommendations. The information content guidelines for aviate tasks are reported in Table 14; guidelines for navigate, communicate, and manage system and operations tasks are in Appendix D7.

Table 14. Information content guidelines for aviating and hazard avoidance tasks (Hobbs & Lyall, 2015).

Information Guideline
The control station should provide the RPIC with information on the status of consumable resources.
The control station should provide the RPIC with health and status information on the control station.
The control station should provide an alert to the RPIC when there is a threat of the UA colliding with another aircraft, terrain, or objects. The alert must be provided in time for the RPIC to effectively respond to make the UA avoid the collision.
The control station should provide information about terrain or ground-based objects within proximity of the projected UA flight path and may become a threat for UA collision.
The control station should provide the RPIC with the information necessary to detect aircraft, obstructions or people while the UA is moving on the ground. This information may be provided through a camera located on the aircraft, or closed circuit television (CCTV) cameras located on the ground.
The control station should provide the RPIC with the information necessary to detect obstructions that may affect launch or takeoff. This information may be provided through a camera located on the aircraft, or CCTV cameras located on the ground.
The control station should provide the RPIC with the information necessary to detect obstructions that may affect approach and landing. This information may be provided through a camera located on the aircraft, or CCTV cameras located on the ground.
The control station should provide the RPIC information about the likelihood of the UA colliding with the upcoming threat so that the RPIC will be able to make a decision about the need to take evasive action to avoid a collision.
The control station should provide the RPIC with a prediction of the time available until the UA would collide with the threat aircraft, object, or terrain.
The control station should provide information about the aircraft surrounding the UA and the collision threat to help in making a decision about maneuvers that would not cause additional risks for collision.
The control station should provide information about the capabilities of the UA for making evasive maneuvers in the current UA situation. This information should include at least the following: • Possible maneuvers that can be made by the UA in the current situation (e.g. climb, descend, or turn within a certain radius). • Time for the UA to accomplish the maneuvers (e.g. how long until the UA reaches a certain turn radius or climb attitude).
The control station should provide the RPIC with information necessary to quickly identify the current state, mode, or setting of all controls that are used to send flight commands to the UA.
The control station should provide the RPIC with information on the flight path that had been assigned to the UA prior to the evasive maneuver.
The control station should provide information about the necessary UA trajectory needed to return to the assigned flight path. This should include the necessary UA heading and altitude changes.
If an autonomous collision avoidance maneuver is carried out, the control station should alert the RPIC that the maneuver is underway, and must notify the RPIC when the maneuver is concluded.

The control station should be capable of providing the RPIC with predictive information on the quality and strength of a C2 link before the link is actively used to control the UA.
The control station should provide information to enable the RPIC to identify which C2 link settings are active (e.g. selected frequency, satellite vs terrestrial).
The control station should provide the RPIC with information to confirm that effective control is established with the correct UA.
The control station should provide the RPIC with information on the geographic limits of the link.
The control station should provide the RPIC with information on spectrum activity from a spectrum analyzer.
The control station should alert the RPIC when the UA is approaching an area where link is likely to be lost.
The control station should alert the RPIC when the link is lost.
The UA will transmit a pre-determined transponder code when the link is lost.
The control station should provide information to enable the RPIC to monitor the strength of the link.
The control station should alert the RPIC whenever the C2 link experiences interference, whether resulting from natural phenomena, payload or other equipment associated with the UAS, or human activities (such as jamming or other users on frequency).
The control station should display to the RPIC the source of downlink transmissions.
Where relevant, the control station should provide the RPIC with information on link latency, in milliseconds.
The control station should provide information to enable the RPIC to anticipate link degradations or diminished link strength. This information may include link footprint, including areas that may be affected by terrain masking.
The control station should provide information to enable the RPIC to manage link security.
The control station should inform the RPIC when a lost link is resumed.

Reviewing Society of Automotive Engineers Aerospace Recommended Practices, FAA regulatory and advisory material, FAA human factors design guide, and other key research papers, Access 5 (2005) reported display requirements for command, control, and communications. Table 15 provides an overview of the display requirements that are within scope of this A7 control station review. In general, the requirements emphasize the importance of feedback to the RPIC, particularly with regard to communication with ATC, sending commands to the UA, and the status of the datalink.

Table 15. Select display requirements for command and control tasks (Access 5, 2005).

Display Requirement
The pilot shall have information available at the control station that indicates authorized datalink actions prior to enabling control of the vehicle flight path or trajectory.
The control station shall display feedback to the pilot regarding the source of downlink transmissions by reference to downlink data displayed at the control station.
The control station shall display timely feedback to the pilot regarding the content of a command and when a command has been entered into the system.
The control station shall display feedback to the pilot when a datalink message arrives by a visual and/or aural alert.
The control station shall display feedback to the pilot regarding the status or quality of each uplink and downlink.
The control station shall display feedback to the pilot for any partial or full failure of a datalink.

3.2 REVIEW OF FEDERAL REGULATIONS

Regulations referring to instruments and indicators, along with their associated information content appear in Appendix D8. Parts 23, 25, and 91 were identified as containing relevant minimum information requirements that are applicable to UAS operation. These parts contain a majority of the regulations that are required for UAS operation in the NAS; work as part of Project A7 Task 8: Control Station Standards and Guidelines will identify gaps in the current regulations resulting from differences between manned and unmanned operation.

3.3 REVIEW OF OPERATIONAL UAS CONTROL STATIONS

The subsections that follow contain reviews of operational UAS control stations. Each subsection contains a background section followed by the design philosophy, a review of the control station itself (including images and tables containing information content of the control station displays), and recommendations for control station design. Recommendations are categorized by information requirements, design guidance, and automation.

The control stations were chosen because they represented a variety of designs, capabilities, and features available in existing control stations. In particular, the General Atomics designers stated that their control station embodied what they considered to be the minimum automation and information requirements for safe operation in the NAS.

A subset of the reviewed control stations was designed primarily for operations within visual or electronic line of sight. In these reviews, which are explicitly identified, the focus of the recommendations is on the design guidance, automation, and other features of the control station design that are relevant for the design of control stations for UAS larger than 55 lb. In other words, less emphasis is placed on the information content itself since the information content in these control stations was designed for line of sight operation, which is not within the scope of this work. Table 16 contains an overview of the control stations reviewed in the following subsections.

Table 16. Overview of designs, capabilities, and features in the reviewed control stations.

Control Station	**Hardware**	**Number of Displays**	**Control Devices**	**Control Automation**	**Takeoff/ Landing Modes**	**Range**
Advanced Cockpit Ground Control Station	Dedicated control station	6	• Keyboard • Stick and throttle • Touch-screen	• Target holds • Waypoint	• ATOL	Beyond visual line of sight
X-Gen Control Station	Dedicated control station	4	• Keyboard • Stick and throttle • Trackball	• Manual control • Target holds • Waypoint	• ATOL • Manual	Beyond visual line of sight
Piccolo Command Center	Desktop computer	1	• Hand-held controller • Keyboard • Mouse	• Target holds • Waypoint	• Manual	Visual line of sight
senseFly eMotion 2 Control Station	Desktop, laptop, or tablet computer	2	• Hand-held controller • Keyboard • Mouse	• Manual control • Waypoint	• ATOL • Manual	Electronic line of sight
Procerus Virtual Cockpit	Laptop computer	1	• Hand-held controller • Keyboard • Touchpad/ Mouse	• Manual control • Target holds • Waypoint	• ATOL • Manual	Visual line of sight

3.3.1 General Atomics Advanced Cockpit Ground Control Station

3.3.1.1 Background

The General Atomics Advanced Cockpit Ground Control Station (ACGCS) is the state-of-the-art control station used to control the General Atomics UASs (Figure 11), including the Predator family of aircraft platforms (e.g. MQ-1, MQ-9), Gray Eagle family of aircraft platforms (MQ-1C), and SkyGuardian. The control station was originally developed for military operations with the MQ-9, but is currently being repurposed for operation with the SkyGuardian UAS, a UAS larger than 55 lb designed to meet airworthiness requirements and fly seamlessly in the NAS. The setup contains two identical control stations and networking hardware to connect the CS to other systems, all contained in a shipping-container-like structure. One control station is for the RPIC and the other is for a sensor operator, but the control stations are redundant and can therefore be used in either role.

Figure 11. General Atomics Advanced Cockpit Ground Control Station designed for military operation.
Retrieved from http://www.ga-asi.com/Websites/gaasi/PhotoGallery/4298135/AdvCkpt01.jpg?20261

3.3.1.2 Design Philosophy

The main design objective for the SkyGuardian is to ensure that it conforms to the standards required to fly IFR in the NAS, requiring navigation capabilities typically provided by a Flight Management System (FMS) in manned transport category aircraft. General Atomics' goal in designing the ACGCS is to replicate the minimum capability required for a manned aircraft cockpit in a UA with a similar level of complexity. General Atomics conducted a hazard analysis (Bahr, 2014) to identify flight critical functions and used the results of the analysis as a guide to modify the military version of the ACGCS for civilian operation, including commercial-off-the-shelf products and products developed by General Atomics. In some cases, an iterative development process with subject matter experts was utilized to design the interfaces in the ACGCS. General Atomics is using STANAG 4671 as the certification basis for the SkyGuardian platform.

3.3.1.3 Operating the UAS

The ACGCS provides three control modes and associated control devices to the RPIC. The station includes a stick and throttle setup, based on a Lockheed Martin F-16 Fighting Falcon cockpit, used for *manual control* of the UA thrust and attitude. However, General Atomics does not intend to certify the stick and throttle control mode since STANAG 4671 does not provide certification criteria for this control mode. The control station also supports holds modes, allowing the RPIC to upload speed, altitude, and heading targets to the UA. A waypoint mode allows upload of one or more waypoints to the UA route, including any altitude, speed, and/or timing constraints associated with the waypoint, similar to 4-D trajectory flight paths currently being developed in manned aviation. Related to the waypoints mode, the ACGCS contains a database for civil waypoints (e.g., navigation aids), including altitude and airspeed constraints for all civil procedures, through the integration and use of a certified FMS. The holds and waypoint modes are controlled via the flight critical display (described later), which includes keyboard, cursor control, and touchscreen inputs. The ACGCS also contains automatic takeoff and landing (ATOL) functionality, which is combined with the FMS to enable instrument procedures including; Standard Instrument Departures (SIDs), Standard Terminal Arrival Routes (STARs), and Instrument Approach Procedures (IAPs). The ACGCS designers stated that UAS operations in the NAS will, at minimum, require hold modes that correspond with modern-day manned aircraft flight modes. The designers stated that manual aircraft control (i.e., control via stick and throttle) is not as good of a design concept for UAS operation in the NAS as the use of higher levels of control automation.

The ACGCS shown in Figure 11 is configured for military operations. Although the configuration of the civilian version is similar (in particular, the control devices and the six-monitor layout), there are several differences between the two versions. Unless otherwise noted, the remainder of this subsection details the features and capabilities for the civilian version of the ACGCS. The top row of three displays contains an out-the-window synthetic vision system view, with the middle display containing heads up display (HUD) symbology (Figure 12). The top row of displays can also be changed to show the payload camera view. The lower left monitor in the control station contains pages for mission-critical information (e.g., payload control functionality, and electronic checklists). Whereas Figure 11 shows that the military version of the ACGCS contains a tactical situation display on the bottom center monitor; the NAS-compliant version of the ACGCS displays this content on the bottom right monitor. The tactical situation display contains a top-down moving map with capability of two-dimensional and three-dimensional presentation of ownship moving through the environment.

Figure 12. Heads up display as part of the General Atomics ACGCS out-the-window synthetic vision system display.

The middle panel on the bottom row of the civilian version of the ACGCS contains the flight critical display, which includes all information and functionality required to operate the SkyGuardian in the NAS. The flight critical display is a commercial off-the-shelf Rockwell Collins Pro Line Fusion glass cockpit system with a 14-inch customizable display containing a primary flight display, horizontal situation indicator, navigation display, engine indication and crew alert system (EICAS), flight planning display, system pages, and a system messages panel. The flight critical display (Figure 13) is used for both control of the UA as well as presentation of critical flight information to the RPIC. General Atomics designers assert that the information and functionality contained in the flight critical display panel are the minimum required to operate the UAS in the NAS, i.e., the RPIC could safely operate the UAS in the NAS using only the flight critical display panel. Figure 13 does not contain any imagery in the system messages panel; the panel can display nine messages (and an additional 20 messages when expanded), which are color-coded based on the severity of the message alert. The EICAS display cannot be changed, moved, or hidden; the primary flight display and horizontal situation indicator can be hidden in favor of a route planning interface; and the system pages portion of the display contains 20 pages across five categories, including the aircraft, autopilot, datalink, ground station, and avionics. The remainder of this section contains tables with the information content of each display contained on the flight critical display.

(a) Rockwell Collins Pro Line Fusion display used as the ACGCS flight critical display (red outlines and large section labels added).

(b) Pro Line Fusion panel containing the display and input devices.

Figure 13. Rockwell Collins Pro Line Fusion setup used in the General Atomics ACGCS.

Table 17. Information content of the General Atomics ACGCS EICAS display.

Information Item	Format
Active contingency plan(s)	Text
Engine RPM	Text and gauge
Engine torque	Text and gauge
Flight mode annunciation	Text
Engine kill switch status	Text
Digital Electronic Engine Control status	Text
Turboprop ignitor status	Color-coded indicator
Oil pressure	Text
Oil temperature	Text
Fuel mode	Text
Fuel pressure	Text
Fuel level	Text
Active fuel tanks	Text
Active fuel pump(s)	Text
Lift/drag device position	Scale
Transmitter temperature	Color-coded text and linear scale

Table 18. Information content of the General Atomics ACGCS flight planning display.

Information Item	Format
Origin	Text
Departure runway	Text
Destination	Text
Charts/terminal procedures	Text
Destination runway	Text
Planned route	Text in a grid
Planned cruise altitude	Text
Departure time	Text
Alternate airport	Text
Active contingency plan(s)	Text in a grid
Emergency landing area(s)	Text in a grid

Table 19. Information content of the General Atomics ACGCS HSI.

Information Item	Format
Magnetic heading	Compass and text
Position relative to desired path over ground	Localizer indicator (scale)
Position relative to desired glidepath	Glideslope indicator (scale)
System warnings	Text
Ground speed	Text
True airspeed	Text
Weather	Graphic overlay
Time of day	Text
Communication frequency	Text

Table 20. Information content of the General Atomics ACGCS navigation display.

Information Item	Format
System alerts	Text
Aircraft position relative to desired flight route	Navigation display
Aircraft position relative to airport	Navigation display
Magnetic heading	Text and compass
Planned route	Lines connecting waypoints
Weather	Graphic overlay
Terrain height	Graphic overlay

Table 21. Information content of the General Atomics ACGCS PFD.

Information Item	Format
Flight mode annunciation	Text
Pitch attitude	Attitude indicator
Roll attitude/bank angle	Attitude indicator
Indicated airspeed	Tape and text
Indicated altitude	Tape and text
Terrain height	Synthetic visualization

Table 22. Information content of the General Atomics ACGCS system pages displays.

Page	Information Item	Format
Air data	Indicated airspeed	Text
	Indicated altitude	Text
	Pitot tube heater status	Text
	Density altitude	Text
	Barometer altitude	Text
	Atmospheric pressure	Text
	Altimeter setting	Text

Airborne radio	Active radio	Text
	Communication channel	Text
	Communication frequency	Text
	Standby frequency	Text
	Receiver sensitivity	Text
	Receiver status	Color-coded indicator
Anti-ice and lights	Ice protection system status	Color-coded indicator
	Pitot tube heater status	Color-coded indicator
	Ice status	Color-coded indicator and visual alert
	AOA probe heater status	Text
	Electro-expulsion deicing system status	Text and color-coded indicator
	Engine inlet anti-ice valve status	Text and color-coded indicator
	Taxi light status	Text and color-coded indicator
	Navigation lights status	Color-coded indicator
	Strobe lights status	Color-coded indicator
Autopilot limiters	Minimum altitude	Text
	Active contingency plan(s)	Text
C-Band Line of Sight	UA signal transmitter power level	Text
	Network data uplink status	Color-coded indicator
	Satellite data uplink status	Color-coded indicator
	Line-of-sight data uplink status	Color-coded indicator
	X-band data uplink status	Color-coded indicator
	Network data downlink status	Color-coded indicator
	Satellite data downlink status	Color-coded indicator
	Line-of-sight data downlink status	Color-coded indicator
	X-band data downlink status	Color-coded indicator
	Ground data terminal signal transmitter power	Text
	Ground data terminal signal transmitter port	Text
	Ground data terminal signal transmitter port status	Color-coded indicator
	Ground data terminal signal receiver port	Text
	Ground data terminal signal receiver port status	Color-coded indicator
	Ground data terminal signal transmitter antenna type	Text
	Planned route	Text
	Command/control link frequency	Text
	Command/control uplink signal strength	Color-coded text
	Command/control downlink signal strength	Color-coded text

Engine	Alcohol water injection tank level percentage	Text
	Alcohol water injection pressure	Text
	Exhaust gas temperature	Text and gauge
	Engine RPM	Text
	Engine mode	Text
	Torque	Text
	Fuel pressure	Text and gauge
	Fuel flow	Text and gauge
	Engine bay temperature	Text
	Engine inlet temperature	Text
	Oil pressure	Text and gauge
	Oil level	Text and scale
	Oil temperature	Text and scale
Electrical	Voltage	Text and scale
	Current	Text and scale
Flight computer	Flight computer status	Color-coded indicator
	Flight computer being used	Color-coded indicator
	Flight mode annunciation	Text
	GPS figure of merit	Color-coded text
	Inertial navigation system status	Color-coded indicator
	GPS status	Color-coded indicator
Flight control	Yaw attitude	Text and scale
	Trim device position	Text and scale
	Lift/drag device position	Text and scale
	Pitch attitude	Text and attitude indicator
	Roll attitude/bank angle	Text and attitude indicator
	Aileron difference	Text and up/down arrow
	Aileron temperature	Color-coded text
	Spoiler temperature	Color-coded text
	Flap temperature	Color-coded text
	Elevator temperature	Color-coded text
	Rudder temperature	Color-coded text
	Aileron amperage	Color-coded text
	Spoiler amperage	Color-coded text
	Flap amperage	Color-coded text
	Elevator amperage	Color-coded text
	Rudder amperage	Color-coded text

Fuel	Locked out tank(s)	Text and graphic
	Fuel level	Text and scale
	Heater status	Text
Landing gear	Landing gear position	Color-coded indicator
	Steering offset	Text
	Steering angle	Scale
	Wheel brake position	Scale
	Left brake offset	Text
	Right brake offset	Text
Transponder	Transponder mode	Text
	Transponder status	Color-coded indicator
	Transponder code	Text
	Transponder address	Text
	Aircraft ID	Text
	Transponder control type	Text
	Transponder antenna	Text

3.3.1.4 Recommendations

3.3.1.4.1 Information Requirements

According to General Atomics personnel, the ACGCS control station (particularly the flight critical display) was designed to contain the minimum information and functionality required to safely operate the SkyGuardian in the NAS. The information presented in Tables 17-22 contains that minimum information set.

3.3.1.4.2 Design Guidance

The design of some displays in the ACGCS is similar to corresponding displays in manned aircraft, such as the navigation display and primary flight display, which may support the transfer of skill and/or knowledge from the manned domain to the unmanned domain for RPICs with manned flight experience. In fact, the Rockwell Collins Pro Line Fusion display is the baseline glass cockpit in a number of modern manned aircraft.

> Recommendation: UAS control stations should use designs and symbology commonly used in manned aviation to support the transfer of knowledge for certified pilots operating UASs.

One potential drawback to the ACGCS design is the information density of the flight critical display; a great deal of information is contained on a fairly small display, which could increase perceptions of display clutter or result in RPIC information overload. However, a similar 14-inch glass cockpit display is certified to fly the Beechcraft King Air and other manned aircraft. Another concern is that there are twenty system status pages through which the RPIC needs to be able to navigate. Although this number of system status pages is generally consistent with the glass cockpit displays of many manned aircraft, inability to access critical information in a timely manner could have undesirable results.

> Recommendation: A balance needs to be maintained between information density on a display and a design requiring the RPIC to navigate through multiple pages. The FAA Human Factors Standard 5.6.1.1.2 (2016) states that the information density on a screen should be minimized by presenting only information that is essential to a user at any given time, but research suggests that the negative effects associated with increased information density are less impactful than those associated with requiring pilots to navigate multiple displays or pages (Hou et al., 2013). Thus, designers should consider reducing the number of pages that regularly need to be navigated.

3.3.1.4.3 Automation

The ACGCS allows the RPIC to select control automation modes (manual, holds, and waypoint), reflecting an adaptable automation paradigm (Sheridan, 2011). This allows the RPIC to change the control paradigm based on the demands of the situation (e.g., a high-workload phase of flight may require a higher level of control automation), and supports the FAA's (2013) requirement that autonomous operations are not permitted in the NAS unless the RPIC has the ability to override automation.

> Recommendation: While not a minimum automation requirement, a better control station design would provide multiple modes of control utilizing an adaptable automation paradigm, allowing the pilot to offload control tasks to the automation when (s)he deems necessary (Miller et al., 2012). This recommendation also matches Nielsen's (1994) design heuristic of user control and freedom.

3.3.1.4.4 Procedures

One difference between unmanned and manned operation is contingency planning for lost link situations. The ACGCS incorporates contingency planning into the flight planning procedure such that a lost link contingency plan is developed for each waypoint along the route. This prevents the RPIC from changing lost link contingency plans during the flight, allowing the RPIC to remain informed of UA actions when the link is lost. Although the RPIC is not required to update contingency plans during flight, (s)he is able to do so when necessary.

> Recommendation: The control station should support contingency planning, to the extent possible, prior to takeoff to lessen the occurrence of contingency planning during simultaneous UAS operation, when RPIC workload is already potentially high.

3.3.2 X-Gen Control Station

3.3.2.1 Background

The Embry Riddle Aeronautical University (ERAU) X-Gen control station, manufactured by URS Simulation, is used primarily to train students to become RPICs (Stansbury et al., 2015). The physical layout of the control station is modeled after the legacy General Atomics Predator control station (Figure 14). The X-Gen control station has two identical workstations that can be used for either flying the UA or for payload operation. The control station is used to control a simulated generic medium altitude long endurance UA for commercial and civil applications. Although the ERAU setup is a full control station setup, the X-Gen system can be adapted for use on a laptop computer or a desktop computer.

(a)

(b)

Figure 14. (a) General Atomics legacy UAS control station and (b) ERAU's X-Gen control station.

3.3.2.2 Operating the UAS

Input devices provided to the RPIC include stick, throttle, pedals, keyboard, and trackball. The stick, throttle, and pedals are used in the *manual control* mode, which allows the RPIC to control the UA thrust and attitude, similar to the legacy Predator control stations (Williams, 2007). The control station also provides a holds mode that allows the RPIC to upload a target heading, speed, or altitude to the UAS. Also provided to the RPIC is a waypoint mode, in which the RPIC can upload one or more waypoints to the UAS route via both keyboard entry of waypoint latitude, longitude, altitude, and speed/timing constraints, or via drag-and-drop control on a top-down map. The control station also provides user-defined performance envelope as well as ATOL functionality.

The top screen in the X-Gen control station, referred to as the tracker display, contains a static map view of the area with overlaid route information, restricted areas, and UA location with respect to the map area (Figure 15). Along the top of the screen is a drop-down menu structure containing menus for flight planning, datalink, miscellaneous controls, view, tools, and system information. The right side of the screen contains several linear scales reflecting the UA status, automation mode status, and a panel for the UAS to report system messages that are color coded by warning severity. The top portion of the left panel contains an area for drop-down menu items (e.g., the waypoint editor appears on the top-left portion of the display when selected from the drop-down menu) and the bottom-left portion of the screen contains a north-up oriented compass rose (to match the north-up static map display), displaying the heading of the UA as well as a heading bug to control the UA heading. Immediately to the right of the compass rose is a linear scale reflecting the strength of the datalink. Table 23 provides the information content presented on the tracker display, as well as the format of the information.

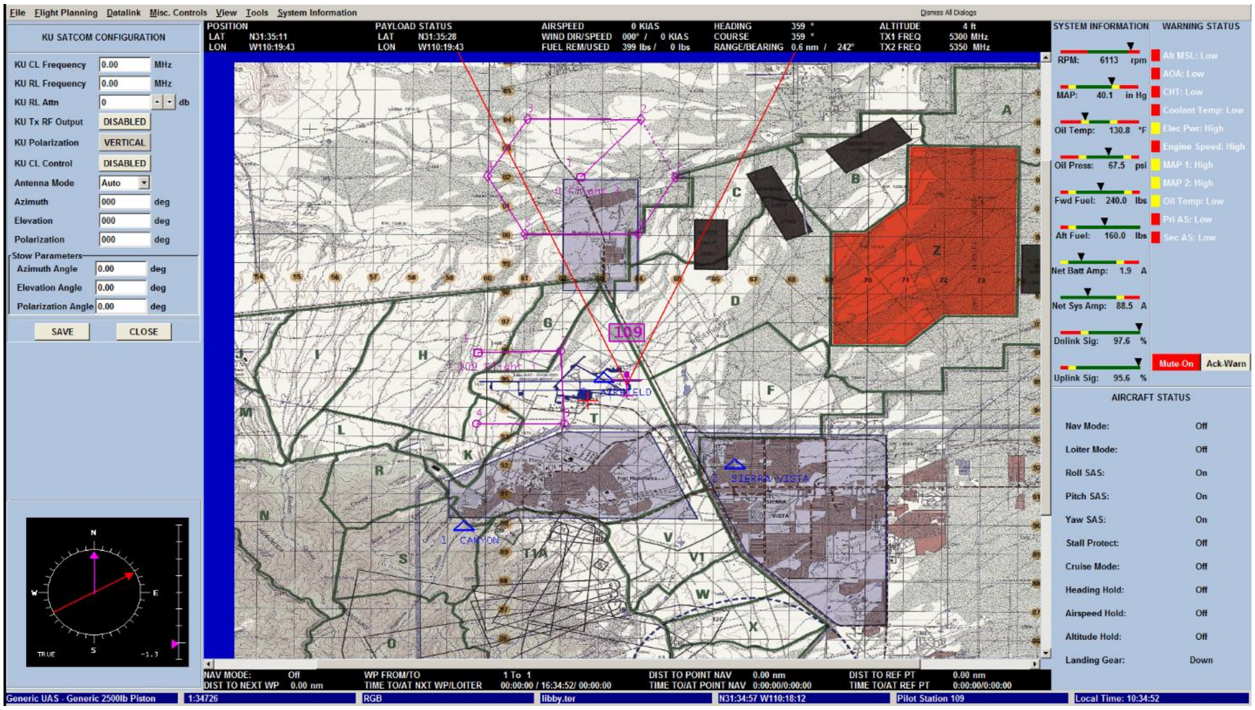


Figure 15. Static map display on the top monitor of the ERAU X-Gen control station. Received via email from URS Simulation.

Table 23. Information content of the ERAU X-Gen tracker display.

Information Item	Format
Latitude	Text
Longitude	Text
Payload view latitude	Text
Payload view longitude	Text
Indicated airspeed	Text
Wind direction	Text
Wind speed	Text
Fuel consumed	Text
Magnetic heading	Text and compass rose
Course	Text
Range	Text
Bearing	Text
Indicated Altitude	Text
Transmitter frequency	Text
Engine RPM	Text and color-coded scale
Atmospheric pressure	Text and color-coded scale
Oil temperature	Text and color-coded scale
Oil pressure	Text and color-coded scale
Fuel level	Text and color-coded scale
Current	Text and color-coded scale
Command/control downlink signal strength	Text and color-coded scale
Command/control uplink signal strength	Text and color-coded scale
Navigation mode status	Text
Loiter mode status	Text
Flight mode annunciation	Text
Landing gear status	Text
Distance to next waypoint	Text
Time to next waypoint	Text
Aircraft position relative to desired flight route	Text

The middle monitor contains an out-the-window view with HUD symbology (Figure 16). The outer border of the display contains functionality for selecting the out-the-window view (e.g., nose camera, IR camera, or payload camera), the autopilot mode(s) currently engaged, HUD elements turned on and off (e.g., airspeed, altitude, heading, or angle of attack), and flight information (e.g., location, altitude, time/distance to next waypoint). The information content of the display is reported in Table 24.

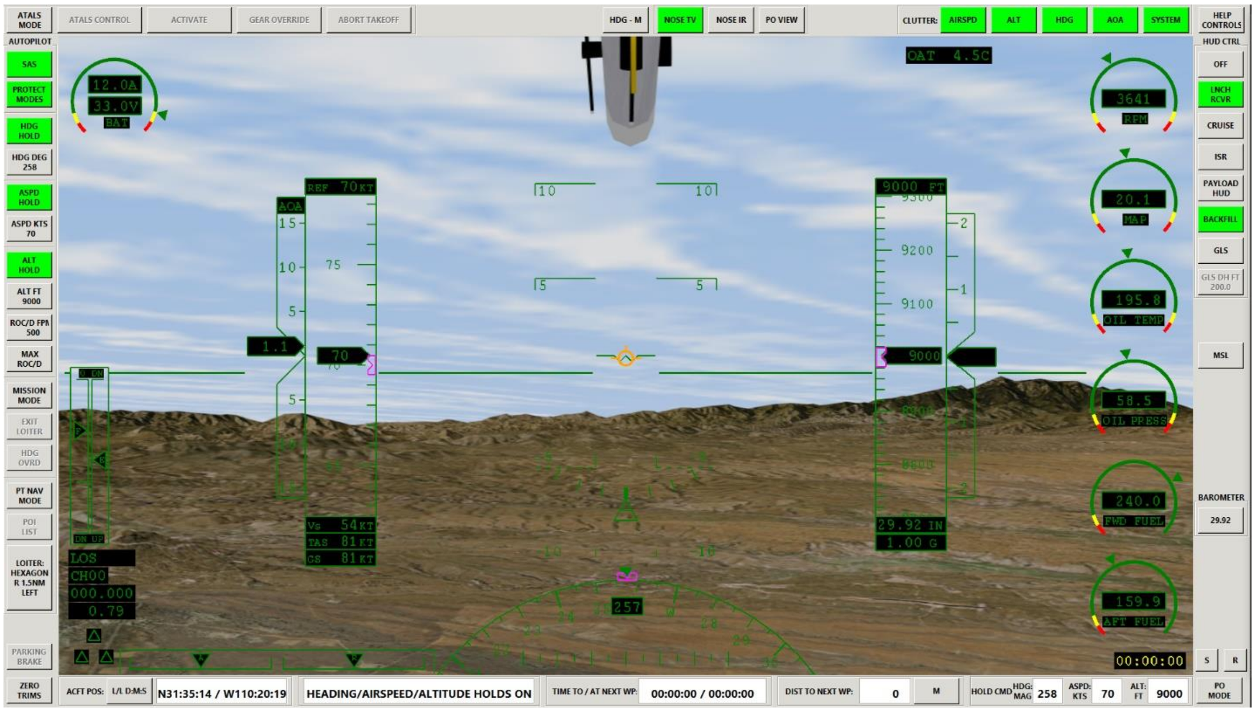


Figure 16. Payload camera view with HUD symbology on the middle monitor of the ERAU X-Gen control station.
Received via email from URS Simulation.

Table 24. Information content of the ERAU X-Gen out-the-window display.

Information Item	Format
Indicated airspeed	Text and speed tape
True airspeed	Text
Ground speed	Text
Indicated airspeed target	Text and bug
Indicated altitude	Text and altitude tape
Altitude target/clearance	Text and bug
Altimeter setting	Text
Pitch attitude	Attitude indicator
Roll attitude/bank angle	Attitude indicator
Angle of attack	Text and AOA tape
Magnetic heading	Text and compass
Battery current	Color-coded text and color-coded gauge
Battery voltage	Color-coded text and color-coded gauge
Engine RPM	Color-coded text and color-coded gauge
Atmospheric pressure	Color-coded text and color-coded gauge
Oil temperature	Color-coded text and color-coded gauge
Oil pressure	Color-coded text and color-coded gauge
Fuel level	Color-coded text and color-coded gauge
Flight mode annunciation	Color-coded indicators
Time to next waypoint	Text
Distance to next waypoint	Text
Latitude	Text
Longitude	Text
Parking brake status	Color-coded indicator

There are two small screens located below the out-the-window display. The left screen contains health and status information on a four-tab display (Figure 17), including tabs for datalink status, engine status, electrical status, and navigation system. The bottom right screen of the X-Gen control station contains information about the simulator and computer that is not relevant for UAS operation.

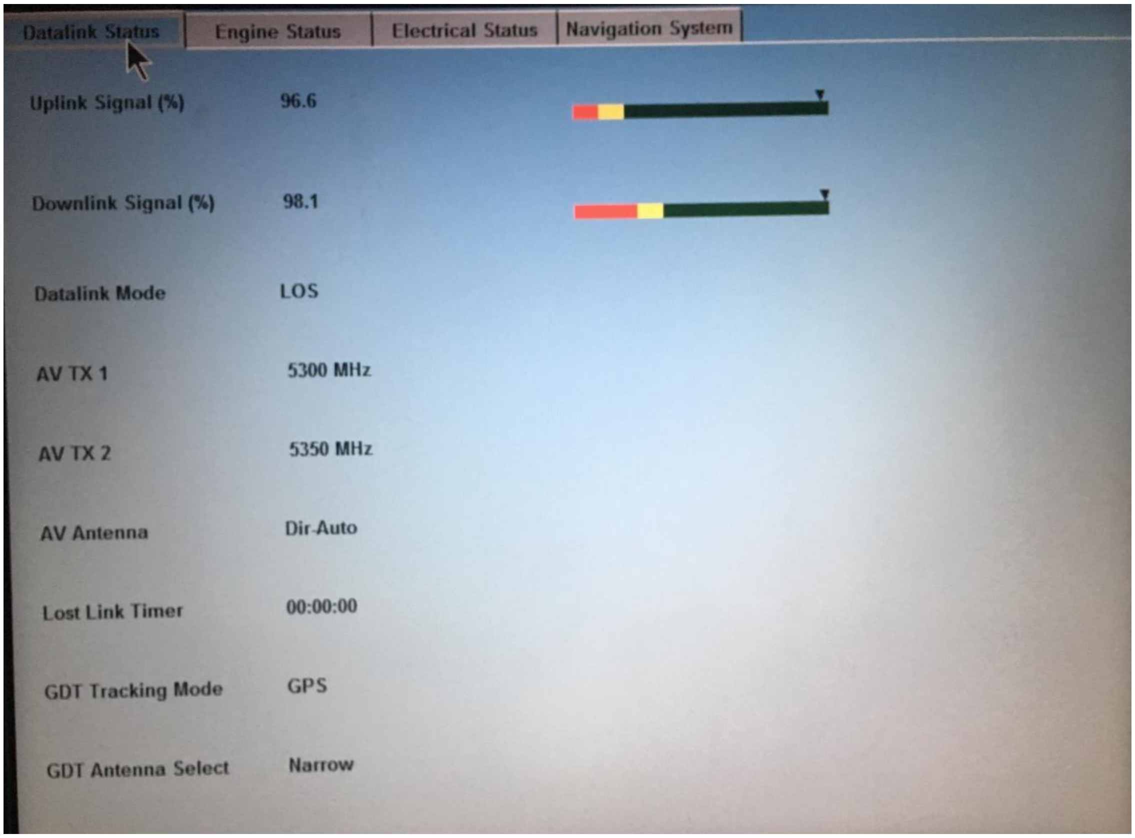


Figure 17. Datalink status panel of the health and status display on the ERAU X-Gen control station.

3.3.2.3 Recommendations

Information Requirements—The X-Gen control station was designed as a training system, including design features to enhance system performance. It was not designed as a demonstration of minimum information requirements.

3.3.2.3.1 Design Guidance

Changing the UA's route requires two steps: editing/implementing the route, and executing the new route (i.e., sending it to the UA). In the X-Gen design, there is no feedback designating whether the route displayed on the map is the executed route or the planned route that has not yet been executed.

> Recommendation: In accordance with HF-STD-001B 5.1.6.1 (Federal Aviation Administration, 2016), the control station should display both the planned route and the executed route, with identification for each route.

When making changes to the planned route, the X-Gen RPIC must remember to explicitly upload the route changes to the UAS. There are instances in which the RPIC deletes one or more waypoints from the route in the X-Gen Control Station, removing them from the static map, but the changes are not automatically uploaded to the UA. Operational aircraft should provide clear feedback to the RPIC on the status of the route upload as well as mitigate any potential negative effects of human error in changing the UAS route.

> Recommendation: The control station should provide clear feedback of whether or not any route changes have been uploaded to the UA, reflecting Nielsen's (1994) design heuristic that the system should provide visibility of the system status.

Changing waypoints can be performed either via a "click and drag" interface directly overlaying the static map, or via keyboard entry of waypoints. When coordinates are uploaded via keyboard entry, there is no error-checking functionality, so if a north latitude is uploaded rather than a south latitude, a waypoint that is potentially thousands of miles away from the route will be uploaded to the UA.

> Recommendation: The control station should provide a representation of the route allowing the RPIC to inspect the new route, reflecting Nielsen's (1994) design heuristic that systems should help its users recognize, diagnose, and recover from errors. There should also be identification that differentiates the new route being planned from the route on which the UA is flying.

Another potential issue with the route interface is that the control station does not include a database of NAS routes or navigation aids, so if the RPIC wants to fly a published route, waypoints must be created manually, introducing the potential for human error.

> Recommendation: Any UAS flying IFR in the NAS should have access to published navaids and routes to facilitate accurate, error-free flight planning. A better method would be to have them available in electronic form such as in a database. This recommendation reflects Nielsen's (1994) design heuristic of preventing errors.

The process of entering waypoints takes approximately 12 steps, and trainers indicated they observed complacency in students changing and entering waypoints while simultaneously aviating the UA.

> Recommendation: The waypoint editing interface should be designed to minimize the time required to change the UA route. This reflects Nielsen's (1994) design heuristic ensuring efficiency of use.

On the bottom, left corner of the tracker display is a compass rose and a scale reflecting the strength of the UAS control link. There are no labels associated with the control link scale, either indicating what the scale is measuring, the units of the scale, or what the hash marks on the scale represent (see Figure 18).

> Recommendation: UAS designers should strive to ensure all scales, gauges, or other display elements clearly identify what is being depicted and/or measured, reflecting Nielsen's (1994) design heuristic stating that the designer should minimize the load on user memory by providing cues promoting recognition rather than requiring the user to rely on recall.

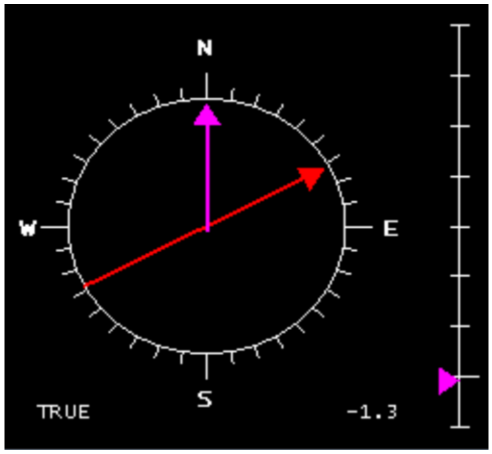


Figure 18. Compass and control signal strength scale on the ERAU X-Gen control station.

3.3.2.3.2 Automation

The X-Gen control station includes flight envelope protection as well as the ability to program limits, such as minimum and maximum altitudes. However, the RPIC is not alerted when the UA approaches or exceeds any of these limits. Therefore, control stations should inform the RPIC, either via presentation of the system status or alerting functionality, when the UA approaches any programmed or structural limits to ensure the UA remains operating safely.

> Recommendation: Alerting should be utilized when the UA approaches any safety-critical threshold, as also recommended in the Project A7 Function Allocation Recommendations (Pankok, Bass, Smith, Dolgov, & Walker, 2017).

Two comments from the ERAU UAS trainers (who are military-trained RPICs) are relevant to UAS automation. First, a UAS trainer indicated that mode confusion is common among the students. Mode confusion might lead to the UAS performing unexpected actions from the RPIC's perspective, increasing RPIC workload. Therefore, it is important that the active autopilot modes are clearly indicated on the control station displays and that the RPIC is thoroughly trained to understand how the autopilot modes operate, and if there are any dependencies or interactions among the autopilot modes.

> Recommendation: In accordance with Nielsen's (1994) design heuristic stating that the system should always keep the user informed of the system status, the UAS control station should clearly provide the RPIC with active and inactive automation modes.

The second comment from the UAS trainers was regarding landing a UAS. In the United States Air Force (USAF), the last portion of RPIC training is for takeoff and landing. It is the most difficult aspect of UAS operation and not all RPICs become qualified for takeoff and landing. For this reason, the USAF has RPICs whose only task is to conduct takeoff and landing operations, handing control over to other crews to fly the airborne phases of flight. Due to the difficulty of takeoff and landing operations, the X-Gen control station provides ATOL functionality. However, one of the trainers noted, "Since takeoff and landing are so difficult, they are expensive. Stakeholders will either need to pay for takeoff/landing through UAS automation capabilities, or through sufficient training of RPICs." Although the X-Gen control station contains ATOL functionality, trainers suggest that with sufficient training, it may be possible for all RPICs to take off and land the UA.

> Recommendation: Sufficient training to a performance criterion needs to be provided for RPICs to safely takeoff and land UASs.

3.3.3 Piccolo Command Center

3.3.3.1 Background

The Piccolo Command Center is the software user interface to control the Piccolo autopilot system, which can be installed across a variety of fixed-wing UA types, both small and larger than 55 lb. The Piccolo Command Center at ERAU is a desktop computer version of the interface containing a single monitor and mouse, keyboard, and hand-held controller input devices. The ERAU system is used to control an AAI Aerosonde UA weighing 42lb fully equipped, advertised for altitudes at or below 15,000ft MSL, and operated within electronic line of sight. The UA has vertical takeoff and landing capability, or can be hand launched and recovered via belly landing or net recovery.

3.3.3.2 Operating the UAS

The RPIC programs a route via mouse and keyboard input, which can be overridden by one or more flight parameter holds when uploaded to the UA. There is no *manual* mode to control the UA, but a hand-held controller is used for launch and recovery. The circles represent loiter areas, and the routes are color-coded based on whether the altitude of the route segment lies within the boundaries of safe operation (e.g., above the terrain and below the maximum defined altitude). Similarly, waypoints are color coded to reflect whether they have been uploaded to the UA; blue shading indicates that the waypoint has been uploaded, and gray indicates that it has not yet been uploaded to the UA. The display can be viewed either in two dimensions or in three dimensions, and a yellow route segment suggests that the route may not provide sufficient clearance over the terrain. A waypoint can be edited by clicking on it, at which point a dialogue box appears, allowing the RPIC to enter waypoint latitude and longitude, enter altitude (either mean sea level of above ground level), skip to a waypoint downstream, and designate the waypoint as a loiter point (including radius around the waypoint and the time to remain in loiter). Finally, if the RPIC wants to override the planned route, (s)he can upload a speed, altitude, bank angle, flap angle, heading, or vertical speed target to the UA. Table 25 provides the information content of the map display and associated pop-up windows.

Table 25. Information content of the ERAU Piccolo Command Center map display and associated pop-up windows.

Information Item	Format
Planned route	Point overlaid on map
Inactive flight plan(s)	Color-coded point
Planned route	Lines connecting waypoints
Loiter area(s)	Circular routes overlaid on map
Route altitude relative to terrain	Color-coded route segments Route overlaid on vertical profile
Aircraft position relative to desired flight route	Ownship symbol relative to route
Terrain height	Vertical profile display
Planned route	Text in pop-up window
Loiter waypoint radius	Text in pop-up window
Loiter waypoint time	Text in pop-up window
Loiter waypoint direction	Text in pop-up window
Indicated airspeed	Text in pop-up window
Indicated airspeed target	Text in pop-up window
Indicated altitude	Text in pop-up window
Altitude target/clearance	Text in pop-up window
Roll attitude/bank angle	Text in pop-up window
Bank angle target	Text in pop-up window
Lift/drag device position	Text in pop-up window
Lift/drag device position target	Text in pop-up window
Magnetic heading	Text in pop-up window
Heading target/clearance	Text in pop-up window
Vertical speed	Text in pop-up window
Vertical speed target	Text in pop-up window

The Piccolo Command Center also includes a primary flight display and an engine status window. The ERAU setup positions these windows to the right of the map display, although the windows can be repositioned. Consistent with the routes overlaying the map view, a green/yellow/red color scheme is used to represent levels of caution and warning on the primary flight display and engine status display. The right panel of the ERAU Piccolo Command Center also contains a system message dialogue that provides messages and alerts that are color-coded based on the level of severity. Table 26 provides the information content of the primary flight display and Table 27 provides the information content of the engine status display.

Table 26. Information content of the ERAU Piccolo Command Center PFD.

Information Item	Format
Indicated altitude	Color coded text and color-coded altitude tape
Vertical speed	Vertical speed tape
Indicated Airspeed	Color coded text and color-coded speed tape
Flight mode annunciation	Text
Position relative to desired path over ground	Localizer indicator
Position relative to desired glidepath	Glideslope indicator
Pitch attitude	Attitude indicator and scale
Roll attitude/bank angle	Attitude indicator and scale
Magnetic heading	Text
Heading target/clearance	Text
Estimated time enroute	Text
Planned route	Text
Engine RPM	Text
Distance to destination	Text

Table 27. Information content of the ERAU Piccolo Command Center engine status display.

Information Item	Format
Engine RPM	Text and color-coded gauge
System voltage	Text and color-coded scale
Throttle position	Text and color-coded scale
Engine time	Text

3.3.3.3 Recommendations

3.3.3.3.1 Information Requirements

The Piccolo autopilot system is designed for VLOS operation, so the information content on the Piccolo Command Center display is likely not sufficient for beyond visual line of sight (BVLOS) operation of a UAS larger than 55 lb. However, the information content provided by the Piccolo Command Center is a subset of the information content required to operate a larger than 55 lb UAS BVLOS. For this reason, the recommendations that follow focus on design guidance of the information content (i.e., format of information representation) that is common to both VLOS and BVLOS operations, as well as automation assistance provided to the RPIC.

3.3.3.3.2 Design Guidance

Across the displays contained on the Piccolo Command Center, a consistent green-yellow-red alerting color scheme is used to reflect UAS status. The green-yellow-red color scheme may promote accurate and fast identification of potential issues.

Recommendation: Color coding should be leveraged, where possible, to promote efficient RPIC processing of display information (Christ, 1975). FAA HF-STD-001B 5.6.6.2.1 (2016) also suggests that color should be used to promote efficient processing of display information.

Control station interfaces should be designed to prevent occlusion of flight-critical displays or information. The control station uses a pop-up window interface, for example, to change/view waypoint data and upload flight targets to the UA. These pop-up windows occlude large portions of the interface, which could potentially hide flight-critical information.

Recommendation: Control stations should be designed to prevent occlusion of flight-critical information.

3.3.3.3.3 Automation

The Piccolo UAS does not provide flight envelope protections, but does provide warnings to the RPIC when the UA approaches any altitude, speed, or airspace limits. If flight envelope protection is not available to a RPIC, alerting him/her in sufficient time to alter the flight prior to reaching the threshold in question could be a viable alternative to maintain safe operation.

Recommendation: If flight envelope protection is not designed into a UAS, alerting should be provided to ensure the UA does not exceed any safety-critical thresholds of operation (Pankok et al., 2017).

Regarding control automation, the Piccolo Command Center operates primarily via a waypoint editing mode; there is no manual mode, but there is a holds mode that can be accessed through the control station menu interface. This could be problematic in time sensitive situations requiring rapid override of the waypoint mode, such as approaching terrain or another vehicle.

Recommendation: A control station should provide the RPIC the ability to override the planned route, in accordance with the FAA's (2013) vision that the RPIC should always have automation override ability for UAS operation in the NAS.

3.3.4 SenseFly eMotion 2 Control Station

3.3.4.1 Background

The senseFly eMotion control station is used to control the eBee sUAS, which is used primarily for aerial surveys and mapping. Operation must be conducted within electronic line of sight, although the UA is GPS equipped. The eBee is hand-launched and belly landed. The system provides capability for control of multiple UAs simultaneously, but the review that follows focuses on single-UA operation. The ERAU eMotion control station is a desktop platform, but the control station can also be operated on a laptop or hand-held tablet computer. The ERAU station also features a large flat panel monitor to view the route rendered in three dimensions in Google Maps (Figure 19).

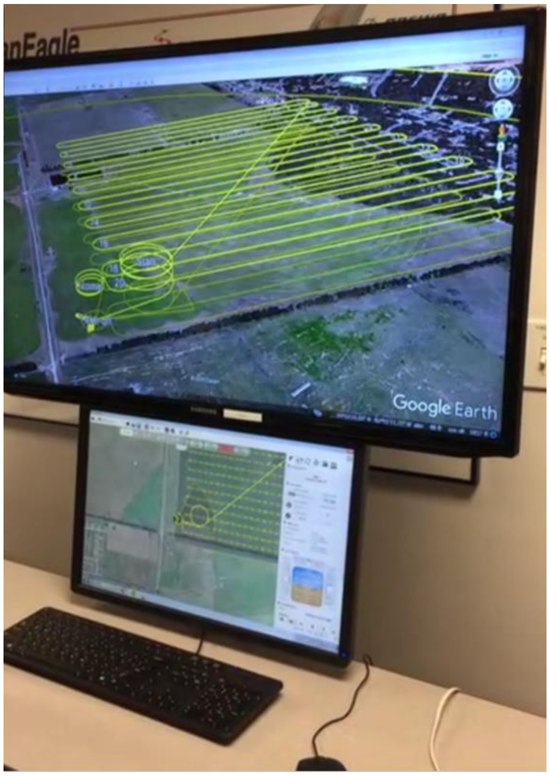


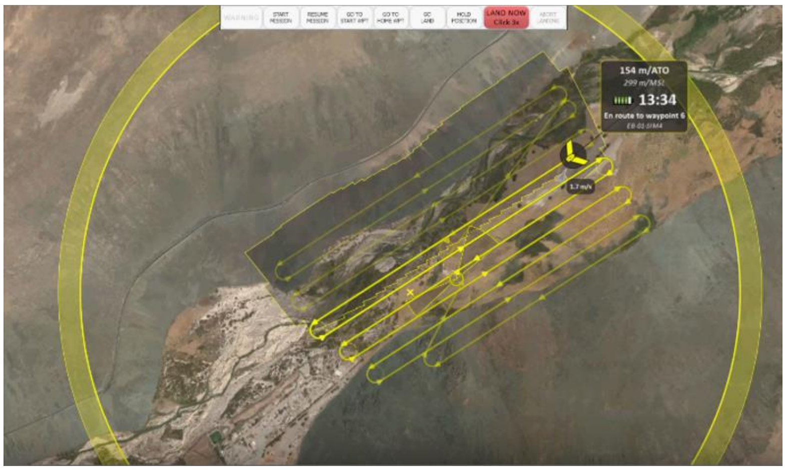
Figure 19. ERAU setup for the eMotion control station.

3.3.4.2 Operating the UAS

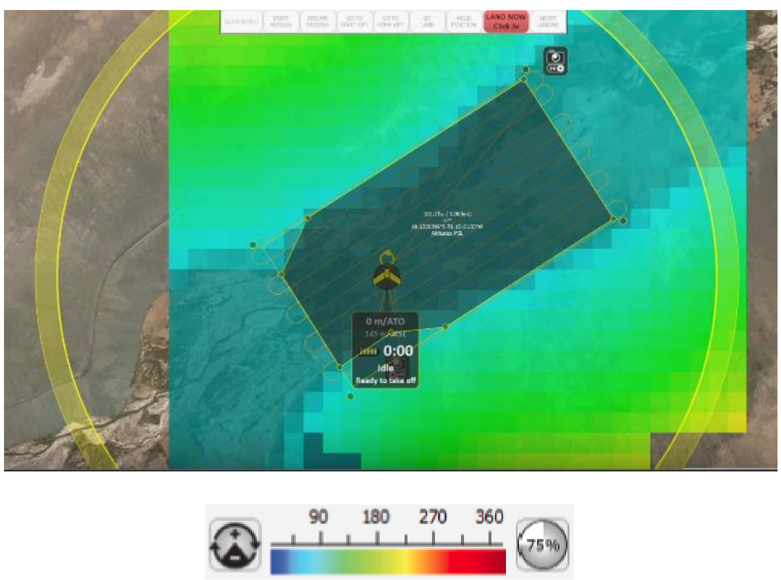
The UA can be controlled either via waypoint editing with a keyboard and mouse, or in one of two manual modes via a hand-held controller. The two control mode capabilities with the hand-held controller are referred to as full manual and assisted manual modes. In the full manual mode, the controller joysticks are used by the RPIC to control the UA thrust, elevator position, and aileron position. In the assisted manual mode, the same joysticks are used by the RPIC to control the UA speed, climb rate, and turn rate. The controller also includes dials to manipulate trim in both modes. ATOL functionality is also supported as part of the waypoint editing mode. The RPIC has two approach configuration options: a linear landing (similar to the traditional approach of a manned aircraft) and a circular landing, in which the UA descends from its operating altitude to the ground in a spiral pattern. Takeoff can also be performed with the full manual mode, but not with the assisted manual mode. Throughout the operation, the UA measures wind direction and speed, using it to adjust the flight dynamics to fly the route uploaded to the UAS.

After planning the flight, the eMotion control station provides the RPIC with a simulation capability to review the flight path before uploading it to the UA. This allows the RPIC to review the route before executing it, particularly as it relates to wind and terrain, both of which can be uploaded to the eMotion system. Once the route is finalized, the software provides the capability to import the route into the Google Earth software, allowing three-dimensional representation of the route. However, the Google Earth functionality does not support real-time ownship position and progress along the route.

The map area (Figure 20) contains route and ownship information overlaid on the map of the area to be surveyed. The UAS supports a user-defined enclosed area outside of which the UA cannot fly (approaching this boundary results in an alert sent to the RPIC). Along the top of the map view is a status bar with selectable buttons allowing the RPIC to upload commands to the UA, as well as determine the status and control mode in which the UAS is operating. Clicking on the ownship symbol opens a data tag that contains various pieces of flight information. A color map reflecting the terrain altitude can also be overlaid onto the map display, as shown in Figure 20(b). The information content contained on the map display is reported in Table 28.



(a) Map view with route overlay and UA location along route.



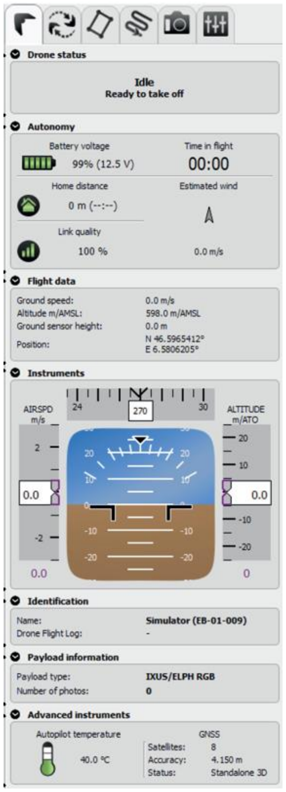
(b) Map view with color map representing terrain elevation and elevation map scale.

Figure 20. Map view of the ERAU eMotion control station with planned route overlay and terrain elevation information.
Retrieved from https://youtu.be/BKzJdF_fk0U.

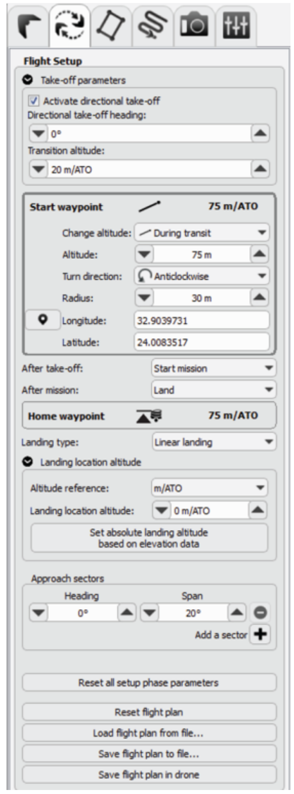
Table 28. Information content of the ERAU eMotion map display.

Information Item	Format
Aircraft position relative to desired flight route	Ownship symbol on map
Planned route	Route overlaid on map
Flight mode annunciation	Color-coded indicator Data tag text
Indicated altitude	Text Data tag text
Battery level	Data tag battery level symbol
Battery time remaining	Data tag text
Latitude	Text
Longitude	Text
Terrain height	Color map overlay
Route segment status (active, inactive, and traversed)	Line format (solid, dashed, and translucent, respectively)
Planned route	Data tag text

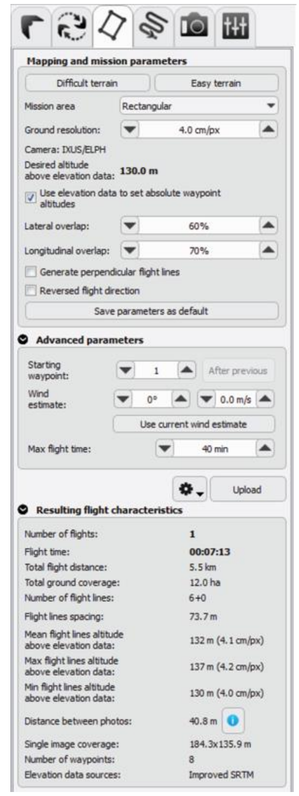
To the right of the map display is a side panel containing six tabs with relevant flight information and control capabilities. The tabs are grouped as follows: (a) flight monitoring, (b) setup phase, (c) mission planning, (d) mission waypoints, (e) camera, and (f) flight parameters tab. Screenshots of the relevant tabs are provided in Figure 21, and the information content (and format of the information presentation) of the tabs is reported in Table 29. The camera tab was excluded since it referred only to payload camera information, which is outside the A7 project scope.



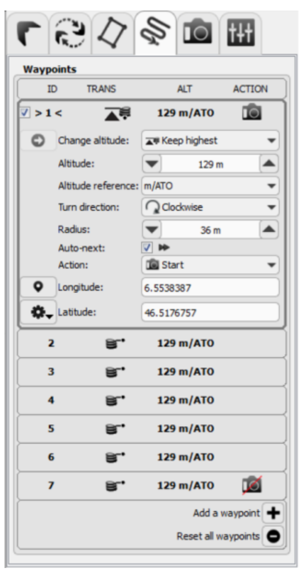
(a) Flight monitoring tab.



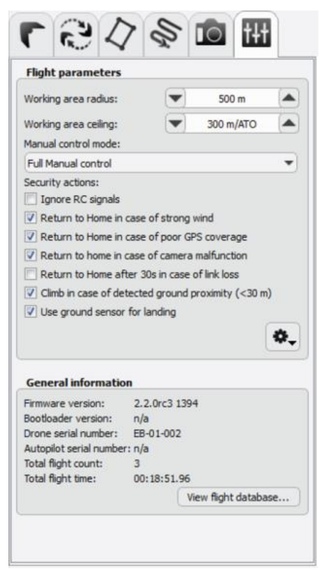
(b) Setup phase tab.



(c) Mission planning tab.



(d) Mission waypoints tab.



(e) Flight parameters tab.

Figure 21. eMotion control station tabs located on the side panel of the display. Retrieved from eBee user manual at [http://95.110.228.56/documentUAV/drone%20manual/[ENG]_2014_Extended_User_Manual_eBee_and_eBee_Ag_v12_1.pdf](http://95.110.228.56/documentUAV/drone%20manual/[ENG]_2014_Extended_User_Manual_eBee_and_eBee_Ag_v12_1.pdf).

Table 29. Information content of the ERAU eMotion side panel tabs.

Tab	Information Item	Format
Flight monitoring	UA status (including warnings and alerts)	Color-coded text
	Battery voltage	Text
	Battery charge remaining	Text and battery level symbol
	Battery flight time remaining	Text
	Distance to next waypoint	Text
	Time to next waypoint	Text
	Command/control link strength	Text
	Wind direction	Chevron direction
	Wind speed	Text
	Ground speed	Text
	Ground sensor height	Text
	Latitude	Text
	Longitude	Text
	Indicated airspeed	Text and speed tape
	Indicated airspeed target	Text
	Magnetic heading	Text and heading tape
	Indicated altitude	Text and altitude tape
	Altitude target/clearance	Text
	Pitch attitude	Attitude indicator
	Roll attitude/bank angle	Attitude indicator
	Aircraft ID	Text
	Autopilot temperature	Text and thermometer symbol
	Number of GPS satellites	Text
	GPS accuracy	Text
	GPS status	Text
Flight parameters	Operational area	Text
	Maximum altitude	Text
	Flight mode annunciation	Text
	Active contingency plan(s)	Text and checkbox
Mission planning	Wind direction	Text
	Wind speed	Text
	Maximum flight time	Text
	Elapsed flight time	Text
	Aircraft position relative to desired flight route	Text
	Mean distance above highest terrain altitude	Text
	Minimum distance above highest terrain altitude	Text
	Maximum distance above highest terrain altitude	Text
	Planned route	Text

Mission waypoints	Planned route	Text
	Altitude format (e.g., ATO, AGL, MSL)	Text
Setup phase	Charts/terminal procedures	Text
	Top of climb altitude	Text
	Home waypoint altitude	Text
	Landing type	Text
	Runway elevation (altitude)	Text
	Approach sector heading	Text
	Approach sector span	Text

3.3.4.3 Recommendations

Information Requirements—Since the eMotion control station is not designed for beyond line of sight (BLOS) operation, the information content on the displays is likely a subset of the information content required for BLOS operation (i.e., the information content is not sufficient for BLOS operation). Therefore, the recommendations that follow are limited to design guidance and automation that may be relevant for BLOS IFR operation, as information requirements differ for BLOS operation versus operation in Class G airspace in electronic line of sight.

3.3.4.3.1 Design Guidance

Data tags in the eMotion control station are translucent, reducing occlusion of potentially flight-critical information. Pop-up windows or data tags should not occlude flight critical information; rather, they should be located on another part of the display.

> Recommendation: Control stations should be designed to prevent occlusion of flight-critical information.

Similar to the other systems reviewed, the eMotion control station provides a two-level alerting paradigm, including the use of the color yellow to indicate caution and the color red to indicate warning.

> Recommendation: Color coding should be leveraged in alerting functionality to promote efficient RPIC processing of display information (Christ, 1975). FAA HF-STD-001B 5.6.6.2.1 (2016) also suggests that color should be used to promote efficient processing of display information.

When a caution or warning is present, the control station provides a *click to acknowledge* functionality, to ensure that the RPIC is aware of the warning or caution. This functionality could be problematic in time critical situations in that it is adding an additional step to the RPIC's troubleshooting procedure.

> Recommendation: Flight critical functions should be able to be performed quickly and efficiently, reflecting Nielsen's (1994) design heuristic ensuring efficiency of use.

The eMotion control station explicitly presents the vertical dimension. Color map functionality is provided to the RPIC, allowing him/her to overlay the planned route on the color map and compare the route altitude with the terrain altitude. Also provided to the RPIC, via the Google Maps import functionality, is the ability to view the route in three-dimensional space and compare it with terrain. An important design objective for UAS control stations is the presentation of information in the vertical dimension to ensure the RPIC is aware of potential obstacles in the UA's flight path.

> Recommendation: Terrain awareness support for phases of flight during which the UA is flying close to the ground, such as takeoff or landing, would be helpful to the RPIC (Alexander & Wickens, 2001; Cook et al., 2010).

3.3.4.3.2 Automation

The UA contains onboard technology that estimates wind speed and direction, and uses the information to adjust the thrust and flight surfaces to maintain flight on the planned route. This is particularly important during approach and landing, during which the UA is attempting to land in a specific area on the ground. UAS designers should consider how the RPIC will account for wind when operating the UAS.

> Recommendation: The presentation of wind speed and direction to the RPIC would help the RPIC from deviating from its planned route. Control automation could also help to reduce possible deviations from the planned route.

3.3.5 Procerus Virtual Cockpit

3.3.5.1 Background

The Lockheed Martin Procerus Virtual Cockpit is a laptop-based control station for control of sUAS. Our review focuses on the use of the Procerus Virtual Cockpit to control an Altavian Nova UA, used primarily for aerial surveying and operated under Visual Meteorological Conditions. The Nova has GPS capability and requires a two-person crew; one to control the UA and the other to observe. The Nova is hand launched and performs a belly landing.

3.3.5.2 Operating the UAS

The primary control mode is a waypoint editing mode; waypoint locations, altitudes, and speed/timing targets can be entered via keyboard entry, or via a drag-and-drop interface overlaying the map display. The Altavian Nova has four control modes, including auto (UA flies the mission as planned), nav to (UA skips one or more waypoints and flies directly to selected waypoint), loiter (UA rotates around selected waypoint), and fly by wire (RPIC has direct control over throttle and yaw, and limited control over pitch and roll via a hand-held controller). The Procerus Virtual Cockpit also provides the ability to override the altitude or airspeed via text entry in the settings panel.

The map display contains the route and waypoints overlaid on a map of the area as well as the location of the ownship along the planned route. Waypoints can be moved via touchpad/mouse input and uploaded to the UA. Clicking on the waypoints also displays a pop-up window containing waypoint data. When the waypoint is a rally point (the last waypoint before initiating approach), the window provides more approach/landing specific options and data. Furthermore, when a flight parameter approaches or exceeds a threshold, the RPIC is alerted via shading of the text. The information content of the map display is reported in Table 30.

Table 30. Information content of the Procerus Virtual Cockpit map display.

Information Item	Format
Aircraft position relative to desired flight route	UA symbol on map
Latitude	Text
Longitude	Text
Target latitude	Text
Target longitude	Text
Distance to next waypoint	Text
Time to next waypoint	Text
Ground speed	Text
Planned route	Route overlaid on map
Wind speed	Text
Wind direction	Compass

The control panel of the Procerus Virtual Cockpit display presents the control mode(s) to the RPIC, as well as the ability to change the control mode. The control panel also provides system health and status information (e.g., control link strength and battery level), as well as a primary flight display. The information content of the control panel is provided in Table 31.

Table 31. Information content of the Procerus Virtual Cockpit control panel.

Information Item	Format
Flight mode annunciation	Color-coded indicator
Battery voltage	Text
Battery level	Battery level symbol
Command/control link strength	Text and signal strength symbol
GPS signal strength	Signal strength symbol
Number of GPS satellites	Text
Indicated airspeed	Text and speed tape
Indicated airspeed target	Text
Magnetic heading	Text and heading tape
Indicated altitude	Text and altitude tape
Altitude target/clearance	Text
Pitch attitude	Attitude indicator
Roll attitude/bank angle	Attitude indicator

The waypoint panel of the Procerus Virtual Cockpit provides the RPIC with a table containing waypoint information as well as the ability to make changes to the waypoints and planned route.

The display of the waypoint panel is controlled by the RPIC. The information content of the waypoint panel is provided in Table 32.

Table 32. Information content of the Procerus Virtual Cockpit waypoint panel.

Information Item	Format
Waypoint ID	Text
Waypoint order	Text
Waypoint speed restriction	Text
Waypoint altitude	Text
Waypoint latitude	Text
Waypoint longitude	Text
Waypoint time restriction	Text
Waypoint turning radius	Text

The Procerus Virtual Cockpit display contains a settings panel (where the RPIC controls whether it is displayed) that provides the pilot with capability to toggle map display information/features, UA control capabilities, and engine and fuel status indications. The settings panel provides the RPIC the ability to upload altitude and airspeed holds that override the waypoint control mode as well as flap and spoiler control of the UA. Table 33 contains the information content of the settings panel.

Table 33. Information content of the Procerus Virtual Cockpit settings panel.

Information Item	Format
Altitude target/clearance	Text
Indicated airspeed target	Text
Engine status	Color coded text
Engine RPM	Text
Engine RPM status	Color coded text
Fuel level	Color coded text
Lift/drag device position	Text and scale

3.3.5.3 Recommendations

Information Requirements—Since the Procerus Virtual Cockpit control station is not designed for BLOS operation, we are limiting our recommendations to design guidance that may be relevant for BLOS IFR operation, as information requirements differ for BLOS operation versus operation in Class G airspace in visual line of sight.

3.3.5.3.1 Design Guidance

The Procerus Virtual Cockpit displays pop-up windows that occlude large areas of the map display, which contains a large amount of information that is important for operating the UA. Similarly, to access the waypoint and settings panels, large areas of the map display are occluded, which could require the RPIC to manipulate the map display to ensure all flight critical information is in view. As mentioned previously, flight critical information should never be occluded.

Recommendation: Control stations should be designed to prevent occlusion of flight-critical information.

3.4 UAS INCIDENT AND ACCIDENT ANALYSIS

3.4.1 NTSB UAS Incident and Accident Reports

A query of https://www.ntsb.gov/_layouts/ntsb.aviation/index.aspx yielded 68 reports. 56 unrelated ones were then culled (the culled ones are listed in Appendix D10). The NTSB reports reviewed are listed below in reverse chronological order. The NTSB findings are from the accident reports. The HFACS findings and recommendations were developed by the A7 performers.

3.4.1.1 DCA16CA197 (Event date 06/28/2016)

In VMC, an Aquila UA (with a certified maximum gross weight of 937 pounds) sustained inflight structural failure on final approach due to turbulence. The report states:

"A structural failure of the wing as a result of exceeding the airspeed envelope due to wind gusts which were beyond the capabilities of the autopilot. Contributing to the accident was an insufficient amount of drag to track the glideslope in the presence of atmospheric disturbances."

The NTSB findings are:

Aircraft	Main frame (on wing) - Failure (Cause)
	Autopilot computer - Capability exceeded (Factor)
Environmental issues	Convective turbulence - Effect on equipment (Cause)

The HFACS categorization for this event relates to preconditions for unsafe acts:

- Technological environment:
    - Main frame (on wing)
    - Autopilot computer - Capability exceeded
- Physical environment: Convective turbulence

3.4.1.1.1 Recommendations

While not directly relevant to function allocation or information requirements, with respect to minimal recommendations, the pilot in command should not fly a UA in conditions in which it is not airworthy.

With respect to higher levels of automation, this event could inform control automation to account for atmospheric disturbances. It could also information analysis automation support to help the pilot understand the environmental situation as well as the limits of the automation.

3.4.1.2 GAA16CA216 (Event date 05/03/2016)

Although this nonfatal event involved an ultralight (Airborne Redback), the pilot's failure to adequately secure the aircraft while manually starting the engine from outside the cockpit resulted in the unmanned aircraft becoming airborne and colliding with a hangar roof.

The NTSB findings are:

Aircraft	Engine starting - Incorrect use/operation (Cause)
Personnel issues	Aircraft control - Pilot (Cause)
	Incorrect action sequence - Pilot (Cause)
Environmental issues	Airport structure - Contributed to outcome

The HFACS categorization for this event includes unsafe acts and preconditions for unsafe acts. With respect to unsafe acts, the finding includes:

- Judgment and decision-making error: Incorrect action sequence

With respect to preconditions for unsafe acts, the findings include:

- Technological environment:
    - Aircraft: Engine starting - Incorrect use/operation
- Physical environment:
    - Airport structure

3.4.1.2.1 Recommendation

While not directly relevant to function allocation or information requirements, with respect to minimal recommendations, this event should inform procedures for engine start.

3.4.1.3 DCA15CA117 (Event date 05/01/2015)

A Titan Solara 5 solar-powered experimental UA (with a certified maximum gross weight of 350 pounds) sustained structural failure of the left wing due to an overspeed condition. The report states:

> "*The operator indicated that the aircraft then encountered significant thermal air mass activity and began to both climb and exceed its design airspeed for an extended period of time… These thermal events were not immediately evident to the pilot due to latency of the aircraft instruments.*"

The NTSB findings are:

Aircraft	Spar (on wing) - Failure (Cause)
Environmental issues	Ability to respond/compensate (Factor)

The HFACS category for this event includes preconditions for unsafe acts:

- Technological environment:
    - Aircraft: Spar (on wing)
- Physical environment: turbulence

3.4.1.3.1 Recommendations

While not directly relevant to function allocation or information requirements, the pilot in command should not fly a UA in conditions in which it is not airworthy.

With respect to higher levels of automation, this event could inform control automation to account for atmospheric disturbances. It could also information analysis automation support to help the pilot understand the environmental situation as well as the limits of the automation.

3.4.1.4 DCA14CS043 (Event date 01/27/2014)

A General Atomics MQ-9 UAS (with a certified maximum gross weight of 12,000 pounds) operated under IFR in VMC was substantially damaged. The crew proceeded to the Flight Termination Point (FTP) and executed an intentional ditching due to a generator failure approximately one hour prior to the ditching. There was insufficient battery power for the UAS to transit to the nearest recovery site. An alert had triggered the pilot to execute the Dual Generator Failure Checklist but restoration of generator operation failed.

At approximately 600 feet MSL, the crew lost link with the aircraft due to a low voltage condition but after approximately two minutes, the crew was able to re-establish the link. The aircraft had started on its lost link profile (last set to 5,000 feet MSL). The crew re-established the command link and positive control. The pilot maneuvered the aircraft back towards the FTP to complete the ditching.

The NTSB findings are:

Aircraft	AC generator-alternator - Failure (Cause)
	AC generator-alternator - Design (Factor)
Personnel issues	Flight crew (Factor)

The HFACS categorization for this event includes preconditions for unsafe acts:

- Technical environment:
    - Aircraft: AC generator-alternator

- Personnel: Checklist and action

3.4.1.4.1 Recommendations

While not directly relevant to function allocation or information requirements, with respect to minimal recommendations, this event should inform procedures for generator failure associated with ditching procedures. This event should inform procedures for lost link due to low battery.

With respect to minimal recommendations, this event should inform information analysis automation support to help the pilot understand the status of the power plant.

3.4.1.5 DCA13CA172 (Event date 07/26/2013)

A National Aeronautics and Space Administration (NASA) Sensor Integration Evaluation Remote Research Aircraft (SIERRA) single-engine fixed wing UAS (with a certified maximum gross weight of 400 pounds) was substantially damaged following an engine power loss and uncontrolled descent into the sea. The Marginal Ice Zone Observations and Processes Experiment (MIZOPEX) Project was under significant time and budget constraints due to a change in project plan from a larger UAS platform requiring payload bay changes within the original funding timeline. The report states:

> "*The flight crew noted a loss of engine RPM and electrical bus voltage on the CloudCap Piccolo Autopilot (AP) system display that was part of the ground control system (GCS). The UAS was beyond the range of the hand held radio and under the control of the Piccolo AP, upon losing power the control station operator was unable to issue any commands to the aircraft. Telemetry data revealed that for a period of about 60 minutes prior to the accident, RPM and altitude fluctuated, and throttle demand increased, indicating the possibility of engine intake icing.*"

The NTSB findings are:

Aircraft	Engine (reciprocating) - Damaged/degraded (Cause)
Environmental issues	Conducive to carburetor icing - Effect on equipment (Factor)
Organizational issues	Adequacy of safety program - Operator (Factor)
	Equipment design - Not specified (Factor)
	Task scheduling/workload - Operator (Factor)

HFACS categorization for this event includes preconditions for unsafe acts.

- Physical environment: Conducive to carburetor icing
- Technical environment:
    - Equipment design: Aircraft engine (reciprocating)

3.4.1.5.1 Recommendations

While not directly relevant to function allocation or information requirements, with respect to minimal recommendations, the pilot in command should not fly a UA in conditions in which it is not airworthy.

With respect to minimum requirements, the event informs information analysis automation support to engine status, autopilot status, and system status.

With respect to higher levels of automation, this event could inform control automation to account for atmospheric disturbances. It could also information analysis automation support to help the pilot understand the environmental situation and the limits of the automation.

3.4.1.6 DCA 12CA023 (Event date 12/19/2011)

An experimental Meridian UAS (with a certified maximum gross weight of 1200 pounds) crashed on final approach. The probable cause of this accident was an aerodynamic stall induced by an inadvertent autopilot Home command. The Home command was entered following a loss of the direct radio link due to improperly set failsafe settings, and an unintentional latching of Home mode from an earlier functionality test. The report states:

> "*Approximately 60 seconds prior to the accident, the pilot took over direct control of the aircraft via 72MHz radio control (similar to a model airplane). On final approach, as the aircraft was commanded low power and nose down pitch, the aircraft lost the 72MHz link, and as programmed the flight control system switched to an autopilot Manual (Assisted) mode. The Manual (Assisted) mode commanded the aircraft to predefined "failsafe" settings of 100 knots airspeed and neutral controls, resulting in about 27 degrees of nose up pitch change. After about one second, the control mode was changed from the failsafe setting to the Home mode, which was inadvertently left latched due to a functionality test earlier in the flight. The Home mode commanded the airplane to climb toward the home waypoint, which was over the runway, and enter an orbit. The airplane was well below the home altitude and at low airspeeds for approach. The command resulted in a power-on stall and steep nose down descent. Radio control link was re-established but too late to recover from the stall.*"

The NTSB findings are:

Aircraft	Angle of attack - Capability exceeded (Cause)
	Autopilot system - Incorrect use/operation (Factor)
	Autopilot system - Unintentional use/operation (Factor)
Organizational issues	Equip certification/testing - Operator (Factor)

The HFACS categorization for this event is preconditions for unsafe acts:

- Technical environment:
  - Aircraft: Angle of attack - Capability exceeded

- Autopilot system - Incorrect use/operation
- Autopilot system - Unintentional use/operation
- Adverse mental states
  - Mode awareness of autopilot system

3.4.1.6.1 Recommendations

While not directly relevant to function allocation or information requirements, with respect to minimal recommendations, this event should inform procedures for approach.

With respect to minimum recommendations this event informs information analysis automation to help the pilot to avoid stalls (stall warning).

With respect to minimum recommendations this event informs information analysis automation to help the pilot with mode awareness.

With respect to higher levels of automation, this event could inform control automation for stall recovery.

With respect to higher levels of automation, this event could inform control automation for automated approach.

3.4.1.7 DCA09FA028 (Event date 02/19/2009)

A General Atomics MQ-9 Predator UAS (with a certified maximum gross weight of 10,500 pounds) experienced a hard landing and tailstrike resulting in substantial damage to the lower vertical stabilizer and propeller. In the landing flare (about six feet above the touchdown zone), a tailwind of approximately 9 knots was recorded. One should increase the pitch to arrest the descent rate and increase power to begin a go-around. However, the aircraft touched down hard on the main gear and lower vertical stabilizer and porpoised a number of times. The go-around was executed and the aircraft landed.

The NTSB findings are:

Personnel issues	Aircraft control - Pilot (Cause)
	Delayed action - Instructor/check pilot (Cause)
Environmental issues	Tailwind - Effect on operation

The HFACS categorization for this event includes unsafe acts and preconditions for unsafe acts.

Unsafe acts:

- Skill-based errors: Student pilot could not do as the instructor suggested
- Judgment and decision-making errors:
  - The student did not know to flare and to add power to initiate a go-around.
  - The instructor did not intervene.

Preconditions for unsafe acts:

- Physical environment: Tail wind

3.4.1.7.1 Recommendations

Although not related to function allocation or information requirements, tailwind landings should be prohibited.

With respect to information acquisition and information analysis automation, a laser altimeter/height annunciator is warranted.

See also NTSB recommendations A-07-065 through A-07-069 for the FAA and A-07-070 through A-07-086 for the Customs and Border Protection (CBP).

3.4.1.8 DCA09FA009 (Event date 11/06/2008)

During a touch and go landing at night, a General Atomics MQ-9 Predator-B UAS (with a certified maximum gross weight of 10,000 pounds) bounced and contacted the runway four times. The magnitude of the bounces and pitch excursions dynamically increased until the nosewheel fractured and the aircraft began to slide. A trainee pilot was completing the touch and go landings. The accident landing was the first during the training session using the Multi-Spectral Targeting Ball (MTS-B) payload camera (as opposed to the fixed nose camera). The payload camera was located about 3 feet lower than the fixed nose camera and thus produced a different angle and field of view. The payload camera was gyro stabilized for mission requirements and gave a different visual perception during landing. With the MTS-B, the pilot initiated the flare closer to the runway and to less of a nose up attitude than normal. The corrective go-around was initiated too late to prevent the accident.

The failure of the pilot to timely flare the aircraft to the appropriate attitude, likely associated with the different sight picture after switching cameras, resulting in a bounced landing; and the evaluator pilot's lack of timely recognition and intervention. Contributing to the accident was the lack of standards and criteria in the Customs and Border Protection initial and recurrent training program for use of the MTS-B camera.

The NTSB findings are:

Aircraft	Landing flare - Not attained/maintained (Cause)
Personnel issues	Aircraft control - Pilot (Cause)
	Delayed action - Instructor/check pilot (Cause)
	Visual illusion/disorientation - Pilot (Cause)
Organizational issues	Training - Operator (Factor)

The HFACS categorization for this event is unsafe acts:

- Skill-based error: Landing flare not attained

- Perceptual errors: Visual illusion/disorientation
- Judgment and decision-making errors:
    - The instructor did not intervene

3.4.1.8.1 Recommendations

With respect to higher levels of automation, this event could inform information analysis automation for landing guidance.

With respect to higher levels of automation, this event could inform control automation for automated landing.

3.4.1.9 DEN08IA160 (Event date 09/24/2008)

An experimental Raytheon Cobra UAS (with a certified maximum gross weight of 110 pounds) flying in VMC conditions was destroyed when it lost engine power and crashed. The aircraft was performing an automatic takeoff and climb to 1,000 feet AGL, flying a programming leg for the benefit of the internal mapping system, entering a grid series of legs, descending to pattern altitude and entering a non-standard traffic pattern from which it would execute an automatic landing.

The aircraft lost engine power while setting up for landing. The autopilot commanded the aircraft to descend, holding airspeed and maintaining its ground track profile.

An observer watching the aircraft from the ground queried the internal pilot (aircraft operator in the truck manning the control console) at the command station regarding the descent. The internal pilot saw a red-highlighted warning on the console indicating that the engine RPMs were at zero. The aircraft aligned with the runway at an altitude approximately 800 feet above the ground. The internal pilot told the pilot to input the "Land Now" command. At the console, instead of inputting the "Land Now" command, the pilot switched the remote control box to "manual" instead and the aircraft pitched down approximately 45 degrees and descended rapidly. The Test Director, also watching from the ground, radioed the command to "pull up." The internal pilot switched the remote-control box back to "automatic." The aircraft leveled off and corrected back over the runway at an altitude of approximately 60 to 70 feet. At approximately 1,400 feet down the runway, the aircraft entered a steep right diving turn and impacted the terrain.

A loss of engine power resulted from an overheated piston, and the pilot’s failure to send the proper command to the UAS. Contributing to the accident was the operation of the engine at high power for an extended period with a lean fuel setting. Coordination among the observer, internal pilot, pilot, test director, and observer may also have contributed.

The NTSB findings are:

Aircraft	Engine (reciprocating) - Failure (Cause)
	Fuel control/carburetor - Incorrect use/operation (Factor)
	Engine (reciprocating) - Incorrect use/operation (Factor)
Personnel issues	Incorrect action selection - Pilot (Cause)
	CRM/MRM techniques - Flight crew

The HFACS categorization for this event includes unsafe acts and precondition for unsafe acts.

Unsafe acts:

- Judgment and decision-making errors: decision to make wrong actions

Preconditions for unsafe acts:

- Technical environment:
    - Aircraft: Engine (reciprocating)

The HFACS also would include unsafe supervision (lack of guidance and/or oversight) but that is not relevant to this analysis.

3.4.1.9.1 Recommendations

With respect to automation, this event could inform information analysis automation for engine power status.

With respect to higher levels of automation, this event could inform control automation for automated landing.

3.4.1.10 DEN08IA130 (Event date 09/24/2008)

An experimental Raytheon Cobra UAS (with a certified maximum gross weight of 80 pounds), flying in VMC conditions, was destroyed when it crashed into a light pole while maneuvering for a pre-programmed landing.

During the turn to final for landing, the aircraft undershot the final approach. The supplemental pilot and observer both called to abort and the internal pilot selected the "abort" command. The aircraft established itself and flew the pattern. During the turn to final on the second landing pattern, the aircraft undershot the turn again. The supplemental pilot and observer both called to abort and the internal pilot again selected the abort command. On the third traffic pattern, the aircraft overshot the final turn waypoint flying approximately 89 feet west of flight path centerline. The supplemental pilot and the observer thought the aircraft would correct itself back to the programmed flight path and miss the pole. The wing-mounted camera showed the UAS west of and above the first of three 80-foot tall stadium lights that aligned the east side of a soccer field. The camera then showed the UAS in a 45-degree bank descending turn, heading toward the middle set of stadium lights. The last image recorded by the aircraft's wing camera had the stadium lights within feet of the camera. The aircraft impacted the top of the lights. The aircraft's right wing fractured and remained in the top bank of lights. The remainder of the aircraft fell to the ground impacting terrain within feet of the base of the light pole. The right wing was subsequently dislodged by the wind and fell to the ground.

The abnormal tracking was due to software and gains parameters being inadequate to compensate for the winds at the aircraft's flight altitude and the programmed aggressive profile. The failure to program the UAS with flight-tested parameters that could tolerate the high-density altitude and tailwind conditions encountered during the flight resulted in two undershoot approaches. An undiscovered software anomaly resulted in a momentary loss of control and overshoot of the final approach course, followed by a steep descent and subsequent collision with a light pole.

The NTSB findings are:

Aircraft	Autopilot system - Capability exceeded
Personnel issues	Performance calculations - Flight crew (Cause)
Environmental issues	Light pole - Contributed to outcome
	High density altitude - Effect on equipment
	Tailwind - Effect on equipment

The HFACS categorization for this event includes unsafe acts and preconditions for unsafe acts.

Unsafe acts:

- Judgment and decision-making errors: Decision to make wrong actions

Preconditions for unsafe acts:

- Technical environment:
    - Lack of support for high density altitude and tailwind conditions
- Physical environment:
    - Flying close to light poles

3.4.1.10.1 Recommendations

While not directly relevant to function allocation or information requirements, with respect to minimal recommendations, the pilot in command should not fly a UA in tailwind conditions.

With respect to higher levels of automation, this event could inform information analysis automation and control automation to avoid excessive speeds.

With respect to higher levels of automation, this event could inform control automation for automated landings.

3.4.1.11 SEA07IA237 (Event date 08/24/2007)

A flight crew of three pilots (flight instructor, a student pilot, and a supplemental pilot) plus observer were operating an experimental Raytheon Cobra UAS (with a certified maximum gross weight of 105 pounds) in VMC.

In order to control the aircraft using the Manual Pilot Console, the address of the specific aircraft to be controlled, the "pilot address," is entered using the Pilot Console. Changing the address on the Pilot Console directs the output of the Manual Pilot Console to the specific aircraft. A mode switch on the Manual Pilot Console is used to switch between automatic and manual control of the aircraft.

The student pilot was using the computer-based interface and not the Manual Pilot Console. The student pilot initiated the automatic landing sequence. The flight instructor’s attention was distracted from the primary flight display by a request from the observer. Meanwhile, the student pilot noticed that the pilot address for the Manual Pilot Console was still on the address of the other aircraft. Without verifying that the mode switch was in the automatic position, he changed the pilot address to the address of the accident aircraft so the supplemental pilot would be able to manually control the aircraft if the autopilot malfunctioned. When he changed addresses, he assumed that the mode switch on the Manual Pilot Console was in the automatic position, which would have resulted in the aircraft continuing the automatic landing. Changing the address with the mode switch in manual position resulted in a disconnect of the accident aircraft's autopilot. Before the supplemental pilot could pick up the Manual Pilot Console and assume control, the aircraft, now in manual mode with the autopilot disconnected, rolled to the left, entered a vertical dive, and impacted the ground.

The student pilot’s failure to follow proper procedures, specifically not verifying that the mode switch was in the automatic position before changing the pilot address, resulted in a loss of aircraft control. Contributing to the accident was the flight instructor's inadequate supervision of the student pilot.

A software/hardware fail-safe change was designed to make it impossible to change the pilot address for the Manual Pilot Console if the mode switch is in the manual position. The switch must now be moved to the automatic position prior to making the pilot address change.

The NTSB findings are:

Personnel issues	Aircraft control not maintained (cause) Procedures not followed (cause)
Environmental issues	Terrain condition-ground
Organizational issues	Inadequate supervisor (factor)

The HFACS categorization for this event includes unsafe acts and preconditions for unsafe acts.

Unsafe acts:

- Judgment and decision-making errors: Decision to make wrong actions

Preconditions for unsafe acts:

- Technical environment:
    - Lack of support for mode awareness

This event also involves unsafe supervisor (inadequate supervision: lack of guidance and/or oversight).

3.4.1.11.1 Recommendations

With respect to minimum recommendations this event informs information analysis automation to help the pilot with mode awareness.

3.4.1.12 CHI06MA121 (Event date 04/25/2006)

A Predator B (with a certified maximum gross weight of 10,000 pounds) crashed within 100 yards of a house in a sparsely populated residential area. There were no injuries to persons on the ground. There are two nearly identical control consoles (PPO-1 and PPO-2). The aircraft control levers (flaps, condition lever, throttle, and speed lever) on PPO-1 and PPO-2 appear identical, but they may have different functions depending on which console controls the UA.

The NTSB determined that the probable causes for this accident included the pilot's failure to use checklist procedures when switching operational control from PPO-1 to PPO-2, which resulted in the fuel valve inadvertently being shut off and the subsequent total loss of engine power, and lack of a flight instructor in the GCS, as required by the CBP's approval to allow the pilot to fly the Predator B. Factors associated with the accident were repeated and unresolved console lockups, inadequate maintenance procedures performed by the manufacturer, and the operator's inadequate surveillance of the UAS program.

The HFACS categorization for this event is:

- Technical environment:
  - Lack of support for mode awareness

Some of the recommendations are the same as those for DCA09FA028. Other recommendations include the need for routes for the lost-link flightpath and a safe zone for a crash landing.

With respect to recommendation for information analysis automation, the UA should allow the continuation of the satellite communication system and the transponder on engine shutdown.

With respect to information analysis automation, the display design should include adequate visual and aural indications for safety-critical fault conditions. Engine data and fault annunciations should be displayed and prioritized. Unique aural annunciation should be associated with the engine-out indication.

Design considerations include ensuring that the control stations for similar roles implement the displays, controls and modes in similar ways.

3.4.2 ASRS Reports

The query of the ASRS database using "UAS or UAV or unmanned" in the search text through February 2017 yielded 229 reports.

85 of these reports were not relevant matches:

- 19 were not relevant because UAS is also an acronym for "Undesired Aircraft State."

- 61 were not relevant because something other than an operating UA was unmanned: airfield, airport, balloon, belt loader, door, equipment, fixed-base operator (FBO), frequency, jetway, parked aircraft or vehicle, position, shift, station or station release, tower, truck, or Unicom.
- Two (2) were not relevant due to a rocket attack.
- Two (2) were not relevant because UAS was mentioned as part of the context but the event had to do with a manned aircraft flight and the UAS was not relevant.
- For one report, it is not clear why there was a match as the report was about clear air turbulence impacting a manned aircraft following a B767.

Twelve (12) other reports were not relevant for the analysis:

- Nine (9) of the reports included a description of non-events where the submission described a situation but there was no event.
- One (1) described the sighting of a UA by a Federal agent.
- Two (2) described autopilot failures.

Forty-five (45) reports were not problems and did not fall into HFACS categories. For example, forty-two (42) reports address identification of a UA:

- UA was identified and avoided either with or without an evasive maneuver (35).
- TCAS RA supported identification (4).
- UA was identified but was not a factor (3).

Three of the forty-five reports address identification of a manned aircraft by UA operator.

Eight reports addressed system known contingency operations:

  - Lost communications (3)
  - Lost link (5)

The remaining 79 relevant reports fell into HFACS categories. Sixty-eight (68) were unsafe acts:

- Perceptual errors: errors occurring when sensory input is degraded (15):
  - No or late identification of a UA (15)
    - Failure to be able to maintain visual contact with UA led to potential LOS (1)
    - Failure to know trajectory of non-cooperative UA led to potential LOS (2)
    - Failure to identify or identify too late to take action (12)
- Exceptional violations (16)
  - Lack of clearance adherence (3)
    - Pilot follows LOA and not clearance (2)
    - Pilot follows programmed flight and not clearance (1)
  - Lack of airworthiness certificate (1)
  - Incorrect registration (as a recreational operator instead of as a commercial operator) (1)

- Lack of procedure adherence by UA pilot (8)
  - Lack of pilot communication (5)
    - Failure to cancel IFR clearance (1)
    - Failure to request clearance (2)
    - Failure to report on UNICOM (1)
    - Failure to identify speaker on UNICOM (1)
  - Failure to follow altitude on flight plan paperwork (1)
  - Gear up landing by chase plane operator (1)
  - Non-pilot in pilot seat (1)
- Lack of procedure adherence by manned AC pilot (1)
  - UA distracted manned pilot and contributed to required communication failure (1)
- Lack of procedure adherence by ATC (2)
  - ATC cleared UA over populated area and pilot requested different clearance (1)
  - ATC cleared manned aircraft for takeoff while slowly taxiing UA on runway

- Judgment and decision-making errors (37)
  - Airspace violations by manned aircraft (3)
  - Airspace violations where the UAS operated in an area that was not authorized: including Canadian airspace; Classes B, C or D; too near an airport; over people; in a temporary flight restriction area, military aircraft in civilian airspace (17)
  - ATC procedure unknown when asked if there is UA activity (1)
  - Lack of procedure for communications for non-pilots on ground: UA operator distracted by passerby (1)
  - Lack of adequate communications between facilities: ATC without knowledge of military UA activity (5)
  - Lack of adequate procedures for integrating manned and unmanned aircraft in the same area (9)
    - Manned and unmanned in same airspace (6)
    - UA distracted ATC and almost lead to LOS of two manned aircraft (2)
    - Violation of procedure/airspace rules for integrating manned and unmanned aircraft leads to potential LOS (1)
  - Inadequate communication by ATC (1)
    - ATC confused "cleared on course" with "cleared direct" (1)

Eleven (11) were preconditions for unsafe acts:

- Crew resource management (1): Poor crew coordination on handover led to a crash of a UA
- Physical environment: adverse impact of the operational environment and/or ambient environment (1)
  - Lack of clearance adherence (1)
    - Disregard clearance due to weather (1)
- Technical environment (9)

- Lack of clearance adherence (4)
  - UA cannot follow ATC clearances (3)
  - Programming issue (1)
- Inadequate documentation/notification (5)
  - Lack of available information about private airports leading to an inability to notify private airport owners about UAS operations (1)
  - Opening of a temporary flight restriction (TFR) (2)
    - One TFR was opened after the manned aircraft takeoff leading to entering restricted airspace
    - One pilot had real-time confirmation that restrictions were not active and then a restriction became active that was not in the available documentation
  - Inadequate NOTAM describing military UA operations (1)
  - Lack of COA information by ATC (1)

3.4.2.1 Recommendations

With respect to lost link, the UA should have a lost link flight plan.

With respect to perceptual errors related to identification of a UA, a system like TCAS could be helpful. With respect to identification of UAs, UA pilots need to make their positions available through voice communication.

With respect to the exceptional violations, training could be helpful. For the procedure adherence, procedure support such as checklists could also be helpful.

For the judgment and decision-making errors with respect to airspace violations, better support for airspace awareness could help. This aid could include better charts as well as notifications.

For the judgment and decision-making errors with respect to inadequate procedures, procedures should be developed. In addition, training could be helpful.

With respect to crew coordination, each pilot controlling the aircraft should have the information necessary to control the UA. Each pilot controlling the aircraft should have access to the voice communications relevant for the flight.

With respect to the physical and technical environments and clearance adherence, the UA should be operated in environments that are congruous with its design. With respect to integration with the NAS, UA control stations should support following ATC clearances.

With respect to notifications, restricted airspace information should be available for UA pilots.

Due to the potential for a UA operator being distracted by a person walking close to the UA, the recommendation is to operate UA away from others.

3.4.3 FAA Sources

As of March 2017, there are five spreadsheets of reports of 2617 UAS sightings: November 2014-August 2015 (764), August 2015-January 2016 (582), February-March 2016 (264), April – June 2016 (534), and July-September 2016 (473).

The main content of the reports addressed the context for the sighting event itself. Content included the following if applicable: time, date, location, type of UA and/or description of UAS, information about the remote pilot, the flight related or location related information of the reporter, proximity of the UA to the reporting aircraft pilot or to objects, whether the event was a near mid-air collision (NMAC), whether evasive action was required if the reporter was inflight, whether there was a collision or a crash, whether a person was injured or property was damaged, what law enforcement contact and actions were made, and whether a report was made to the Domestic Events Network (DEN).

3.4.3.1 Recommendations

With respect to communication, several events described information regarding the fact that a UA was operating in the location. Such communication is critical for safe operations.

Several reports described an inability to see the UA. A related recommendation is to consider whether there are certain paints or other surfaces that would make UAs easier to spot.

One report described that the sun was reflecting off of the UA and the pilot was blinded. A related recommendation is to consider whether the UA could have surfaces less likely to reflect light to blind manned aircraft pilots.

3.4.4 Review of UAS Accident and Incident Meta Analysis

The literature search identified eleven meta analyses. Four did not provide explicit recommendations for safe UAS operation and are not considered further (Oncu & Yildiz, 2014; Rash, LeDuc, & Manning, 2006; Taranto, 2013; Williams, 2004).

For the remaining seven UAS accident and incident meta analyses, the analysis below considers the domain (e.g., military branch), the classification scheme used in the analysis, and any recommendations for UAS operation. The subsection concludes with an overview of recommendations that span across the meta analyses.

3.4.4.1 Overview of UAS Meta Analyses

Schmidt and Parker (1995) identified the causes for 170 Pioneer UA mishaps/incidents between the years of 1986-1993 for the United States Navy. Causes of Pioneer UA incidents included launch error, landing error, mechanical failures, electrical system failures, and engine failures. Schmidt and Parker provided the following recommendations for safe UA operation:

- establish UAS personnel aeromedical screening and monitoring guidelines,
- create better personnel selection procedures and tests,
- develop UAS crew coordination training program,

- develop better training tools and training requirements,
- create a tailored aviation physiology training program, and
- enhance human-system integration in design.

Seagle (1997) used a predecessor to the HFACS taxonomy to analyze 203 military UA mishaps between the years of 1986-1997, 88 of which were attributed to human causal factors. Seagle provided the following recommendations for safe UAS operation:

- establish aircrew selection criteria,
- establish simulator and training programs,
- require annual flight physicals,
- increase automation in difficult operations (e.g., landing, adverse weather), and
- establish dedicated training pipeline and career path for crew members.

Ferguson (1999) used the same HFACS predecessor taxonomy as Seagle (1997) to develop a stochastic model of Pioneer UA mishaps based on incident and accident data from the United States Navy and Marines. Based on the classification of accidents and stochastic simulation (which incorporated the costs incurred as a function of the incident and accident causal factors), Ferguson provided the following recommendations:

- increase use of simulators for training and skill retention,
- implement improved aircrew coordination training,
- improve crew resource management,
- appoint unit leaders that have operational experience, and
- establish dedicated training pipeline and career path for crew members.

Manning, Rash, LeDuc, Noback, and McKeon (2004) used two categorization schemes to analyze Unites States Army UAS accidents between 1997-2003: HFACS and the *Army Accident Investigation and Reporting* system (Department of the Army Pamphlet 385-40). Manning et al. provided the following recommendation:

- develop training programs that focus on addressing the items in the HFACS taxonomy (i.e., unsafe acts, preconditions for unsafe acts, unsafe supervision, and organizational influences).

Asim, Ehsan, and Rafique (2005) analyzed 56 United States Army Pioneer, Hunter, and Predator UA accidents using the HFACS taxonomy. The authors present recommendations organized by HFACS categories:

- Organizational influences
    - Promote an organizational culture focused on safety
    - Commitment from high-level management
    - Improvement organizational procedures
- Unsafe supervision
    - Establish extensive training programs
    - Promote a system of checks and balances
    - Provide leadership workshops

- Precondition for unsafe acts
    - Improve man-machine interface
    - Improve environmental and operating conditions
- Unsafe acts
    - Increase the quality and/or frequency of refresher trainings
    - Enhance pilot ability to respond to non-normal situations
    - Improve workstation ergonomics

Tvaryanas and colleagues (2005, 2006) use HFACS to characterize 221 UAS accidents from 1994-2003 in the United States Air Force, Army, Marines, and Navy. The following recommendations were provided based on the analysis:

- evaluate and optimize RPIC selection and training criteria,
- evaluate and optimize the control station with regard to basic human-systems integration principles,
- improve technical publications, checklists, and initial RPIC training programs to include a specific curriculum emphasis on crew resource management,
- improve job and workstation design,
- assess manpower requirements,
- develop empirically-based training programs and formal procedures and guidance,
- address failures in organizational culture, management, and acquisition processes, and
- utilize simulation systems for crew training, especially for challenging, off-nominal situations.

3.4.4.2 General Recommendations

Below is a generalized list of recommendations and interventions that span the UAS accident meta analysis literature:

- crewmember selection criteria and associated procedures,
- crewmember aeromedical screening,
- training tool development (e.g., simulators),
- training curriculum and program development,
- display design (information content and representation),
- automation and control interface/mode design,
- job/procedure design,
- organizational culture emphasizing commitment to safety,
- UAS crewmember career development and growth opportunities, and
- physical control station design/layout.

4. DISCUSSION OF LIMITATIONS TO THIS RESEARCH

With respect to the development of minimum information requirements, there are limitations to this research. They include the following

1. Outside of the DAA task, the literature is limited with respect to information requirements for operations unique to UAS (e.g., command and control link, communications, handovers)
2. There is little work on tasks during flight phases other than en route
3. There is little research focusing on near-term UAS integration into the NAS (i.e., UAS flying VFR flight under ATC supervision), in which the RPIC will be required to use the information in the workstation along with ATC clearances to successfully fly in the NAS
4. Most human factors research focuses on displays that best support system performance and not on minimum requirements

In addition, there are limits to the generalizability of results obtained. For research conducted with existing systems as well as results based on operational data, the results are limited to the specifics of the UAS, including the interfaces of those systems as well as the ways in which the organizations chose to operate the systems.

For designed experiments, participant demographics, the specific procedures that the participants were asked to follow, the instructions given to the participants, and the complexity of the operating environment potentially limit generalizability of results obtained. With respect to RPIC demographics, researchers have used participants that range from having no prior flying experience (Cook et al., 2010; Donmez et al., 2008), to those who have manned flying experience but no experience operating a UAS (Fern & Shively, 2011; Kenny, Shively, & Jordan, 2014), to trained RPICs (Rorie & Fern, 2014, 2015; Rorie et al., 2016). As there is a possible interaction on performance for pilot knowledge/experience and display content and features, the research results need to be considered through this lens.

With respect to procedures, Kenny et al. (2014) assessed two ATC communication strategies: one in which ATC was fully responsible for separation, and another in which ATC detected a conflict and delegated separation responsibility to the RPIC. However, other studies required no coordination with ATC (Friedman-Berg, Rein, & Racine, 2014).

Regarding varying instructions in designed experiments, RPICs were sometimes told to prioritize one or more tasks over others, while in other experiments they were provided with no instructions regarding prioritization. For example, Rorie and Fern's (2015) participants were instructed to prioritize tasks to (1) comply with ATC clearances and DAA alerts, (2) maintain cleared course as closely as possible, and (3) monitor and respond to secondary chat and health/status information. Alternatively, Wickens and Dixon (2002) did not instruct participants to prioritize any of their four tasks (operating the aircraft, monitoring system and health, and monitoring the payload display).

With respect to the range of operational environment complexities, experiments requiring participants to balance the demands of multiple complex tasks, such as conducting a defined mission while also maintaining separation from intruder traffic (Santiago & Mueller, 2015), could yield differing results than part-task simulations requiring the RPIC to focus on only one or two simpler tasks (Williams, 2012). Such differences represent limitations in the current body of UAS research that need to be considered when using the results to inform UAS control station information requirements or design guidelines.

The work in this review has generally focused on error-free behaviors; no studies were found that analyze error prevention/mitigation strategies that are unique to UAS operation. Future work should identify tasks for which error prevention and mitigation is necessary, and whether there are error mitigation/prevention strategies unique to UAS operation.

5. KEY POINTS

The following list of key points summarizes the work. The first set of key points focuses on design guidance and the second set of key points focuses on information content recommendations for safe UAS operation in the NAS.

5.1 DESIGN GUIDANCE

Key points for design guidance are categorized by control automation design, information representation and organization, and alerting. Each point includes its source(s) in parentheses.

5.1.1 Control Automation Design

UASs should include different control modes, ranging from tactical to strategic control modes. Better UAS design supports tailoring the control mode to the task concept (Calhoun et al., 2013). Specific key points are:

- Use of autopilot (as compared to manual control) reduces workload, allowing RPICs to reallocate their perceptual resources to other tasks (Wickens & Dixon, 2002; Wickens et al., 2003).
- Waypoint editing control may be beneficial for decreasing RPIC workload while also decreasing flight technical error; however, a waypoint editing interface may not be sufficient for instances requiring the RPIC to quickly re-route the aircraft (e.g., due to an impending collision) (Williams, 2012).
- Control actions requiring multiple steps to complete could be problematic in time critical situations (SenseFly eMotion 2 Control Station).

UAS designers should map the task to the interface type. As an example:

- Touchscreen gestures may be better for some interfaces and functions, such as map zoom functionality, than more traditional mouse-and-keyboard control (Haber & Chung, 2016).

5.1.2 Information Representation and Organization

UAS designers need to consider information organization as well as how to best represent information in the control station:

- Added information content on a display, potentially cluttering the display, is worth the tradeoff of not requiring the user to navigate between multiple displays (Hou et al., 2013).

Map displays are commonly used to assist the RPIC with navigation tasks. Specific key points are:

- The benefits of track-up vs. north-up map displays are dependent on the context of the operation; however, the default mode should be track up to promote consistency with an out-the-window view, when one is provided (Rodes & Gugerty, 2012).
- Two-dimensional moving-map displays are superior to three-dimensional moving-map displays for tasks requiring precise position judgments (Cook et al., 2010).
- The moving map should contain information about surrounding traffic (Trujillo et al., 2015).

As stated in FAA HF-STD-001B Section 5.6.6.2.1 (2016), color should be used to facilitate perception and processing of information. In addition:

- Color coding reflecting battery life was found to be useful by the participants in one experiment, and textual presentation less useful (Fuchs et al., 2014).
- A green-yellow-red color scheme may promote accurate and fast identification of potential issues (Piccolo Command Center).

Control station interfaces should be designed to prevent occlusion of flight-critical displays or information. Specific design ideas are illustrated in current systems:

- Pop-up windows, for example, can occlude substantial portions of the interface, which could potentially hide flight-critical information (Piccolo Command Center).
- Translucent pop-up windows reduce occlusion of potentially flight-critical information (SenseFly eMotion 2 Control Station).

Designers have flexibility over the modalities for presenting information, and they need to consider the mapping of the type of information to the specific modality. For example:

- RPICs need to be provided with turbulence information, but joystick force-feedback is likely not the optimal modality for information delivery, as it can impede RPIC control of the vehicle (Ruff et al., 2000).

UAS designers should utilize non-visual modalities when possible, as some modalities are better than others for the display of information. For example:

- Auditory sonifications can improve monitoring performance (i.e., decrease response time) compared to visual alerts, but the use of a tactile display does not significantly improve RPIC monitoring performance (Arrabito et al., 2013).

UAS designers may want to utilize multiple modalities of information presentation since RPICs are typically subject to high levels of visual information (Hocraffer & Nam, 2017). For example:

- There is promise in redundant cueing (in the form of auditory or haptic cues added to a visual alert). However, there is no evidence suggesting that the tactile modality is more effective for alert cue delivery than the auditory modality, or vice versa (Calhoun et al., 2004).

- Tactile and auditory redundant cueing are both sufficient for reducing response time, but tactile alerting may be associated with lower cognitive workload than auditory alerting (Calhoun et al., 2005).

RPICs are subject to periods of multitasking, so UAS designers need to incorporate features to ensure that the RPIC does not become overloaded while operating the UAS. For example:

- Control of a UAS can yield high utilization rates of the RPIC's manual resources, so offloading secondary tasks to speech input methods may lower RPIC workload (Williamson et al., 2005).

5.1.3 Alerting

Since RPIC visual resources have the potential to be overloaded, UAS designers should utilize non-visual resources to alert the RPIC. For example:

- Continuous haptic alerting of cross-track error may yield quicker response times to large cross-track error than discrete feedback (Donmez et al., 2008).
- Aural alerting may be superior to tactile alerting during UAS operation (Calhoun et al., 2003).
- Alerting using the haptic or aural channels may reduce the visual resources necessary to track the UA along its path. However, overloading the RPIC's aural perceptual resources needs to be avoided (Donmez et al., 2008).
- Aural cues are superior to visual-only alerts, likely because the visual system is already subjected to a large amount of visual information (Williams, 2012).
- Aural alerting and depiction of traffic information on a moving map (i.e., not relying on RPIC visual detection of traffic) may be necessary for safe UAS operation (Trujillo et al., 2015).

UAS designers need to identify information for which alerting is necessary while also ensuring that the RPIC is not subject to too many alerts. For example:

- The control station should inform the RPIC, either via presentation of the system status or alerting functionality, when the UA approaches any programmed or structural limits (X-Gen Control Station).
- The control station should contain information sufficient to help the RPIC to avoid stalls (such as a stall warning) (UAS Incident and Accident Analysis).
- The control station should provide an alert to the RPIC when there is a threat of the UA colliding with another aircraft, terrain, or objects. The alert must be provided in time for the RPIC to effectively respond to make the UA avoid the collision (Hobbs & Lyall, 2015).
- The control station should alert the RPIC when the UA is approaching an area where link is likely to be lost (Hobbs & Lyall, 2015).
- The control station should alert the RPIC when the link is lost (Hobbs & Lyall, 2015).
- The control station should alert the RPIC whenever the C2 link experiences interference, whether resulting from natural phenomena, payload or other equipment associated with the

UAS, or human activities (such as jamming or other users on frequency) (Hobbs & Lyall, 2015).
- The control station shall display feedback to the pilot when a datalink message arrives by a visual and/or aural alert (Access 5, 2005).

5.2 INFORMATION CONTENT RECOMMENDATIONS

Below is a list of key points regarding information content recommendations from the sources reviewed. The bullets constitute the information recommendations gathered from the various sources that were reviewed. The source(s) of the information content recommendation are in parentheses after each recommendation. These recommendations will be considered as part of Task 8 Control Station Standards and Guidelines and Recommendations for Future Research.

The following information content recommendations are related to UAS control, control automation, and automation modes.

- The control station shall display timely feedback to the pilot regarding the content of a command and when a command has been entered into the system (UAS Incident and Accident Analysis, Access 5, 2005b).
- The control station should provide the RPIC with information necessary to quickly identify the current state, mode, or setting of all controls that are used to send flight commands to the UA (Hobbs & Lyall, 2015).
- Active autopilot modes should be clearly indicated on the control station displays (X-Gen Control Station).
- The control station should contain information sufficient to support RPIC mode awareness (UAS Incident and Accident Analysis).

The following information content recommendations are related to navigation.

- RPICs require sufficient terrain and airspace information (i.e., information on aeronautical charts) to successfully perform re-routing tasks when the UA is operating close to the ground, such as during takeoff and landing (Cook et al., 2009). Aeronautical charts may be sufficient to provide this information to the RPIC.
- The control station should provide the RPIC with information on the flight path that had been assigned to the UA prior to a maneuver or deviation from the flight path (Hobbs & Lyall, 2015).
- During a maneuver or deviation from the assigned flight path, the control station should provide information about the necessary UA trajectory needed to return to the assigned flight path. This should include the necessary UA heading and altitude changes (Hobbs & Lyall, 2015).
- The control station should provide clear feedback to the RPIC on the status of the route upload (X-Gen Control Station).

The following information content recommendations are related to the command and control link status.

- The control station should be capable of providing the RPIC with predictive information on the quality and strength of a C2 link before the link is actively used to control the UA (Hobbs & Lyall, 2015).
- The control station should provide information to enable the RPIC to identify which C2 link settings are active (e.g. selected frequency, satellite vs terrestrial) (Hobbs & Lyall, 2015).
- The control station should provide the RPIC with information to confirm that effective control is established with the correct UA (Hobbs & Lyall, 2015).
- The control station should provide the RPIC with information on the geographic limits of the link (Hobbs & Lyall, 2015).
- The control station should provide the RPIC with information on spectrum activity from a spectrum analyzer (Hobbs & Lyall, 2015).
- The control station should provide information to enable the RPIC to monitor the strength of the command/control link (Hobbs & Lyall, 2015).
- The control station should display to the RPIC the source of downlink transmissions (Hobbs & Lyall, 2015).
- Where relevant, the control station should provide the RPIC with information on link latency, in milliseconds (Hobbs & Lyall, 2015).
- The control station should provide information to enable the RPIC to anticipate link degradations or diminished link strength. This information may include link footprint, including areas that may be affected by terrain masking (Hobbs & Lyall, 2015).
- The control station should provide information to enable the RPIC to manage link security (Hobbs & Lyall, 2015).
- The control station should inform the RPIC when a lost link is resumed (Hobbs & Lyall, 2015).
- The pilot shall have information available at the control station that indicates authorized datalink actions prior to enabling control of the vehicle flight path or trajectory (Access 5, 2005).
- The control station shall display information to the pilot regarding the source of downlink transmissions by reference to downlink data displayed at the control station (Access 5, 2005).
- The control station shall display information to the pilot regarding the status or quality of each uplink and downlink (Access 5, 2005).
- The control station shall display information to the pilot for any partial or full failure of a datalink (Access 5, 2005).

The following information content recommendations are related to system health and status.

- The control station should provide the RPIC with information on the status of consumable resources (Hobbs & Lyall, 2015), such as fuel level or battery life remaining.
- The control station should provide the RPIC with health and status information on the control station (Hobbs & Lyall, 2015).

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8. APPENDIX D2: UAS CONTROL STATION LITERATURE TAXONOMY

Context

Airspace Context

The national airspace context portion of the taxonomy includes the airspace class that the UAS operated in (including oceanic airspace), the surface portion of the flight, and the flight rules associated with UAS operation in the literature. The surface subcategory captured where the UAS flight originated and returned to, such as an airport, a non-airport (e.g., automated launcher or net retrieval system), and watercraft (e.g., an aircraft carrier). The details for this part of the taxonomy include:

1. Airspace
    a. Class A
    b. Class B
    c. Class C
    d. Class D
    e. Class E Below A
    f. Class E Above A
    g. Class G
2. Oceanic
3. Surface
    a. Airport (Ramp, Taxiway, Runway)
    b. Non-airport Ground
    c. Watercraft
4. Flight Rules
    a. Visual Flight Rules
    b. Instrument Flight Rules

Study Approach

The type of study identifies the experiment methodology used by the researchers. Some documents may include more than one type. The types of study considered in this review include:

1. Human in the loop Simulation
2. Field Test
3. Accident Data Analysis
4. Literature Review/Meta Analysis
    a. General Human-Automation Interaction
    b. UAS-Specific
5. Products of the Systems Engineering Lifecycle
    a. Operational Concept/Integration Plan
    b. Requirements/Design Recommendations
    c. Design

    d. Prototype
6. Human Factors Design and Evaluation of an Existing System
    a. Task Analysis
    b. Observation
    c. Participant Questionnaire
    d. Heuristic Evaluation
    e. Think-Aloud Verbal Protocol
    f. Subject Matter Expert Interview
    g. Focus Group
7. Computational Modeling
    a. Agent Based Simulation
    b. Discrete Event Simulation
    c. Markov Decision Process

Participants/Crew

This portion of the taxonomy addresses the participants and their roles as well as critical demographics. Pilot-in-command was defined as the operator responsible for control of the aircraft, generally located in a control station. Schreiber, Lyon, Martin, and Confer (2002) report differences in required training time for Predator RPICs with prior UAS experience, operators with prior manned aircraft flying experience, and operators with no prior flying experience in manned or unmanned operations. Therefore, the taxonomy accounts for prior experience of the pilot(s)-in-command used in the study (prior unmanned experience, manned experience, mixed experience, no experience, or unspecified). Some systems require takeoff and landing by an external pilot (EP), who is located at an airport and is responsible for takeoff and landing of the aircraft via hand-held controller. On takeoff, once the aircraft is airborne, the EP transfers control of the aircraft to the pilot-in-command and before the aircraft reaches the runway on arrival, the pilot-in-command transfers control of the aircraft to the EP to land the aircraft. The payload operator is a crewmember that operates the payload on the UAS (e.g., a camera for target search or sensors for chemical monitoring). Visual observers are personnel who remain in visual contact with the UAS and communicate with the pilot-in-command instructions to avoid obstacles. The mission commander is defined as any crewmember that manages and coordinates the crew without operating the vehicle or payload him/herself.

Environment

This portion of the taxonomy accounts for the external environment in which the UAS operated (Federal Aviation Administration, 2014):

1. Atmospheric
    a. Wind
    b. Visibility
    c. Weather
    d. Sky Conditions
    e. Air Temperature

f. Pressure
g. Precipitation
h. Turbulence
i. Ice

2. Lighting
   a. Day
   b. Night
3. Intruder Traffic
   a. Vehicle Type
      i. Airship
      ii. Glider
      iii. Helicopter
      iv. Manned Powered Aircraft
      v. Unmanned Powered Aircraft
   b. Position Broadcast Equipment
      i. Radar-Based
      ii. Satellite-Based
      iii. ADS-B
      iv. Mixed
      v. None
   c. Density
      i. None
      ii. Unspecified
      iii. <5 Intruder Encounters
      iv. 5-10 Intruder Encounters
      v. >10 Intruder Encounters
4. Geography
   a. Restricted Airspace
   b. Buildings
   c. Natural Obstacle
   d. No Obstacles
   e. Other Obstacle

Ownship

Ownship refers to the type of UAS operated (RTCA Inc., 2010; Scheff, 2014; Williams, 2007). The types considered include:

1. A160 Hummingbird
2. AAI Aerosonde Mark 4.7
3. ACR Manta
4. ACR Silver Fox
5. ADCOM YABHON
6. Aero Design and Development Hornet
7. Aeronautics Defense Systems Aerolight

8. Aeronautics Defense Systems Aerosky
9. Aeronautics Defense Systems Aerostar
10. Aeroscout B1-100
11. Aeroscout Scout B1-100
12. Aerosonde Mk47
13. Aerosystems ZALA 421
14. AeroVironment Helios
15. AeroVironment Pathfinder
16. AeroVironment Puma
17. AeroVironment Raven B
18. Arcturus T-20
19. ATE Vulture
20. Aurora Flight Sciences Centaur
21. Aurora Flight Sciences Excalibur
22. Aurora Flight Sciences Goldeneye-80
23. Aurora Flight Sciences Orion
24. Aurora Flight Sciences Perseus
25. BAE Systems Kingfisher
26. BAE Systems Phoenix
27. BAE Systems Silverfox
28. BAE Systems Skylynx
29. Baykar Makina
30. Bell 206
31. Bell Helicopter Textron Eagle
32. Boeing Insight
33. Boeing Integrator
34. Cessna 172
35. Cessna 182
36. Cessna Caravan
37. Cyber Tech CyberEye
38. Cyber Tech CyberQuad
39. Cyber Tech CyberWraith
40. Cyber Tech CyBird
41. Dara Aviation D-1
42. DarkStar
43. Denel Dynamics Bateleur
44. Denel Dynamics Seeker
45. DRS Neptune RQ-15
46. EADS Dornier
47. Elbit Systems Hermes
48. EMIT Sparrow
49. EMT LUNA X-2000
50. ENICS BERTA
51. ENICS E08 Aerial Decoy
52. Explorer Tandem Wing
53. Fuji RPH-2A

54. General Atomics Altair
55. Generic Helicopter
56. Generic MALE
57. Generic Multirotor
58. Global Observer HALE
59. GNAT 750
60. Gulfstream 550
61. Heron
62. Honeywell RQ-16A T-Hawk
63. Hummingbird A-160
64. Husky Autonomous Helicopter
65. IAI NRUAV
66. Innocon MicroFalcon
67. Innocon minFalcon
68. Integrated Dynamics Border Eagle
69. Integrated Dynamics Explorer
70. Integrated Dynamics Hawk
71. Integrated Dynamics Vector
72. Integrated Dynamics Vision MK
73. International Aviation Supply Raffaello
74. King Air 200
75. L-3 TigerShark
76. L-3 Viking
77. MBDA Fire Shadow
78. Meggitt Barracuda
79. Meggitt Hammerhead
80. Meggitt Vindicator
81. MLB Super Bat
82. MQ-1 Predator A
83. MQ-1C ER/MP Sky Warrior/Gray Eagle
84. MQ-9 Predator B/Reaper
85. MSI BQM
86. MSI Chukar
87. MSI Falconet
88. MSI Firejet
89. MSI High Speed Maneuvarable Surface Target
90. MSI MQM
91. MSI QST-35
92. MSI QUH-1 Rotary Wing
93. Northrup Grumman BAT-12
94. Northrup Grumman LEMV Airship
95. Ranger
96. Raven
97. Raytheon Cobra
98. Raytheon KillerBee
99. Rheinmetall Fledermaus

100. Rheinmetall KZO
101. Rheinmetall Mucked
102. Rheinmetall OPALE
103. Rheinmetall Tares/Taifun
104. RMAX TYPE II
105. Rodian/Automasjonsutvikling AS Xr-T8
106. Rodian/Automasjonsutvikling AS Xr-T9
107. RQ-2 Pioneer
108. RQ-4 Global Hawk
109. RQ-5 Hunter
110. RQ-6 Outrider
111. RQ-7 Shadow
112. RQ-8A FireScout
113. SA 60 LAA
114. SA-200 Weasel
115. Sagum Crecerelle
116. Sagum Patroller
117. Sagum Sperwer
118. SAIC Vigilante
119. Satuma Flamingo
120. Satuma Jasoos
121. Satuma Mukhbar
122. ScanEagle
123. Schiebel Camcopter
124. Selex Galileo Falco
125. Selex Galileo Mirach
126. Skycam Hawk
127. Snap Defense Systems Aggressor
128. Snap Defense Systems Bandit
129. Snap Defense Systems Blacklash
130. Snap Defense Systems Centurion
131. Snap Defense Systems Scout
132. Snap Defense Systems Sea Vixen
133. Snap Defense Systems Stingray
134. TAI ANKA
135. Thales Watchkeeper WK450
136. Ucon System RemoEye
137. Unmanned Systems Group ATRO-X
138. Unmanned Systems Group CT-450 Discover 1
139. Unspecified
140. Uvision Blade Arrow
141. Uvision Blue Horizon
142. Uvision MALE UAS
143. Uvision Sparrow
144. Warrior Gull
145. WLD 1B

146. X-47B N-UCAS
147. Xian ASN

Task

This portion of the taxonomy considers the task work. Task work is considered by flight phase, general function, mission, and flight event (nominal and failure). Phase of flight includes the traditional aviation flight phases plus it includes the specific mission which, due to its complexity, is specified separately.

The phases of flight include:

- Flight Planning
- Engine Start
- Taxi
- Takeoff
- Departure
- En Route
- Aerial Work/Mission
- Descent
- Approach
- Landing

The generic functions include (Hobbs & Lyall, 2015; Hobbs & Shively, 2013):

1. Manage
    a. Plan for Normal Conditions
    b. Plan for Non-normal Conditions
    c. Make Decisions in Normal Conditions
    d. Recognize and Respond to Non-normal Conditions
    e. Transfer Control
2. Aviate
    a. Monitor and Control Aircraft Systems (Including Automation)
    b. Monitor Consumable Resources
    c. Monitor and Configure Control Station
    d. Maneuver Aircraft to Avoid Collision
    e. Monitor and Control Status of Control Links
3. Navigate
    a. Control and Monitor Aircraft Location and Flight Path
    b. Remain Clear of Terrain, Airspace Boundaries, and Weather
    c. Self-separate from Other Aircraft
    d. Ensure Lost Link Procedure Remains Appropriate
    e. Terminate Flight
4. Communicate

a. Air Traffic Control
    i. Ground Control
    ii. Local Control
    iii. Terminal Radar Approach Control
    iv. Air Route Traffic Control Center
b. Pilots of Other Aircraft
c. Crew Members
d. Ancillary Services (e.g., weather)

5. Mission

The mission is the specific purpose for the flight (Nehme, Crandall, & Cummings, 2007; RTCA Inc., 2010):

1. Military
    a. Reconnaissance/Surveillance
    b. Tactical Strike
    c. Communication Relay
    d. Signal Intelligence
    e. Maritime Patrol
    f. Penetrating Strike
    g. Suppression of Enemy Air Defenses (SEAD)
    h. Aerial Refueling
    i. Counter Air
    j. Airlift
    k. Target Search
    l. Target Identification
2. Civil
    a. Atmospheric Research
    b. Border Patrol
    c. Disaster Response
    d. Hurricane Measurement and Tracking
    e. Forest Fire Monitoring and Support
    f. Search and Rescue
    g. Maritime Surveillance
    h. Law Enforcement
    i. Humanitarian Aid
    j. Aerial Imaging and Mapping
    k. Drug Surveillance and Interdiction
    l. Monitor and Inspect Critical Infrastructure
    m. Natural Hazard Monitoring
    n. Airborne Pollution Observation and Tracking
    o. Chemicals and Petroleum Spill Monitoring
    p. Communications Relay
    q. Traffic Monitoring
    r. Port Security
3. Commercial
    a. Crop Monitoring

b. Fish Spotting
c. Remote Imaging and Mapping
d. Utility Inspections
e. Mining Exploration
f. Agricultural Applications
g. Communication Relay
h. Petroleum Spill Monitoring
i. Site Security
j. Broadcast Services
k. News Media Support
l. Filming
m. Real Estate Photos
n. Aerial Advertising
o. Cargo

Control Station

Hardware

Four hardware components were identified, including laptop computer, tablet computer, desktop computer, and control station suite. A desktop computer hardware setup was defined as any system utilizing one monitor in an office setting, while a control station suite included multiple displays either in an office setting or in a dedicated control station. A study can include more than one hardware component. For example, a setup can include a desktop setup in addition to a laptop computer to control a real or simulated UAS.

Control Device

The list of control devices was populated based on the control station simulators and prototypes used in the literature reviewed as part of the A7 function allocation review, as well as the UAS control device inventory by Williams (2007). Furthermore, we used Scheff (2014) to further augment our list with the control devices identified in his UAS inventory. The inventory contained 107 control stations; identification of control devices is reported in Appendix D4. The control device options are listed below:

- Hand held controller
- Joystick
- Keyboard
- Knobs
- Mouse
- Slider control
- Stick and throttle
- Touchpad
- Touchscreen
- Trackball

Information Interface

An important aspect of the control station design is the interface contained in the UAS to present relevant information, command and control the aircraft, or both. Interfaces range from those originally developed for use in manned aircraft cockpits (e.g., primary flight display) to those supporting functions unique to UAS operation (e.g., chat communication client). Reported below, the list of interface types was constructed based on the A7 function allocation review as well as those reported by Kayayurt and Yayla (2013):

- Clock
- Communication
    - Communication client
    - Radio (voice) communication
- Electronic checklist
- Landing gear position (if relevant)
- Navigation display
    - Horizontal situation indicator
    - Moving map
    - Weather information (as an overlay)
- Out-the-window view
- Payload status
- Pitot heat indicator
- Powerplant
    - Engine status and related information (e.g. air intake door position, coolant, fuel pump, manifold pressure, oil pressure, tachometer. temperature if relevant)
    - Power/fuel status
    - Thrust indicator
    - Thrust reverser status
- Primary flight display
    - Airspeed indicator
        - Speed warnings
    - Altitude indicator
    - Attitude indicator/pitch ladder
    - Control mode display
    - Heading indicator/magnetic direction indicator
        - Turn bank indicator/turn coordinator, Slip/Skid indicator
- System status
- Traffic Collision Avoidance System (TCAS) display
    - Traffic information
- Vertical situation display
- Wing flap position indicator

Displayed Information

Since control stations can differ in terms of what specific information is being presented and how it is being presented, the displayed information portion of the taxonomy contains information presented to the RPIC via the control station interfaces (listed below). The information was initially populated using the results from the A7 function allocation review along with the list of information presented by Kamine and Bendrick (2009), and information was added as needed during the literature review process. Information is grouped into six general categories, including environment, mission, ownship, route, sensor, and crew.

- Communication
    - Data communication
    - Frequency in use
    - Radio in use
    - Radio settings
    - Radio signal reception strength
- Environmental conditions
    - Air temperature
    - Cloud coverage
    - Cloud height
    - Ice
    - Precipitation
    - Pressure
    - Storm cell location
    - Turbulence
    - Visibility
    - Wind direction
    - Wind speed
- National Airspace System
    - Airport (including locations of traffic on the surface; outlining runways on a situation indicator display or map to indicate status).
        - Runway and taxiway layout
        - Runway status
        - Surface traffic
        - Taxiway status
    - Airspace
        - Alert area location(s)
        - Controlled firing area location(s)
        - Military operations area location(s)
        - National security area location(s)
        - Prohibited area location(s)
        - Restricted area location(s)
        - Sector boundaries
        - Warning area location(s)
- Navigation

  - Distance to destination
  - Distance to next waypoint
  - Flight plan cleared route
  - Past re-planning tasks
  - Pending re-planning tasks
  - Taxi route
  - Time to destination
  - Time to next waypoint
  - Waypoint location
- Out-the-window
  - Enhanced vision
  - Highway-in-the-sky
  - Night vision
  - Out-the-window video feed
  - Synthetic vision
- Ownship
  - Air intake door status
  - Airspeed
  - Aircraft maximum flaps extended speed (V_{FE})
  - Aircraft maximum landing gear operating speed (V_{LO})
  - Aircraft maximum speed for normal operations (V_{NO})
  - Aircraft maximum operating limit speed (V_{MO})
  - Aircraft maximum operating maneuvering speed (V_{O})
  - Aircraft minimum control speed (V_{MC})
  - Aircraft never exceed speed (V_{NE})
  - Aircraft stall speed (V_{S})
  - Aircraft stall speed in landing configuration for which the aircraft is still controllable (V_{S1})
  - Aircraft stall speed in landing configuration (V_{S0})
  - Aircraft type
  - Altitude
  - Attitude
  - Bank angle
  - Battery temperature
  - Carburetor air temperature
  - Command sent status
  - Control link status
  - Control mode
  - Current lost link procedure
  - Cylinder head temperature
  - Distance ring
  - Electric power system quantity (voltage, current)
  - Engine rotor speed (RPM)

- Engine rotor speed limit (RPM)
    - Fuel flow
    - Fuel level
    - Fuel pressure
    - Fuel pump status
    - Fuel strainer contamination level
    - Fuel system heater status
    - Fuel temperature
    - Generator/alternator status
    - Ground speed
    - Ice protection system status
    - Heading
    - History trail
    - Hydraulic system pressure
    - Landing gear position (if relevant)
    - Location
    - Manifold pressure
    - Oil pressure
    - Oil quantity
    - Oil strainer contamination level
    - Oil temperature
    - Pilot identification data
    - Pitot heating system status
    - Powerplant status
    - Powerplant valve position
    - Rate of climb
    - Rate of turn
    - Slip/skid status
    - Telemetry data
    - Thrust level
    - Thrust reverser status
    - Trajectory
    - Transponder status
    - Trim device position
    - Usable fuel quantity
    - Usable oil quantity
    - Vertical trend
    - Vertical velocity
    - Wing flap position
- Terrain
    - Elevation
    - Location
- Time

  - Time of day
  - Time of day (origin)
  - Time of day (destination)
  - Elapsed flight time
- Traffic
  - Intruder
    - Absolute altitude
    - Aircraft ID
    - Aircraft length
    - Aircraft width
    - Airspeed
    - Bearing
    - Climb/descent direction
    - Climb/decent rate
    - Ground speed
    - Heading
    - Heading predictor
    - History trail
    - Location
    - Manned/unmanned
    - Onboard equipment (e.g., TCAS II and ability to generate resolution advisory alerts)
    - Range
    - Relative altitude
    - Threat level
    - Vector line
    - Vertical trend
    - Vertical velocity
  - Conflict detection (information used to convey conflict geometry)
    - Closest point of approach (CPA) location
    - Distance to CPA
    - Time to CPA
  - Conflict resolution
    - Suggested maneuver
    - Maneuver success (i.e., whether the RPIC's planned maneuver successfully meets an objective, such as resolving a conflict)

Measures

Attention Allocation

Operating a UAS is a visually demanding task, so it is important to monitor RPIC attention allocation to ensure (s)he is allocating the proper amount of attention to the various pieces of information at the correct time. Attention is comprised of fixations and saccades: a fixation is defined as any time during which RPIC attention remains relatively stationary (e.g., gaze velocity less than 100 deg/sec for more than 100 msec) while a saccade is defined as the gaze movement between consecutive fixations. Glances are defined as the total time the RPIC's gaze is within an area of interest (AOI), accounting for both fixations and saccades. Note that blink rate and pupil diameter are common objective indicators of RPIC mental workload (Wickens, Lee, Liu, & Gordon Becker, 2003). The list below also contains eye tracking measures relevant for measuring RPIC attention patterns (Holmqvist et al., 2011):

- Fixation duration
- Fixation frequency
- Number of fixations
- Fixation rate
- Glance duration
- Glance frequency
- Number of glances
- Total viewing time
- Convex hull area
- Scan path length
- Saccade length
- Rate of transitions
- Blink duration
- Blink rate
- Pupil diameter

Control

The control portion of the measures taxonomy includes Fitts' Law (Fitts, 1954), target tracking performance, and response time (RT). The *Measured Response* times included in the table were developed to assess the various stages of the Detect and Avoid (DAA) procedure (Fern et al., 2015; Rorie & Fern, 2014, 2015). The measures are:

- Fitts' Law
- Response time
    - Abnormal system state
    - Air traffic control
    - Airspace configuration
    - Alert

  - Detect and avoid measured response
    - Aircraft response time
    - Compliance time
    - Initial edit time
    - Initial response time
    - Notification time
    - Total edit time
    - Total response time
    - Verbal response time
  - Target
  - Transfer of control
- Target tracking performance

Detection and Assessment

Detection and assessment measures include the Lens Model, Signal Detection Theory, and Skill Score (listed below). Detailed descriptions of these measures were documented in the A7 function allocation review, and are presented in Appendix D3.

- Lens model
  - Accuracy
  - Consistency
  - Judgment strategy
- Signal detection
  - Response bias
  - Sensitivity
    - Correct rejection rate
    - False alarm rate
    - Hit rate
    - Miss rate
- Skill score
  - Conditional bias

Human-Computer Interaction

RPIC interaction with a control station is a specialized case of the broader field of human-computer interaction. Therefore, traditional human-computer interaction measures are relevant for assessing control station designs and information levels. Relevant measures for control station design are presented below:

- Information access time
- Information sufficiency
- Number of clicks
- Preference

-
    - Information level
    - Control feature
- Search time
- Subjective clutter
- Subjective usability
    - Most useful feature
    - System controllability
    - Display effectiveness
    - Display type ranking
    - Distraction rating
    - Information readability
    - Information usefulness
    - Information understandability
    - Layout rating
    - Ease of use
    - Alert effectiveness

Mission Performance

Differing UAS control station designs or information levels will necessarily impact aviation-specific measures reflecting RPIC control of the vehicle. Commonly-used RPIC performance measures, adapted from the A7 function allocation review, are reported below.

- Completion time
- Compliance
    - Air traffic control
    - Automated resolution
    - Mission commander
- Conflict resolution maneuver quality
- Delay
- Flight path error
    - Lateral
    - Vertical
- Fuel consumption
- Landing performance
    - Distance off centerline
    - Glideslope error
    - Lateral velocity
    - Nose position
    - Vertical velocity
- LOS severity
- Map reconstruction accuracy
- Minimum separation distance

- Number of encounters with multiple uploads
- Number of Losses of Separation (LOSs)
    - Intruder aircraft
    - Terrain
    - Weather
- Perceived performance
- Preference
    - Maneuver
- Speed error
- Training required to meet performance criterion

Compliance refers to the proportion of time the RPIC performs the suggested or required action, such as when air traffic control (ATC) instructs the RPIC to perform a maneuver.

Conflict resolution maneuver quality reflects whether the maneuver was successful and/or the magnitude of deviation off the path (with larger deviations relating to less efficient maneuvers).

Delay refers to the difference in scheduled arrival time and the actual arrival time (to a waypoint or destination).

Flight path error refers to the magnitude of deviation from the cleared path and altitude, and can be measured laterally or vertically. Fuel consumption refers to the amount of fuel consumed during a specified period of flight.

Landing performance is defined by the accuracy of the actions the RPIC takes to successfully land the UA.

Regarding number of collisions, a collision can be defined as any time the separation between the UA and an obstacle is below a pre-defined threshold (e.g., Mueller, Santiago, and Watza (2016) define a UAS collision threshold as 4,000 ft horizontally and 450 ft. vertically).

Perceived performance measures the RPIC's self-rating of his/her task execution (e.g., perceived performance in avoiding conflicts with other aircraft) while preference is defined as subjective preference for an aspect of the mission, such as maneuver type.

Speed error refers to the difference between the planned/cleared speed and the actual speed of the aircraft.

Researchers and practitioners assess control station design by the amount of time or number of training sessions required to meet a threshold level of performance, labeled as *training required to meet performance criterion* in the taxonomy.

RPIC State

RPIC state measures refer to the RPIC's internal/cognitive state while operating a UAS, subject to differing control station designs or information levels. These measures include mental workload, situation awareness, and utilization:

- Mental workload
    - Subjective
        - Likert scale rating
        - NASA TLX
        - Cooper-Harper
    - Objective
        - Heart rate variability
        - Attention allocation
- Situation awareness
    - Subjective
        - Likert scale rating
        - Situation awareness rating technique
        - Subjective workload dominance (SWORD)
        - Observer rating
    - Objective
        - Situation awareness global assessment technique (SAGAT)
        - Posttest questionnaire
        - Real time questionnaire
- Utilization

Reduced mental workload has generally been associated with increased RPIC performance, but low levels of workload sustained over extended periods of time can promote RPIC boredom and reduced attention to relevant information. Workload is typically measured subjectively, using a single-dimension Likert scale rating or a multi-dimensional rating scale (e.g., NASA Task Load Index; TLX; Hart and Staveland (1988)), and/or via objective physiological measures such as heart rate variability, blink rate, etc. (Wickens, Lee, et al., 2003).

Situation awareness (SA) has been described as the perception of environmental cues, comprehension of the meaning of those cues, and the ability to use the cues to project future system states (Endsley, 1995b). SA can be measured subjectively (e.g., using a Likert scale). A common subjective awareness measure is the Situation Awareness Rating Technique (SART) (Hughes & Takallu, 2002; Stark, Comstock, Prinzel, Burdette, & Scerbo, 2001; Takallu, Wong, Bartolone, Hughes, & Glaab, 2004). SART was developed by interviewing experienced aircrew and identifying 10 SA constructs and these 10 constructs were found to cluster into three broad categories: attentional demand, attentional supply, and understanding (Selcon & Taylor, 1990; Taylor, 1990). While SART and similar rating techniques have been correlated with performance measures (Selcon & Taylor, 1990), they have also been shown to be correlated with RPIC confidence (Endsley, Selcon, Hardiman, & Croft, 1998). Methods for objectively measuring SA exist, including measures in which the scenario freezes and a series of queries is presented to the RPIC about the current system state and possible future system states (Endsley, 1995a). Other paradigms present SA queries at the end of an experimental trial. Other researchers develop specific situation awareness measures tailored to the task (Bolton & Bass, 2009).

Utilization is defined as the percentage of time that the RPIC is actively engaged in a task, typically calculated in agent-based models of dynamic systems (Cummings, Marquez, & Visser, 2007). Control station design and information presentation strategy influences the efficiency with which the RPIC can find and process relevant information, altering his/her utilization.

9. APPENDIX D3: DETECTION AND ASSESSMENT TAXONOMY

Signal Detection Theory

The probability-based signal detection theory paradigm has been used to model the detection of an even in the presence of an evidence variable, "X", and noise (Green & Swets, 1989). The human judge has the task of differentiating the signal (often in the presence of noise) from the noise alone. There is a threshold or cutoff above which the stimulus or evidence variable must be for detection to occur. The signal detection theory model assumes that the person has such a cutoff value, C_h, a bias measure. When the properties of X exceed C_h, the person would then assert that the signal is present. The combinations of the states of the world (signal or noise only) and the two possible responses ("yes", there is a signal or "no", there is no signal) create four classes of joint events: two are correct responses (hit and correct rejection) and two are errors (false alarm and miss) From the four possibilities, four probabilities are calculable:

- P(H): Probability of a hit (number of hits/number of signal events)
- P(FA): Probability of a false alarm (number of false alarms/number of noise only events)
- P(M): Probability of a miss (number of misses/number of signal events)
- P(CR): Probability of a correction rejection (number of correct rejections/number of noise only events)

Signal Detection Theory uses two parameters to model detection (sensitivity and response criterion or bias) (Green & Swets, 1989). Sensitivity is an index of the human's ability to distinguish the signal from the noise. Response bias is the human's tendency to respond positively or negatively as a function of the four outcomes and the likelihood of a signal being present. With the assumptions of normality and of equal variance for the two distributions, the index of sensitivity is calculated as the distance between the means of the signal and the noise scaled to the standard deviation of the noise distribution. The response criterion is the likelihood ratio that an effect of the cutoff criterion is due to signal plus noise as opposed to noise alone.

Double System Lens Model

Judgment analysis uses the lens model (Brunswik, 1956) which has been applied to describe how people make judgments about their environments. A double system design is a model that considers the judgment process and the task conditions and computes judgment accuracy with respect to an objective criterion or other standard. This commonly used form of the Lens Model provides symmetric models of both the human judge and the environment. The model describes the human judge, the task environment, and the interrelationships between these two entities. The task environment is modeled in terms of the cues available and the environmental criterion to be judged. Cues and the criterion are related by statistical correlations known as ecological validities (e.g., ecological validity of a cue measures how well it specifies the true state of the environmental criterion to be judged). Correlations reflect environmental relationships between the cues and the criterion within the task environment.

A judge uses the cue values to render a judgment about the environmental criterion. Over cases, one will find various correlations between the cue values and human judgments, and these are known as cue utilizations, the r_s values. The particular pattern of cue utilizations exhibited by a human judge determines the cognitive judgment strategy. Achievement will be maximized when the pattern of cue utilizations (in the cognitive judgment strategy) mimics the pattern of ecological validities (in the task environment). Achievement, r_a, is measured by correlating the criterion, Ye, to the judgments, Ys. The lens model structure yields the lens model equation (Hursch, Hammond, & Hursch, 1964; Tucker, 1964):

$$r_a = G R_e R_s + C\sqrt{1 - R_e^2}\sqrt{1 - R_s^2}$$

where:
r_a = Achievement
G = Linear Knowledge
R_e = Environmental Predictability
R_s = Cognitive Control
C = Nonlinear Knowledge

As a correlation, the highest achievement value is one. If achievement is less than one, it can be decomposed via the lens model equation in order to understand why judgment performance is not perfect. The first part of the equation is the product of Environmental Predictability (R_e), Cognitive Control (R_s), and Linear Knowledge (G).

Environmental Predictability, R_e, measures a limit to judgment performance based on the predictability of the environment. Environmental predictability is based on task factors (e.g., task specific features, cue reliabilities) and is calculated as the multiple correlation of the environmental linear regression model (regressing the criterion on the cue values).

The consistency with which a judge can execute his or her strategy is captured by cognitive control. Even though a judge might have perfect task knowledge, performance can be limited by the judge's inability to apply that knowledge in a controlled and consistent fashion over time or cases (Bisantz et al., 2000). Importantly, it is possible to measure the separate, independent contributions of task knowledge and cognitive control as performance limiting factors using judgment analysis (for a review, see the cognitive information related results (Balzer, Doherty, & O'Connor, 1989)). Cognitive control is calculated by regressing human judgments on the cue values. R_s is the resulting multiple correlation obtained as a result of this regression analysis.

Linear Knowledge (G) is the correlation between the predictions of the two (environmental and cognitive) regression models. In judgment analysis, the adequacy of a judgment strategy (in terms of beta weights in the linear regression model of the strategy) is the linear knowledge. G indicates the level of judgment performance if the environment and the human judge were completely linearly predictable (where a G of 1 indicates that the judge has perfect linear knowledge of the environment and a G value of 0 indicates that the judge has no linear knowledge of the environment). Even highly experienced domain experts can vary in terms of whether their judgment strategy mirrors the beta weights describing the task environmental structure. Limitations in linear knowledge are associated with a failure to correctly understand the reliabilities of the various judgment cues (for a review, see the task information related results in Balzer et al. (1989)).

The second term in the lens model equation deals with any nonlinear effects not captured by the purely linear effects represented in the first term. C is the "Nonlinear Knowledge" (a measure of any correlation between the human's judgments and the environmental criterion that cannot be explained linearly). In judgment analysis, nonlinear knowledge, or C, is calculated as the correlation between the residuals of the environmental linear regression model and the cognitive linear regression model. Its role is to identify if the judge is capturing non-linear components in the environment that are not captured in a linear model. A low value for C cannot, however, be interpreted as an actual lack of unmodeled response variance as it may indicate substantial but unrelated and unmodeled variance (Cooksey, 1996).

Skill Score

Stewart and Colleagues (Stewart, 1990; Stewart & Lusk, 1994) expanded the Lens Model to include two additional parameters. The expansion is based on Murphy's skill score (SS), a relative measure of judgment goodness. Murphy (1988) considered the "distance" between data sets to conceptualize judgment goodness. Mean Square Error (MSE), a measure of the squared Euclidean distance between two data sets (Cooksey, 1996), defines the concept of distance:

$$MSE_Y = (1/n)\ \Sigma(Y_{si} - Y_{ei})^2$$

Several different decompositions of MSE have been suggested in the literature (Cooksey, 1996; Lee & Yates, 1992). In some decompositions, one judgment system serves as a reference against which the other judgment system is compared. To measure the goodness of the standard, Stewart (1990) suggested using a constant judgment based on the average value of the situational states being judged:

$$MSE_R = (1/n)\ \Sigma(Y_{ei} - Y_{ei})^2$$

To derive the measure of skill requires the ratio between the MSE of the RPIC's judgment and the MSE of the standard. This ratio is then subtracted from unity to create the skill score (SS):

$$SS = 1 - [MSE_Y / MSE_R]$$

Murphy (1988) developed the SS to enable the MSE to be decomposed. SS can be decomposed

$$SS = (r_a)^2 - [r_a - (\sigma_{Ys}/\sigma_{Ye})]^2 - [(Y_s - Y_e)/\sigma_{Ye}]^2$$

into three components: shape, scale error, and magnitude:

The shape component, also called *Resolution*, measures the ability to discriminate between the occurrence and nonoccurrence of situational events (Stewart & Lusk, 1994). SS reduces to a measure of shape (correlation) only when the remaining two components (scale error and magnitude error) are equal to zero (Murphy, 1988). It is calculated in the same manner as the Lens model achievement.

A regression bias manifests as a general tendency to produce judgments on an interval that is larger than found in the true situation (Lee & Yates, 1992; Stewart & Lusk, 1994). The judge must adjust the variability of his or her judgments to be proportional to the variability of the environmental criterion in order to account for regression toward the mean. Making judgments with either too little or too great a range or variation results in a regression bias. The scale error component, also called *Conditional Bias* or *Regression Bias*, measures whether the RPIC has appropriately scaled judgmental variability to situational variability. It is zero when the slope of the regression line predicting the observed events from the RPIC's judgments is 1.0 (Stewart & Lusk, 1994).

Consistently erring either on the side of caution or risk results in a base rate bias (Stewart, 1990). The mean value of human judgments should be equal to the mean value of the environmental criterion (i.e. the objective base rate) or else a base rate bias is evident. The magnitude error component, also called *Unconditional Bias* or *Base Rate Bias* measures the overall (unconditional) bias in the RPIC's judgments, thus diagnosing a tendency to over- or underestimate the judged situation. This bias equals zero when the mean of the RPIC's judgments equals the mean of the judged states (i.e., the objective base rate).

10. APPENDIX D4: CONTROL DEVICE REVIEW OF SCHEFF (2014) INVENTORY

Control Station	Control Device(s)
A-LEVEL AEROSYSTEMS ZALA AERO STANDARD GROUND CONTROL STATION (GCS)	All required UAV control applications are operated via a touch screen laptop virtual control display which the RPIC can modify including waypoints, speed, altitude, maps and set missions at any time to help analyze real-time video. A-Level Aerosystems also develops a handheld version of the control station.
AAI EXPEDITIONARY GROUND CONTROL STATION (EGCS)	Operated via a point-and-click interface.
AAI ONE SYSTEM GROUND CONTROL STATION (OSGCS)	Operated via a point-and-click interface.
ADCOM ADNAV GROUND CONTROL STATION (GCS)	Operated via a point-and-click interface.
ADVANCED UAV TECHNOLOGY GROUND CONTROL STATION (GCS)	Operated via a point-and-click interface, joystick, or touch screen.
AERO DESIGN & DEVELOPMENT (AD & D) GROUND CONTROL STATION (GCS)	The "Virtual Instrument" interface provides on-screen controls and interfaces with panel hardware controls such as joysticks, sliders, and knobs. Command to change dynamic variables (e.g., velocity, altitude, and heading holds) of the vehicle via automatic control system is the second level of control. The higher level of control concerns waypoint navigation. The user can determine a new set of waypoints by point clicking with a trackball on the scrolling map. The new waypoints will then be uplinked to the vehicle.
AEROSCOUT ADVANCED GROUND CONTROL STATION (AGCS)	A touch screen is used for main UAV commands selection, as well as a water-resistant keyboard, and two intelligent joysticks.
AEROVIRONMENT GLOBAL OBSERVER GROUND STATION (GCS)	The pilot's primary interface includes full manual controls (stick, power lever, and rudders) should there be a failure of the automatic control system.

BAE SYSTEMS SILVER FOX INTEGRATED GROUND CONTROL SYSTEM (iGCS)	Operated via mouse and keyboard input or touchscreen.
BAYKAR MAKINA GROUND CONTROL STATION (GCS)	Operated via mouse and keyboard input or joystick.
BLUE BEAR SYSTEMS NEXUS GROUND CONTROL STATION (GCS)	Operated via mouse and keyboard input.
BOEING DATA EXPLOITATION, MISSION PLANNING, AND COMMUNICATIONS (DEMPC) SYSTEM	The workstation is equipped with desktop AV controls (a throttle together with flap and undercarriage controls), a keyboard (with trackball and joystick), and floor-mounted AV brake/rudder pedals.
CDL SYSTEMS VEHICLE CONTROL STATION (VCS)	Each control station provides on-screen controls, and can interface with selected hardware controls such as joysticks and trackballs, or with existing hardware control panels. Graphic interfaces for control and monitoring have been developed for land, sea and air vehicles.
CLOUD CAP TECHNOLOGY GROUND STATION	Operated via keyboard and mouse control.
CRADANCE SERVICES GROUND CONTROL STATION (“CS)	Operated via "stick" and "knob" interfaces.
CRADANCE SERVICES MINIATURE GROUND CONTROL STATION (MGCS)	Operated via keyboard, joystick, and track ball; also contains "stick" and "knob" modes.
DARA AVIATION GROUND CONTROL STATION (GCS)	Operated via keyboard and mouse interface; the GCS also comes with a hand-held controller, which is used to control the UAV during take-off and landing.
DRS DEFENSE SOLUTIONS NEPTUNE RQ-15 GROUND CONTROL STATION (GCS)	Operated via keyboard control.
ELTA SYSTEMS EL/S-8825 GENERIC COMMAND AND CONTROL STATION (GCCS)	An RPIC panel that includes a keyboard and a ‘mini-mouse’ pointing device

EMIT MINIATURE GROUND CONTROL STATION (MGCS)	Operated via keyboard, joystick, and track ball.
EMT LUNA X-2000 GROUND CONTROL STATION (GCS)	Interface contains buttons that can be selected via mouse or touchscreen.
GENERAL ATOMICS AERONAUTICAL SYSTEMS ADVANCED COCKPIT	Operated via stick and throttle, joystick, keyboard, and touchscreen.
INTEGRATED DYNAMICS GCS-1200 PORTABLE GROUND CONTROL STATION (PGCS)	Operated via joystick.
ISRAEL AEROSPACE INDUSTRIES (IAI) MALAT UAV DIVISION INNOVATIVE UNIFIED CONTROL SYSTEM (IUCS)	Operated via keyboard and mouse, or via optional joystick.
KUTTA TECHNOLOGIES UNIFIED GROUND CONTROL STATION (UGCS)	Operated via touchscreen hand-held controller; touchscreen wrist-mounted controller; and/or keyboard and touchpad interface.
L-3 COMMUNICATIONS REMOTELY OPERATED VIDEO ENHANCEMENT RECEIVER (ROVER) FAMILY	Operated via handheld controller, touch screen, and button interfaces.
MEGGITT DEFENSE SYSTEMS UNIVERSAL TARGET CONTROL STATION (UTCS)	All parameters are controlled by ‘point and click’ techniques on custom control panel windows.
MEGGITT DEFENSE SYSTEMS WIZARD AERIAL TARGET C2 GROUND STATION	Operated via point and click interface.
RHEINMETALL DETEC KZO UAS GROUND CONTROL STATION (GCS)	Operated via keyboard and trackball.
RODIAN COMMUNICATIONS /AUTOMASJONSTVIKLING AS GROUND CONTROL STATION (GCS)	Operated via point-and-click or joystick interfaces.

SAIC VIGILANTE GROUND CONTROL STATION (GCS)	Operated via keyboard and trackball interface or via joystick.
SATUMA GROUND CONTROL STATION (GCS)	Operated via ‘point and click’ interface.
SCHIEBEL CAMCOPTER GROUND CONTROL STATION (GCS)	The pilot control unit consists of a control stick and a control panel.
SCION UAS	Operated via keyboard and touchpad laptop interface. All vehicle commands can be implemented via an attached joystick, or via onscreen menu commands. Touchscreen and tablet computer options are also available.
SNAP DEFENSE SYSTEMS (SDS) AGS-21A GROUND CONTROL STATION (GCS)	Operated via a point-and-click interface, joystick device, and toggle controls.
UCONSYSTEM GROUND CONTROL STATION (GCS)	Operated via touchscreen monitors/displays/panels.
UVISION MINIATURE GROUND CONTROL STATION (MGCS)	Operated via keyboard and trackball interface and a joystick interface.
VIGILANT SPIRIT CONTROL STATION (VSCS)	Operated via keyboard, mouse, and joystick.

11. APPENDIX D5: SQL QUERIES FOR TAXONOMY CATEGORIZATION COUNTS

Control Station

```
SELECT cs_2, count(title)
FROM papers_output_tbl
WHERE cs_1 = 'control device'
GROUP BY cs_2;

SELECT cs_2, count(title)
FROM papers_output_tbl
WHERE cs_1 = 'display type'
GROUP BY cs_2;

SELECT cs_2, cs_3, cs_4, count(title)
FROM papers_output_tbl
WHERE cs_1 = 'displayed information'
GROUP BY cs_2, cs_3, cs_4;

SELECT cs_2, count(title)
FROM papers_output_tbl
WHERE cs_1 = 'hardware'
GROUP BY cs_2;

SELECT cs_1, count(title)
FROM papers_output_tbl
WHERE cs_1 is not null
GROUP BY cs_1;
```

Effectiveness Measures

```
SELECT measures_2, count(title)
FROM papers_output_tbl
WHERE measures_1= 'attention allocation'
GROUP BY measures_2;

SELECT measures_2, measures_3, measures_4, count(title)
FROM papers_output_tbl
WHERE measures_1 = 'control'
GROUP BY measures_2, measures_3, measures_4;

SELECT measures_2, measures_3, measures_4, count(title)
FROM papers_output_tbl
WHERE measures_1 = 'detection and assessment'
GROUP BY measures_2, measures_3, measures_4;
```

```
SELECT measures_2, measures_3, count(title)
FROM papers_output_tbl
WHERE measures_1 = 'human-computer interaction'
GROUP BY measures_2, measures_3;

SELECT measures_2, measures_3, count(title)
FROM papers_output_tbl
WHERE measures_’ = 'mission performance'
GROUP BY measures_2, measures_3;

SELECT measures_2, measures_3, measures_4, count(title)
FROM papers_output_tbl
WHERE meas’res_1’= 'operator state'
GROUP BY measures_2, measures_3, measures_4;

SELECT measures_1, count(title)
FROM papers_output_tbl
WHERE measures_1 is not null
GROUP BY measures_1;
```

Context

```
SELECT context_2, context_3, count(title)
FROM papers_output_tbl
WHERE context_1 = 'airspace context'
GROUP BY context_2, context_3;

SELECT context_2, context_3, count(title)
FROM papers_output_tbl
WHERE context_1 = 'approach'
GROUP BY context_2, context_3;

SELECT context_2, context_3, count(title)
FROM papers_output_tbl’
WHERE context_1 = 'crew'
GROUP BY context_2, context_3;

SELECT context_2, context_3, context_4, count(*)
FROM papers_output_tbl
WHERE context_1 = 'environment'
GROUP BY context_2, context_3, context_4;

SELECT context_2, count(title)
FROM papers_output_tbl
```

```
WHERE context_1 = 'ownship'
GROUP BY context_2;

SELECT context_1, count(title)
FROM papers_output_tbl
WHERE context_1 is not null
GROUP BY context_1;

SELECT context_2, context_3, context_4, context_5, count(title)
FROM papers_output_tbl
WHERE context_1 = 'task'
GROUP BY context_2, context_3, context_4, context_5;
```

12. APPENDIX D6: TAXONOMY CATEGORIZATION SUMMARY

Control station categorization document counts.

Category	**Total**
Hardware	38
Control Station Suite	24
Desktop Computer	9
Laptop Computer	2
Tablet Computer	1
Unspecified	2
Control Device	76
Hand Held Controller	5
Joystick	10
Keyboard	23
Knobs	1
Mouse	23
Slider Control	1
Stick and throttle	7
Touchpad	1
Touchscreen	4
Trackball	1
Information Interface	123
Clock	0
Communication	17
Frequency in use	0
Radio (voice) communication	0
Data link communication	17
Electronic checklist	7
Landing gear position	0
Navigation display	27
Horizontal situation indicator	0
Moving map	27
Weather information	0
Out-the-window view	25
Payload status	4
Pitot heat indicator	0
Powerplant	0
Engine status and related information	0
Power/fuel status	0
Thrust indicator	0
Thrust reverser status	0
Primary flight display	9
Airspeed indicator	7
Speed warnings	0

Altitude indicator	0
Altitude indicator/pitch ladder	0
Control mode display	0
Heading indicator	0
Turn bank indicator/turn coordinator	0
System status	25
Traffic Collision Avoidance System	1
Traffic information	1
Vertical situation display	8
Wing flap position indicator	0
Displayed Information	453
Communication	15
Frequency in Use	1
Radio in Use	3
Radio Settings	2
Radio Signal Reception Strength	1
Control Station Health and Status	8
Environmental conditions	7
Air temperature	0
Cloud coverage	0
Cloud height	0
Ice	0
Precipitation	0
Pressure	0
Storm cell location	3
Turbulence	0
Visibility	0
Wind direction	2
Wind speed	2
National Airspace System	7
Airport	2
Runway and taxiway layout	2
Runway status	0
Surface traffic	0
Taxiway status	0
Airspace	5
Restricted area location(s)	5
Prohibited area location(s)	0
Warning area location(s)	0
Military operations area location(s)	0
Alert area location(s)	0
Controller firing area location(s)	0
National security area location(s)	0
Airspace class boundaries	0

Navigation	69
Distance to destination	0
Distance to next waypoint	6
Flight plan cleared route	24
Past re-planning tasks	1
Pending re-planning tasks	3
Taxi route	0
Time to destination	2
Time to next waypoint	6
Waypoint location	27
Out-the-window	15
Enhanced vision	1
Highway-in-the-sky	0
Night vision	0
Out-the-window video feed	12
Synthetic vision	2
Ownship	151
Air intake door status	0
Airspeed	19
Aircraft maximum flaps extended speed (V_{FE})	0
Aircraft maximum landing gear operating speed (V_{LO})	0
Aircraft maximum speed for normal operations (V_{NO})	0
Aircraft maximum operating limit speed (V_{MO})	0
Aircraft maximum operating maneuvering speed (V_O)	0
Aircraft minimum control speed (V_{MC})	0
Aircraft never exceed speed (V_{NE})	0
Aircraft stall speed (V_S)	0
Aircraft stall speed in landing configuration for which the aircraft is still controllable (V_{S1})	0
Aircraft stall speed in landing configuration (V_{S0})	0
Aircraft type	0
Altitude	27
Attitude	6
Bank angle	0
Battery temperature	0
Carburetor air temperature	0
Command sent status	1
Control link status	5
Control mode	0
Current lost link procedure	0
Cylinder head temperature	0
Distance ring	10
Electric power system quantity	0
Engine rotor speed (RPM)	0
Engine rotor speed limit (RPM)	0

Fuel flow	0
Fuel level	5
Fuel pressure	0
Fuel pump status	0
Fuel strainer contamination level	0
Fuel system heater status	0
Fuel temperature	0
Generator/alternator status	0
Ground speed	5
Ice protection system status	0
Heading	26
History trail	0
Hydraulic system pressure	0
Landing gear position	0
Location	29
Manifold pressure	0
Oil pressure	0
Oil quantity	0
Oil strainer contamination level	0
Oil temperature	0
Pilot identification data	0
Pitot heating system status	0
Powerplant status	0
Powerplant valve position	0
Rate of climb	0
Rate of turn	0
Skip/skid status	0
Telemetry data	0
Thrust level	0
Thrust reverser status	0
Trajectory	7
Transponder status	1
Trim device position	0
Usable fuel quantity	0
Usable oil quantity	0
Vertical trend	3
Vertical velocity	7
Wing flap position	0
Terrain	15
Elevation	5
Location	10
Time	7
Time of day	0
Time of day (origin)	0
Time of day (destination)	0

Elapsed flight time	7
Traffic	159
Intruder	130
Absolute altitude	13
Aircraft ID	10
Aircraft length	0
Aircraft width	0
Airspeed	2
Bearing	7
Climb/descent direction	0
Climb/descent rate	1
Ground speed	10
Heading	10
Heading predictor	4
History trail	3
Location	19
Manned/unmanned	1
Onboard equipment	1
Range	6
Relative altitude	11
Threat level	15
Vector line	3
Vertical trend	9
Vertical velocity	5
Conflict detection	14
Closest point of approach	7
Distance to CPA	1
Time to CPA	6
Conflict resolution	15
Maneuver success	8
Suggested maneuver	7

Measure categorization document counts.

Category	Total
Attention Allocation	7
Fixation Frequency	2
Glance Duration	1
Fixation Duration	1
Total Viewing Time	3
Number of Fixations	0
Fixation Rate	0
Glance Frequency	0
Number of Glances	0

Convex Hull Area	0
Scan Path Length	0
Saccade Length	0
Rate of Transitions	0
Blink Duration	0
Blink Rate	0
Pupil Diameter	0
Control	41
Response Time	38
Alert	9
Air Traffic Control	0
Target	2
Airspace Configuration	0
Abnormal System Status	2
Transfer of Control	1
Detect and Avoid	24
Aircraft Response Time	1
Compliance Time	1
Initial Edit Time	4
Initial Response Time	4
Notification Time	3
Total Edit Time	4
Total Response Time	6
Verbal Response Time	1
Target Tracking Performance	0
Fitts' Law	0
Detection and Assessment	5
Signal Detection	5
Response Bias	0
Sensitivity	5
Correct Rejection Rate	0
False Alarm Rate	0
Hit Rate	2
Miss Rate	3
Lens Model	0
Accuracy	0
Consistency	0
Judgment Strategy	0
Skill Score	0
Conditional Bias	0
Skill Score	0
Unconditional Bias	0
Human-Computer Interaction	36
Information Access Time	1
Information Sufficiency	3

Number of clicks	0
Preference	6
Control feature	2
Displayed information	4
Search Time	0
Subjective Clutter	0
Subjective Usability	25
Alert effectiveness	5
Display effectiveness	5
Display type ranking	1
Distraction rating	1
Ease of use	3
Information readability	2
Information usefulness	2
Information understandability	2
Layout rating	1
Most useful feature	2
System controllability	1
Mission performance	54
Collision severity	1
Completion time	3
Compliance	4
Air traffic control	1
Automated resolution	2
Mission commander	1
Conflict resolution maneuver quality	2
Delay	1
Flight path error	18
Lateral	11
Vertical	7
Fuel consumption	0
Landing performance	3
Distance off centerline	2
Glideslope error	0
Lateral velocity	0
Nose position	1
Vertical velocity	0
Map reconstruction	1
Minimum separation distance	2
Number of LOSs	9
Intruder aircraft	4
Terrain	3
Weather	0
Restricted airspace	2
Number of encounters with multiple uploads	1

Perceived performance	3
Preference	2
Maneuver	2
Proportion of collision encounters	0
Speed error	0
Time on task	1
Training required to meet performance criterion	1
RPIC State	29
Mental Workload	18
Objective	0
Heart rate variability	0
Attention allocation	0
Subjective	18
Cooper-Harper	1
Likert scale rating	5
NASA TLX	12
Situation Awareness	11
Objective	3
Posttest questionnaire	1
Real-time questionnaire	1
SAGAT	1
Subjective	9
Likert scale rating	7
Observer rating	1
SWAT	0
SWORD	0
Utilization	0

Study context categorization document counts.

Category	**Total**
Airspace Context	29
Airspace	12
Class A	1
Class B	0
Class C	0
Class D	1
Class E above A	7
Class E below A	0
Class G	3
Flight Rules	13
Instrument	11
Visual	2
Oceanic	0

Surface	0
Airport	1
Non-airport ground	3
Watercraft	0
Approach	82
Accident Data Analysis	4
Computational Modeling	1
Agent-Based Simulation	1
Discrete-Event Simulation	0
Markov Decision Processes	0
Field Test	2
Human Factors Design and Evaluation	9
Focus Group	0
Heuristic Evaluation	0
Observation	1
Participant Questionnaire	2
Subject Matter Expert Interview	1
Task Analysis	3
Think Aloud Verbal Protocol	2
Human in the loop Simulation	35
Literature Review/Meta Analysis	12
Products of the Systems Engineering Lifecycle	19
Operational Concept/Integration Plan	0
Requirements/Design Recommendations	10
Design	7
Prototype	2
Crew	55
External Pilot	3
Pilot in Command	44
Manned Aircraft Experience	9
Unmanned Aircraft Experience	13
Mixed Experience	7
No Prior Flying Experience	8
Unspecified	7
Visual Observer	0
Ground	0
Airborne	0
Mission Commander	5
Payload Operator	3
Environment	46
Atmospheric	8
Wind	3
Visibility	0
Weather	3
Sky Conditions	0

Air Temperature	0
Pressure	0
Precipitation	0
Turbulence	2
Ice	0
Geography	9
Restricted Airspace	4
Buildings	1
Natural Obstacle	3
No Obstacles	1
Other Obstacle	0
Lighting	1
Day	1
Night	0
Intruder Traffic	28
Density	17
None	3
Unspecified	5
<5 Intruder Encounters	3
5-10 Intruder Encounters	6
>10 Intruder Encounters	0
Position Broadcast Equipment	3
Radar-Based	0
Satellite-Based	0
ADS-B	1
Mixed	0
None	2
Vehicle Type	8
Airship	0
Glider	0
Helicopter	0
Manned Powered Aircraft	8
Unmanned Powered Aircraft	0
Unspecified	0
Task	348
Phase of Flight	56
Flight Planning	1
Engine Start	0
Taxi	1
Takeoff	4
Departure	2
En Route	9
Aerial Work/Mission	27
Descent	0
Approach	5

Landing	7
Generic Functions	243
Manage	71
Plan for Normal Conditions	4
Plan for Non-normal Conditions	5
Make Decisions in Normal Conditions	27
Recognize and Respond to Non-normal Conditions	31
Transfer Control	4
Aviate	75
Monitor and Control Aircraft Systems (Including Automation)	38
Monitor Consumable Resources	11
Monitor and Configure Control Station	3
Maneuver Aircraft to Avoid Collision	20
Monitor and Control Status of Control Links	3
Navigate	73
Control and Monitor Aircraft Location and Flight Path	36
Remain Clear of Terrain, Airspace Boundaries, and Weather	15
Self-separate from other Aircraft	17
Ensure Lost Link Procedure Remains Appropriate	3
Terminate Flight	2
Communicate	24
Air Traffic Control	18
Ground Control	0
Local Control	0
Terminal Radar Approach Control	2
Air Route Traffic Control Center	8
General	8
Pilots of other Aircraft	0
Crew Members	1
Ancillary Services (e.g., Weather)	5
Mission	35
Military	19
Reconnaissance	6
Surveillance	4
Tactical Strike	4
Communication Relay	0
Signal Intelligence	0
Maritime Patrol	1
Penetrating Strike	0
Suppression of Enemy Air Defenses (SEAD)	0
Aerial Refueling	0
Counter Air	0
Airlift	1
Target Search	1
Target Identification	2

Civil	14
Atmospheric Research	0
Border Patrol	0
Disaster Response	1
Hurricane Measurement and Tracking	0
Forest Fire Monitoring and Support	4
Search and Rescue	2
Maritime Surveillance	4
Law Enforcement	0
Humanitarian Aid	1
Aerial Imaging and Mapping	0
Drug Surveillance and Interdiction	0
Monitor and Inspect Critical Infrastructure	0
Natural Hazard Monitoring	0
Airborne Pollution Observation and Tracking	1
Chemicals and Petroleum Spill Monitoring	0
Communications Relay	0
Traffic Monitoring	1
Port Security	0
Commercial	2
Crop Monitoring	0
Fish Spotting	0
Remote Imaging and Mapping	0
Utility Inspections	1
Mining Exploration	0
Agricultural Applications	0
Communication Relay	0
Petroleum Spill Monitoring	0
Site Security	0
Broadcast Services	0
News Media Support	0
Filming	0
Real Estate Photos	0
Aerial Advertising	0
Cargo	1
Flight Event	14
Nominal	8
Failure	6
Vehicle Equipment	4
Control Station Equipment	0
Control Link	2
ATC Communication	0
Ownship	58
A160 Hummingbird	0
AAI Aerosonde Mark 4.7	0

ACR Manta	0
ACR Silver Fox	0
ADCOM YABHON	0
Aero Design and Development Hornet	0
Aeronautics Defense Systems Aerolight	0
Aeronautics Defense Systems Aerosky	0
Aeronautics Defense Systems Aerostar	1
Aeroscout B1-100	0
Aeroscout Scout B1-100	0
Aerosonde Mk47	0
Aerosystems ZALA 421	0
AeroVironment Helios	1
AeroVironment Pathfinder	1
AeroVironment Puma	1
AeroVironment Raven B	1
Arcturus T-20	0
ATE Vulture	0
Aurora Flight Sciences Centaur	0
Aurora Flight Sciences Excalibur	0
Aurora Flight Sciences Goldeneye-80	1
Aurora Flight Sciences Orion	0
Aurora Flight Sciences Perseus	1
BAE Systems Kingfisher	0
BAE Systems Phoenix	0
BAE Systems Silverfox	0
BAE Systems Skylynx	0
Baykar Makina	0
Bell 206	0
Bell Helicopter Textron Eagle	1
Boeing Insight	0
Boeing Integrator	0
Cessna 172	1
Cessna 182	0
Cessna Caravan	0
Cyber Tech CyberEye	0
Cyber Tech CyberQuad	0
Cyber Tech CyberWraith	0
Cyber Tech CyBird	0
Dara Aviation D-1	0
DarkStar	0
Denel Dynamics Bateleur	0
Denel Dynamics Seeker	0
DRS Neptune RQ-15	0
EADS Dornier	0
Elbit Systems Hermes	0

EMIT Sparrow	0
EMT LUNA X-2000	0
ENICS BERTA	0
ENICS E08 Aerial Decoy	0
Explorer Tandem Wing	0
Fuji RPH-2A	0
General Atomics Altair	1
Generic Helicopter	0
Generic MALE	4
Generic Multirotor	0
Generic sUAS	2
Global Observer HALE	1
GNAT 750	0
Gulfstream 550	0
Heron	0
Honeywell RQ-16A T-Hawk	0
Hummingbird A-160	0
Husky Autonomous Helicopter	0
IAI NRUAV	0
Innocon MicroFalcon	0
Innocon minFalcon	0
Integrated Dynamics Border Eagle	0
Integrated Dynamics Explorer	0
Integrated Dynamics Hawk	0
Integrated Dynamics Vector	0
Integrated Dynamics Vision MK	0
International Aviation Supply Raffaello	0
King Air 200	0
L-3 TigerShark	0
L-3 Viking	0
MBDA Fire Shadow	0
Meggitt Barracuda	0
Meggitt Hammerhead	0
Meggitt Vindicator	0
MLB Super Bat	0
MQ-1 Predator A	4
MQ-1C ER/MP Sky Warrior/Gray Eagle	0
MQ-9 Predator B/Reaper	11
MSI BQM	0
MSI Chukar	0
MSI Falconet	0
MSI Firejet	0
MSI High Speed Maneuvarable Surface Target	0
MSI MQM	0
MSI QST-35	0

MSI QUH-1 Rotary Wing	0
Northrup Grumman BAT-12	0
Northrup Grumman LEMV Airship	0
Ranger	0
Raven	0
Raytheon Cobra	0
Raytheon KillerBee	0
Rheinmetall Fledermaus	0
Rheinmetall KZO	0
Rheinmetall Mucked	0
Rheinmetall OPALE	0
Rheinmetall Tares/Taifun	0
RMAX TYPE II	0
Rodian/Automasjonsutvikling AS Xr-T8	0
Rodian/Automasjonsutvikling AS Xr-T9	0
RQ-2 Pioneer	2
RQ-4 Global Hawk	2
RQ-5 Hunter	2
RQ-6 Outrider	0
RQ-7 Shadow	3
RQ-8A FireScout	1
SA 60 LAA	0
SA-200 Weasel	0
Sagum Crecerelle	0
Sagum Patroller	0
Sagum Sperwer	0
SAIC Vigilante	0
Satuma Flamingo	0
Satuma Jasoos	0
Satuma Mukhbar	0
ScanEagle	0
Schiebel Camcopter	0
Selex Galileo Falco	0
Selex Galileo Mirach	0
Skycam Hawk	0
Snap Defense Systems Aggressor	0
Snap Defense Systems Bandit	0
Snap Defense Systems Blacklash	0
Snap Defense Systems Centurion	0
Snap Defense Systems Scout	0
Snap Defense Systems Sea Vixen	0
Snap Defense Systems Stingray	0
TAI ANKA	1
Thales Watchkeeper WK450	0
UCon System RemoEye	0

Unmanned Systems Group ATRO-X	0
Unmanned Systems Group CT-450 Discover 1	0
Unspecified	15
UVision Blade Arrow	0
UVision Blue Horizon	0
UVision MALE UAS	0
UVision Sparrow	0
Warrior Gull	0
WLD 1B	0
X-47B N-UCAS	0
Xian ASN	0

13. APPENDIX D7: REVIEW OF NON-AVIATING TASK RESEARCH

Control Station Simulators

Vigilant Spirit Control Station

In the first of a series of human in the loop simulation studies assessing DAA display information requirements, an experiment was conducted assessing two DAA information levels and their locations within the VSCS configuration (Fern et al., 2015; Monk et al., 2015; Santiago & Mueller, 2015). Two levels of DAA information were presented to RPICs, including basic (containing intruder location, range, bearing, heading, relative altitude, vertical trend, heading predictor, and threat level; data tag information, which was presented only when selected or when projected to lose separation with ownship, included ground speed, vertical velocity, absolute altitude, and aircraft ID) and advanced (containing the basic display information plus an additional collision avoidance alerting level, a depiction of predicted closest point of approach (CPA), a 0.8-nm “well clear” threshold ring, a vertical situation display, a single maneuver recommendation, and trial/vector planning tools). Regarding the display location, the DAA display was presented either as a standalone display or integrated with the moving map. Monk et al. (2015), who reported the subjective measures collected in the experiment, revealed higher ratings for the advanced displays in facilitating quick responses to collision avoidance threats than for the basic displays. There was consistent preference for the advanced display, particularly when it was integrated with the moving map display. Furthermore, the intruder predictive outlining feature was rated as the most useful feature, followed by the vertical situation display, lateral and vertical trial planners, and then the time-to-CPA feature. Fern et al. (2015) reported the effects of the manipulations on *Measured Response* times, which measure the response times (RTs) of the phases of the DAA task. The total maneuver edit time and total response time were significantly shorter for advanced displays than for basic displays, and there was a significant interaction between display type and location for initial edit time such that the shortest time occurred when the advanced display was integrated with the moving map display. Santiago and Mueller (2015) reported a decrease in the number of losses of well clear (LoWCs) for the integrated-advanced display condition than for the remaining three display combinations. Their calculations reveal that alert times should be at least 40 seconds before LoWC in order to give the RPIC sufficient time to maneuver the aircraft. The experiment results suggest that the information contained in the basic display is not sufficient for RPICs to perform self-separation, and that DAA information should be integrated with the moving map display in order to prevent the RPIC from mentally combining the information from two displays to avoid conflicts.

In a continuation of the research assessing the basic vs. advanced display configurations, Rorie and Fern (2015) and Santiago and Mueller (2015) attempted to decouple the features comprising the advanced display to assess which specific feature was most beneficial to RPICs. In a human in the loop experiment, RPICs were asked to fly a simulated UAS on an Instrument Flight Rules (IFR) flight plan while complying with ATC clearances and monitoring secondary chat and vehicle health/status tasks. The display combinations were a full crossing of vector planning tools (allowing RPICs to determine predicted threat level associated with various heading and altitude vectors) and auto-resolutions (the RPIC is provided a text box containing a recommended maneuver). All displays contained standard intruder information (location, altitude, speed, etc.), graphical depiction of CPA, and a multi-level alerting system. Reported by Santiago and Mueller

(2015), fewer LoWCs and smaller response times occurred with the displays containing the maneuver recommendation functionality, but there was a lack of statistical differences among the displays. Referring to the *Measured Response* times, the display conditions containing a suggested maneuver consistently resulted in the fastest response times (Rorie & Fern, 2015), likely due to the increased engagement time required to use the vector planning tools. Generally, the results suggest that a recommended maneuver should be provided to RPICs when encountering an obstacle requiring a maneuver, particularly in time-sensitive situations.

Building on the findings about the basic vs. advanced displays as well as the performance enhancements associated with maneuver suggestion vs. vector planning tools, a follow-on study had the objectives to investigate performance differences between various DAA display combinations and to reveal the most efficient manner to communicate an automation-generated recommended maneuver on a stand-alone DAA display (Pack, Draper, Darrah, Squire, & Cooks, 2015). The authors conducted a human in the loop experiment to assess five DAA displays:

- Informative Basic (IB): Provided ownship location, alert level, relative altitude, history trails, and vertical velocity up/down arrows.
- Informative Advanced (IA): Information contained in IB plus a collision avoidance ring around ownship, 30-second predictive heading lines for intruder and ownship, vertical situation display, CPA indications, time-to-CPA, and predictive collision avoidance alerting.
- Text Display: Information contained in IB plus a text-based recommended maneuver.
- Vector Display: Information contained in the Text Display plus a depiction of the resolution vector.
- Banding Display: Information contained in the Text Display plus continuous display of an arc presenting areas of acceptable maneuvering.

The researchers also manipulated the presence of weather cells on the DAA display in half of the trials, representing another constraint to maneuver formulation. Results revealed no difference in maneuver preference, reliance on maneuver recommendation, or RT to alerts. However, the banding display scored the highest in post-experiment subjective preference ratings. The results suggest that continuous presentation of successful maneuver vectors and altitude, such as in the banding display, may be the most effective way to convey maneuver success information.

Given the promise of the banding display for conveying maneuver success information to RPICs (Pack et al., 2015), a follow-on experiment was conducted using the VSCS to compare two different banding display alerting algorithms with vector planning and information-only interfaces (Mueller et al., 2016; Rorie et al., 2016). In their human in the loop simulation, participants flew one of two missions in the Oakland Air Route Traffic Control Center (ARTCC) with one of the four DAA displays. The baseline, Information-Only display contained basic information about each intruder, including relative altitude, bearing, and range along with alerts for intruders predicted to lose well clear. The Vector Planner display contained all of the intruder information contained in the Information-Only display with the addition of the vector planner tool, in which the vector arrow changed color reflecting predicted maneuver success. Regarding the two banding displays, the No Fly Bands display contained banding that provided a continuous indication of safe headings and altitudes (two levels- safe or unsafe) as well as color-coded relative altitudes reflecting safe vs. unsafe altitudes. The Omni Bands display used the same banding approach, but presented three levels of alerts on the band and color coded absolute altitudes reflecting alert levels for altitude maneuvers. The results in Mueller et al. (2016) revealed no differences between the two banding displays for proportion of LoWC and time spent in LoWC, but the measures were significantly smaller than the Vector Planner and Information-Only displays. However, there were no significant differences between the four displays for severity of LoWC. *Measured Response* times to complete maneuvers revealed the banding displays to yield significantly shorter initial response time, but the Vector Planning display yielded the smallest total edit time of the four display types. There were no significant differences between the displays for total response time, maneuver type, maneuver size, or encounters with multiple maneuver uploads. The results suggest that maneuver success information should be continuously provided to RPICs, with the researchers recommending using a band-type display to convey maneuver success information.

Multiple-UAS Simulator Control Station

The Multiple UAS Simulator (MUSIM) is a Linux-based system that has been used by NASA for assessing multiple-UAS control (Fern & Shively, 2009), and for single-UA operations in the NAS. The control station is typically displayed on one monitor, and has been used to present a CSD, a moving map, out-the-window view, a TSD, primary flight displays (PFDs), system health and status, and control handover displays. Next is an overview of the UAS-in-the-NAS research conducted using MUSIM. Using MUSIM, Fern, Kenny, Shively, and Johnson (2012) sought to assess the effects of the inclusion of a cockpit situation display (CSD) in a realistic, single-UA simulated control scenario. The CSD presented aircraft trajectories (both ownship and intruders) and shaded intruders based on their relative altitude to ownship; the CSD did not include any conflict alerting functionality. The experimental manipulation was the presence/absence of the display, as well as low/high intruder traffic density. Experienced air traffic controllers were asked to maintain separation of the aircraft, promoting the realism of the experiment. There was no effect of the CSD condition on minimum distance between ownship and intruders, the number of losses of separation (LOSs), or on the NASA Task Load Index (TLX) workload ratings. However, Likert-scale situation awareness ratings revealed SA to be higher with the inclusion of the display than without the CSD. The results suggest that ATC will have increased workload associated with separation upon UAS integration into the NAS. This finding is especially relevant given that the FAA’s UAS roadmap (2013) specifies that ATC will be responsible for separation services as required by airspace class and type of flight plan. Regarding information requirements, the results suggest that aircraft trajectories and relative altitudes enhance RPIC SA, and therefore should be included on control station traffic displays.

Building on the Fern et al. (2012) experiment, Kenny et al. (2014) assessed the feasibility of UAS performing delegated separation in the NAS with two levels of traffic information in the control station (Figure 22).The two levels of separation delegation included extended delegation, during which ATC was responsible for identifying potential conflicts, notifying the RPIC, and transferring separation responsibility to the RPIC. The second level of separation delegation, called full delegation, assigned full detect and avoid responsibility to the RPIC; however, (s)he was still responsible for informing ATC of any deviations off of the cleared route. These two levels of delegation were crossed with two levels of traffic display information in a human in the loop simulation: basic included intruder ID, altitude, airspeed, and color coded relative altitude; while advanced included basic information plus visual and auditory conflict detection alerts (but no maneuver recommendations). There was a generally low occurrence of LOSs across the experimental conditions, including no significant effects of either independent variable on number of LOSs, in-flight workload probes, post-flight NASA TLX ratings, or post-flight subjective SA ratings. However, the advanced information display yielded significantly higher in-flight SA probe accuracy, and post-experiment questionnaires revealed RPIC preference for conflict detection alerting. Regarding implications for control station design, conflict detection information may not be sufficient for cases in which RPICs are responsible for self-separation. However, these results taken with the results presented by Fern et al. (2012) suggest that traffic information alone may be sufficient when ATC is assigned conflict detection responsibility.

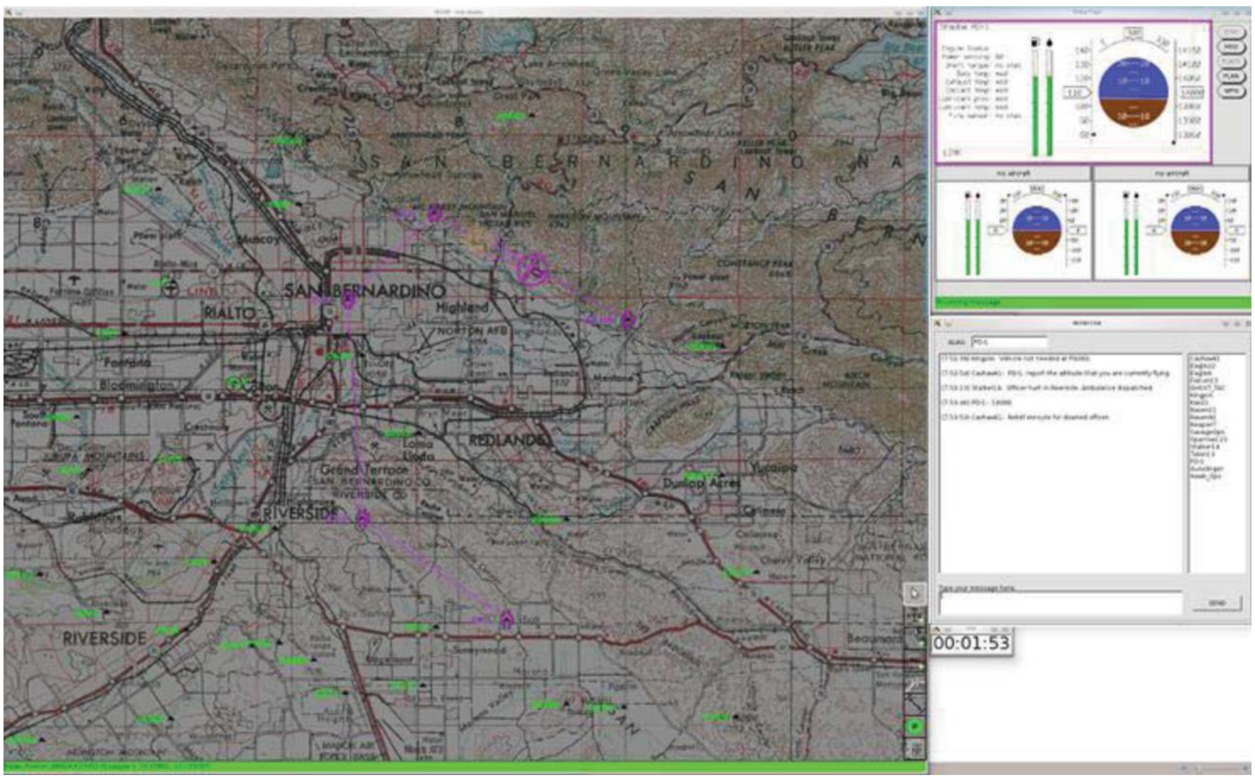

Figure 22. MUSIM interface used in Kenny et al.'s (2014) experiment.

Focusing on a task unique to UAS, Fern and Shively (2011) assessed four display types for UAS control handover between crews. The four display types included: (1) a baseline display, (2) a text display, (3) a graphics display, and (4) a map display. The baseline display reflected current operations, in which the receiving crew must read through the UAS's message history to identify the relevant information for accepting control of the aircraft. The text display presented relevant information to the receiving crew in a text format. The graphics display presented relevant information on a standalone map display (separate from the tactical situation display, which was the main control interface). The map display integrated the graphics display format with MUSIM's tactical situation display, preventing the need to integrate information from two separate displays. The human in the loop simulation results revealed that the three non-baseline conditions yielded more efficient processing of information, leading to decreased time required to understand airspace and aircraft system status, increased SA, and decreased workload compared to the baseline display. Post-experiment display preference rankings revealed preference for the map overlay display, followed by graphics, text, and then baseline. Regarding control station design and information requirements, the results suggest that crews receiving control of the UAS should be given processed UAS state data (rather than being required to search through chat history), including information on planned route, airspace clearances, restricted airspace, etc.

Generic Custom Control Station Simulators

UAS researchers use generic simulators developed for the purposes of answering specific research questions. The control interfaces range from hand-held remotes to sophisticated point-and-click, and display interfaces range from visual line of sight (VLOS) to suites containing multiple high definition displays.

Arteaga, Kotcher, Cavalin, and Dandachy (2016) developed a detect-and-avoid (DAA) display for use with an ADS-B system, which detects future aircraft using the NASA-developed Stratway Algorithm and provides visual and auditory resolution advisories (RAs) to the RPIC. Arteaga et al. (2016) conducted a usability study on the system to evaluate DAA maneuver time requirements over a broad range of encounter geometries. The five participants had a mix of fighter jet, large transport, general aviation, and UAS flying experience. Each RPIC was asked to fly an encounter scenario and to provide a series of usability ratings. The pilots generally agreed that five minutes is a reasonable look-ahead time for a DAA display and should not be exceeded. They generally agreed that 90-seconds is a reasonable velocity vector length (projecting the future path of aircraft on the display), but there were mixed opinions on whether the vector line should always be presented as a straight line, or if it should project any turning arc. There was no consensus about what distances should constitute a collision volume or a near mid-air collision avoidance volume (these thresholds inform which level of alerting is provided to the RPIC). All pilots agreed that conflict alerting would be helpful during flight, but they did not find the resolution advisories as useful as the conflict detection functionality. Regarding information requirements, the results suggest that conflict alerting should be a minimum information requirement, but the resolution advisories may not be useful to RPICs.

With the objective of developing a platform-agnostic DAA capability, Draper, Pack, Darrah, Moulton, and Calhoun (2014) reviewed existing interface concepts and used them to design and conduct part-task studies, to design and conduct an RPIC information requirements survey, and to develop SAA prototypes. DAA information that RPICs stated should be present at all times appears in Table 34. This information, along with other information that RPICs stated would also be helpful, were used to develop a basic and advanced DAA prototype display, which were used in later human in the loop experiments (Fern et al., 2015).

Table 34. DAA information that should be presented to the RPIC at all times (Draper et al., 2014).

Intruder ID
Intruder traffic location and alerts
Intruder relative position
Intruder threat level
Intruder location
DAA task priorities and status

Maneuver recommendations
Flight restrictions
Weather
Navigation data
Visual alerts

In order to conduct an experiment assessing displays containing various levels of DAA information, Friedman-Berg et al. (2014) utilized a control station simulation that was used in domestic operations and was representative of a high-performance UAS with a moderate level of automation. The workstation featured a keyboard and mouse for data entry and manipulation; a stick, throttle, flaps, and rudder pedals for control; a system status display; a head-up display containing aircraft altitude and other positional data overlaying the video feed from a payload camera; a moving map containing mission information; and a traffic information display. In the experiment conducted by Friedman-Berg et al. (2014), four levels of intruder information were presented to RPICs in a DAA display (Table 35). Beyond DAA information, four delegated separation conditions were manipulated ranging from the RPIC having full separation responsibility to the RPIC having delegation authority only in an emergency situation (e.g., conflict requiring immediate maneuvering). In general, the dependent variables tended to plateau at the Prediction level of information; including subjective workload ratings, subjective "display effectiveness ratings", number of near mid-air collisions (NMACs), and fixation time. Ratings on the perceived performance of the information revealed the following to be the most necessary pieces of intruder information: relative altitude, vertical trend arrow, range, alert color coding, bearing, heading chevron, and vector lines. The results suggest that the minimum intruder information set required by RPICs to successfully perform the DAA task consist of position, direction, and prediction information.

Table 35. DAA information included on the four display types in Friedman-Berg et al.'s (2014) experiment.

Information Type	**Display Type**			
	Position	*Direction*	*Prediction*	*Rate*
Intruder ID	X	X	X	X
Range	X	X	X	X
Bearing	X	X	X	X
Relative altitude	X	X	X	X
Range	X	X	X	X
Absolute altitude	X	X	X	X
Heading chevron		X	X	X
Heading		X	X	X
Vertical trend arrow		X	X	X
Alert color coding			X	X
Vector lines			X	X
Ground speed				X
Climb/descent rate				X
History trails				X

In a two-UA supervisory control task, Calhoun, Miller, Hughes, and Draper (2014) hypothesized that providing RPICs with information on DAA logic would enhance performance in a surveillance operation. The control station consisted of a map display with overlaid route and airspace restriction information, a vehicle status and DAA algorithm status panel, and a display containing video feeds from the aircraft. Two DAA logic conditions were presented to participants. In the baseline condition, the UA route was color coded to reflect what the DAA system was doing- returning the UA to the planned path, avoiding an intruder, or overridden by the RPIC. In the augmented condition, added to the color-coding was a “worm” emanating from the UAS symbol reflecting the DAA system’s planned maneuver and a minimum separation ring around the UA symbol, which turned red whenever an intruder’s track was within 45 sec of penetrating the minimum separation distance. Results revealed no significant effect of the display condition on flight path deviation, time to complete the mission, or number of no-fly-zone breaches. However, questionnaire data revealed participants rated their performance as better with the augmented display condition, including ability to minimize deviations from the flight path. Mental workload was also rated as lower for the augmented display condition. Regarding information requirements and display design, the results suggest that providing algorithm transparency could reduce RPIC workload and facilitate an accurate mental model of the automation’s decision process.

De Vries, Koeners, Roefs, Van Ginkel, and Theunissen (2006) report two human in the loop simulations assessing display information for terrain avoidance while performing UAS landing operations. The control station consisted of a display containing a payload camera view containing altitude, heading, and speed information overlaid on the camera view, and a touchscreen with a map view allowing the RPIC to control the aircraft via buttons located on the touch screen interface. Included on the map display were the planned route and intruder aircraft. In their first experiment, there was no significant effect of three levels of automation on ability to avoid terrain or intruders, nor any differences in SA. Leveraging these results, the authors conducted a second experiment in which they modified the map display, including overlay of the traffic situation information on the terrain map, directional intruder icons, a vertical profile display, and an ego-view tunnel display of the future flight path. The addition of these features decreased subjective workload ratings compared to the first experiment, but had no other effects on ability to avoid conflicts. The results generally suggest the potential utility of the information that was added for the second experiment, but it is possible that the low workload, high level of automation, or combination of both employed in the experiments led to the lack of significant differences in conflict avoidance performance.

Control Station Agnostic Research

Tasked with addressing functional requirements for UAS human system interfaces, Access 5 (2006) conducted a functional analysis of future UAS operation in the NAS. They had two basic assumptions in formulating their recommendations, including (1) the UAS has very little to no autonomy and (2) there is a 1:1 RPIC-to-UA ratio. The analysis yielded information and control requirements across four general functional categories, including aviate, navigate, communicate, and avoid hazards. Their information requirements, which are relevant for the A7 minimum information recommendations, are reported in Table 36.

Table 36. Information requirements (Access 5, 2006).

Task	Information Requirement
Aviate	Convey information to the RPIC to monitor maneuvers
	Convey spatial information to the RPIC
	Convey aviate systems to the RPIC
Navigate	Convey information to the RPIC to determine the UA's position, ground track, and ground speed
	Convey navigational information to the RPIC
Communicate	Convey status of the communication system to the RPIC
Avoid Hazards	Convey information to the RPIC to avoid cooperative aircraft
	Convey the relative location of all cooperative aircraft within the CCA system's surveillance volume to the RPIC
	Convey the track profiles associated with any of the cooperative aircraft detected
	Convey that the potential for collision exists
	Convey guidance commands to avoid the potential for collision
	Convey environment status to the RPIC
Cross-Cutting	Convey information to the RPIC to determine the health and status of the UAS

Hobbs and Lyall (2015) compiled UAS human factors guidelines and recommendations for information content of displays, control inputs, properties of the interface, and other general UAS design recommendations. The information content guidelines are reported in Table 37, organized by the generic tasks aviate, navigate, communicate, and manage system and operations.

Table 37. Information content guidelines (Hobbs & Lyall, 2015).

Task	Information Guideline
Aviate/Avoid Hazards	The control station should provide the RPIC with information on the status of consumable resources.
	The control station should provide the RPIC with health and status information on the control station.
	The control station should provide an alert to the RPIC when there is a threat of the UA colliding with another aircraft, terrain, or objects. The alert must be provided in time for the RPIC to effectively respond to make the UA avoid the collision.
	The control station should provide information about terrain or ground-based objects within proximity of the projected UA flight path and may become a threat for UA collision.
	The control station should provide the RPIC with the information necessary to detect aircraft, obstructions or people while the UA is moving on the ground. This information may be provided through a camera located on the aircraft, or closed circuit television (CCTV) cameras located on the ground.

	The control station should provide the RPIC with the information necessary to detect obstructions that may affect launch or takeoff. This information may be provided through a camera located on the aircraft, or CCTV cameras located on the ground.
	The control station should provide the RPIC with the information necessary to detect obstructions that may affect approach and landing. This information may be provided through a camera located on the aircraft, or CCTV cameras located on the ground.
	The control station should provide the RPIC information about the likelihood of the UA colliding with the upcoming threat so that the RPIC will be able to make a decision about the need to take evasive action to avoid a collision.
	The control station should provide the RPIC with a prediction of the time available until the UA would collide with the threat aircraft, object, or terrain.
	The control station should provide information about the aircraft surrounding the UA and the collision threat to help in making a decision about maneuvers that would not cause additional risks for collision.
	The control station should provide information about the capabilities of the UA for making evasive maneuvers in the current UA situation. This information should include at least the following: Possible maneuvers that can be made by the UA in the current situation (e.g. climb, descend, or turn within a certain radius). Time for the UA to accomplish the maneuvers (e.g. how long until the UA reaches a certain turn radius or climb attitude).
	The control station should provide the RPIC with information necessary to quickly identify the current state, mode, or setting of all controls that are used to send flight commands to the UA.
	The control station should provide the RPIC with information on the flight path that had been assigned to the UA prior to the evasive maneuver.
	The control station should provide information about the necessary UA trajectory needed to return to the assigned flight path. This should include the necessary UA heading and altitude changes.
	If an autonomous collision avoidance maneuver is carried out, the control station should alert the RPIC that the maneuver is underway, and must notify the RPIC when the maneuver is concluded.
	The control station should be capable of providing the RPIC with predictive information on the quality and strength of a C2 link before the link is actively used to control the UA.
	The control station should provide information to enable the RPIC to identify which C2 link settings are active (e.g. selected frequency, satellite vs terrestrial).
	The control station should provide the RPIC with information to confirm that effective control is established with the correct UA.
	The control station should provide the RPIC with information on the geographic limits of the link.
	The control station should provide the RPIC with information on spectrum activity from a spectrum analyzer.

	The control station should alert the RPIC when the UA is approaching an area where link is likely to be lost.
	The control station should alert the RPIC when the link is lost.
	The UA will transmit a pre-determined transponder code when the link is lost.
	The control station should provide information to enable the RPIC to monitor the strength of the link.
	The control station should alert the RPIC whenever the C2 link experiences interference, whether resulting from natural phenomena, payload or other equipment associated with the UAS, or human activities (such as jamming or other users on frequency).
	The control station should display to the RPIC the source of downlink transmissions.
	Where relevant, the control station should provide the RPIC with information on link latency, in milliseconds.
	The control station should provide information to enable the RPIC to anticipate link degradations or diminished link strength. This information may include link footprint, including areas that may be affected by terrain masking.
	The control station should provide information to enable the RPIC to manage link security.
	The control station should inform the RPIC when a lost link is resumed.
Navigate	UA position in airspace. The control station should provide a representation of the UA within the airspace. This information should provide: Representation of UA within the airspace. Heading of UA. Altitude of UA. Speed of UA. Attitude of UA. Position of UA relative to other aircraft, terrain, and obstacles.
	Programmed flight plan and predicted flight path of UA. The control station should provide a representation of the predicted flight path of the UA based on the flight plan programmed into the flight management system based on the assigned flight clearance. This information should include: Indication of UA current position along programmed flight path. Predicted flight path relative to UA and other traffic, terrain, and obstacles. Distance to waypoints along flight path. Indication of position in flight path when new commanded altitude will be attained. Indication of turning radius and path when making turns along flight path.
	The RPIC should be able to display flight corridors, controlled airspace and any other relevant airspace co-ordination information.
	The control station should display weather information to the RPIC.
	The control station should provide the RPIC with information on the location of icing conditions, especially if the UA is not certificated for flight in icing conditions.
	The control station should alert the RPIC when the UA enters icing conditions.

	The control station should alert the RPIC when the UA encounters significant air turbulence.
	The control station should provide the RPIC with a display indicating the future flight path of the aircraft should a lost link occur.
	The control station should alert the RPIC whenever the execution of a lost link procedure would create a hazard (such as directing the aircraft towards terrain, or into non-authorized airspace).
	The control station should provide the RPIC with real-time imagery of the selected impact, ditching or parachute descent site to confirm that a safe termination can be accomplished.
	The control station should provide an alert to the RPIC to indicate that the flight termination system is about to be activated.
Communicate	The control station should include alternate means for the RPIC to communicate with ATC in the event of a loss of C2 link.
	The control station should provide the RPIC with information about the current state, mode, or setting of the controls used for communication with ATC.
	The control station should provide the RPIC with imagery of the aircraft whenever the RPIC has control of the aircraft on the ground and ground support personnel are interacting with the aircraft.
	The control station should provide the RPIC with a communication link with ground support personnel while they are interacting with the aircraft.
Manage Systems and Operations	During transfer of control, the RPIC should be presented with information necessary to confirm that flight-critical settings in the receiving control station are consistent with settings in the giving control station.
	The control station should provide a level of involvement indicator to the RPIC to show whether the control station has been set to only receive telemetry from the UA, or to receive telemetry and transmit commands to the UA.

In a NASA-led project, a review of the literature was conducted with the objective of making functional requirement recommendations for UAS collision avoidance technology (Access 5, 2005a). Sources reviewed included Society of Automotive Engineers Aerospace Recommended Practices, FAA regulatory and advisory material, FAA human factors design guide, plus others. Regarding information requirements, the review concluded that sufficient information needs to be conveyed to the RPIC to enable him/her to perform conflict resolutions in a timely manner. This process includes alerting the RPIC of potential conflicts, guidance on choosing and implementing a successful maneuver, and a traffic display that gives the RPIC more information about the immediate surroundings of the UA. Table 38 reports select display requirement recommendations for collision avoidance.

Table 38. Select collision avoidance display requirements (Access 5, 2005a).

Category	Display Requirement
General	The information provided by the system should enable the pilot to perform conflict resolutions, or respond to resolution guidance, in a timely manner.
Alerting	Once a loss of separation has been detected or forecast, the system shall alert the pilot.
	Visual alerts may be provided to warn the pilot that a response to traffic is required.
	Aural alerts may be provided to warn the pilot that a response to traffic is required.
	Based on system ability to determine the urgency of a traffic situation, alerts shall be presented to the pilot that describe the level of urgency in an unambiguous manner. Different alerts shall be provided for alerts with different urgencies.
	Alerts annunciated to the pilot shall correspond to the presentation of traffic information (on displays) to the pilot and/or command information presented (visually or aurally) to the pilot.
	Any failure or degradation of the system shall be detected and communicated to the pilot.
	The operating mode of the system shall be clearly indicated to the pilot. All mode changes shall be emphasized to aid the pilot in determining that a mode change has occurred.
Guidance	Guidance is required and shall be displayed to direct the pilot to make the appropriate response.
	When guidance information is employed, the pilot shall have a clear understanding of the action to perform to resolve the conflict
	The command guidance shall be removed as soon as the alert condition no longer exists.
Cockpit Display of Traffic Information	The display format and information content shall be dependent on the intended use and operation of the CDTI.
	In addition to an alerting function, the system shall have a function that allows the pilot to obtain more detailed information about the traffic situation.

Again reviewing Society of Automotive Engineers Aerospace Recommended Practices, FAA regulatory and advisory material, FAA human factors design guide, and other papers, Access 5 (2005b) reported display requirements for command, control, and communications. Table 39 provides an overview of the display requirements that are within scope of this A7 control station review. In general, the requirements emphasize the importance of feedback to the RPIC, particularly with regard to communication with ATC, sending commands to the UA, and the status of the datalink.

Table 39. Select display requirements for UAS command, control, and communications (Access 5, 2005b).

Category	Display Requirement
Voice Communications with ATC	The pilot shall have the capability to determine the radio in use by referring to displays and/or indicators in the control station.
	The pilot shall have capability to receive feedback regarding radio operation at the control station. This includes capability to know radio on and off status, display of frequency selected for transmission and reception, reception volume setting, and radio modes (subject to radio design).
	The control station shall display to the pilot the LOS and BLOS status of communications.
Data Communications with ATC	The control station shall display feedback to the pilot regarding transponder operation at the control station. This includes capability to present transponder on and off status, display of code selected, and transponder modes.
Command and Control	The pilot shall have information available at the control station that indicates authorized datalink actions prior to enabling control of the vehicle flight path or trajectory.
	The control station shall display feedback to the pilot regarding the source of downlink transmissions by reference to downlink data displayed at the control station.
	The control station shall display timely feedback to the pilot regarding the content of a command and when a command has been entered into the system.
	The control station shall display feedback to the pilot when a datalink message arrives by a visual and/or aural alert.
	The control station shall display feedback to the pilot regarding the status or quality of each uplink and downlink.
	The control station shall display feedback to the pilot for any partial or full failure of a datalink.

14. APPENDIX D8: REVIEW OF APPLICABLE FEDERAL REGULATIONS

Table 40. 14 CFR 23—Airworthiness standards: Normal, utility, acrobatic, and commuter category airplanes.

Indicator/Warning	Required For	Required Based On	Information Represented
Airspeed Indicator	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1303 - (a)	§23.1323 - (a): Indicates true airspeed (at sea level with a standard atmosphere) with a minimum practicable instrument calibration error when the corresponding pitot and static pressures are applied. §23.1545 - (b): The following markings must be made: (1) never-exceed speed V_{NE}, a radial red line. (2) For the caution range, a yellow arc extending from the red line specified in paragraph (b)(1) of this section to the upper limit of the green arc specified in paragraph (b)(3) of this section. (3) For the normal operating range, a green arc with the lower limit at V_{S1} with maximum weight and with landing gear and wing flaps retracted, and the upper limit at the maximum structural cruising speed V_{NO} established under §23.1505(b). (4) For the flap operating range, a white arc with the lower limit at V_{S0} at the maximum weight, and the upper limit at the flaps-extended speed V_{FE} established under §23.1511. (c) If V_{NE} or V_{NO} vary with altitude, there must be means to indicate to the pilot the appropriate limitations throughout the operating altitude range. (d) Paragraphs (b)(1) through (b)(4) and paragraph (c) of this section do not apply to airplanes for which a maximum operating speed V_{MO}/M_{MO} is established under §23.1505(c). For those airplanes, there must either be a maximum allowable airspeed indication showing the variation of V_{MO}/M_{MO} with altitude or compressibility limitations (as appropriate), or a radial red line marking for V_{MO}/M_{MO} must be made at lowest value of V_{MO}/M_{MO} established for any altitude up to the maximum operating altitude for the airplane. §23.1563: There must be an airspeed placard in clear view of the pilot and as close as practicable to the airspeed indicator. This placard must list— (a) The operating maneuvering speed, V_O; and (b) The maximum landing gear operating speed V_{LO}. (d) The airspeed placard(s) required by this section need not be lighted if the landing gear operating speed is indicated on the airspeed indicator or other lighted area such as the landing gear control and the airspeed indicator has features such as low speed awareness that provide ample warning prior to V_{MC}.

	Reciprocating Engine-Powered Airplanes	Subpart F - §23.1303 - (a)	§23.1545 -(b): The following markings must be made: (5) For reciprocating multiengine-powered airplanes of 6,000 pounds or less maximum weight, for the speed at which compliance has been shown with §23.69(b) relating to rate of climb at maximum weight and at sea level, a blue radial line. (6) For reciprocating multiengine-powered airplanes of 6,000 pounds or less maximum weight, for the maximum value of minimum control speed, V_{MC}, (one-engine-inoperative) determined under §23.149(b), a red radial line. §23.1563: There must be an airspeed placard in clear view of the pilot and as close as practicable to the airspeed indicator. This placard must list— (c) For reciprocating multiengine-powered airplanes of more than 6,000 pounds maximum weight, the maximum value of the minimum control speed, V_{MC} (one-engine-inoperative) determined under §23.149(b).
	Turbine Engine Powered Airplanes & Other Airplanes Mentioned in Subpart F - §23.1303 - (e)(2)	Subpart F - §23.1303 - (a)	§23.1563: There must be an airspeed placard in clear view of the pilot and as close as practicable to the airspeed indicator. This placard must list— (c) For turbine engine-powered airplanes, the maximum value of the minimum control speed, V_{MC} (one-engine-inoperative) determined under §23.149(b).
Altimeter	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1303 - (b)	§25.1325 - (d): Indicates pressure altitude in a standard atmosphere, with a minimum practicable calibration error when the corresponding static pressures are applied. AC 23-8C: Measures the difference between a sea level barometer pressure set on the instrument and static pressure, and indicates in units of feet
Magnetic Direction Indicator	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1303 - (c)	§23.1321 - (d): Indicates direction of flight §23.1547: (a) A placard meeting the requirements of this section must be installed on or near the magnetic direction indicator. (b) The placard must show the calibration of the instrument in level flight with the engines operating. (c) The placard must state whether the calibration was made with radio receivers on or off. (d) Each calibration reading must be in terms of magnetic headings in not more than 30 degree increments. (e) If a magnetic nonstabilized direction indicator can have a deviation of more than 10 degrees caused by the operation of electrical equipment, the placard must state which electrical loads, or combination of loads, would cause a deviation of more than 10 degrees when turned on.
Free Air Temperature Indicator	Reciprocating Engine-Powered Airplanes	Subpart F - §23.1303 - (d)	
	Turbine Engine Powered Airplanes & Other	Subpart F - §23.1303 - (d)	

	Airplanes Mentioned in Subpart F - §23.1303 - (e)(2)		
Speed Aural Warning Device	Turbine Engine Powered Airplanes & Other Airplanes Mentioned in Subpart F - §23.1303 - (e)(2)	Subpart F - §23.1303 - (e)	§23.1303 - (e): Aural warning (differing distinctively from aural warnings used for other purposes) to the pilots whenever the speed exceeds Vmo plus 6 knots or Mmo + 0.01. The upper limit of the production tolerance for the warning device may not exceed the prescribed warning speed. The lower limit of the warning device must be set to minimize nuisance warning
Attitude Display	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1303 - (f)	
Maximum Allowable Airspeed Indicator	Commuter Category Airplanes	Subpart F - §23.1303 - (g)	§23.1303 - (g): If airspeed limitations vary with altitude, maximum allowable airspeed indicator shows the variation of VMO with altitude.
Fuel Quantity Indicator	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1305 - (a) Subpart F - §23.1337 - (b)	§23.1337 - (b): Indicates the quantity of usable fuel in each tank during flight. (1) Each fuel quantity indicator must be calibrated to read “zero” during level flight when the quantity of fuel remaining in the tank is equal to the unusable fuel supply determined under §23.959(a); (4) There must be a means to indicate the amount of usable fuel in each tank when the airplane is on the ground (such as by a stick gauge) §23.1553: A red radial line must be marked on each indicator at the calibrated zero reading, as specified in §23.1337(b)(1). §23.1555: (c) For powerplant fuel controls— (1) Each fuel tank selector control must be marked to indicate the position corresponding to each tank and to each existing cross feed position; (d) Usable fuel capacity must be marked as follows: (1) For fuel systems having no selector controls, the usable fuel capacity of the system must be indicated at the fuel quantity indicator. (2) For fuel systems having selector controls, the usable fuel capacity available at each selector control position must be indicated near the selector control. Refer to "Oil Pressure Indicator" Information Content
Oil Pressure Indicator	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1305 - (a)	§23.1549: For each required powerplant and auxiliary power unit instrument, as appropriate to the type of instruments— (a) Each maximum and, if applicable, minimum safe operating limit must be marked with a red radial or a red line; (b) Each normal operating range must be marked with a green arc or green line, not extending beyond the maximum and minimum safe limits; (c) Each takeoff and precautionary range must be marked with a yellow arc or a yellow line; and (d) Each engine, auxiliary power unit, or propeller range that is restricted

			because of excessive vibration stresses must be marked with red arcs or red lines.
Oil Temperature Indicator	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1305 - (a)	Refer to "Oil Pressure Indicator" Information Content
Oil Quantity Indicator	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1305 - (a) Subpart F - §23.1337 - (d)	§23.1337 - (d): Indicates the quantity of oil in each tank— (1) On the ground (such as by a stick gauge); and (2) In flight, to the flight crew members, if there is an oil transfer system or a reserve oil supply system. §23.1551: Each oil quantity indicator must be marked in sufficient increments to indicate readily and accurately the quantity of oil. Refer to "Oil Pressure Indicator" Information Content
A Fire Warning Means for those airplanes required to comply with §23.1203	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1305 - (a) Subpart E - §23.1203	§23.1203: (a) There must be means that ensure the prompt detection of a fire (d) There must be means to allow the crew to check, in flight, the functioning of each fire detector electric circuit. Refer to "Oil Pressure Indicator" Information Content
Induction System Air Temperature Indicator	Reciprocating Engine-Powered Airplanes	Subpart F - §23.1305 - (b)	Refer to "Oil Pressure Indicator" Information Content
Tachometer Indicator	Reciprocating Engine-Powered Airplanes	Subpart F - §23.1305 - (b)	§23.1305 - (c): Indicates the speed of the rotors with established limiting speeds for each engine. Refer to "Oil Pressure Indicator" Information Content
	Turbine Engine Powered Airplanes & Other Airplanes Mentioned in Subpart F - §23.1303 - (e)(2)	Subpart F - §23.1305 - (c)	§23.1305 - (c): Indicates the speed of the rotors with established limiting speeds for each engine. Refer to "Oil Pressure Indicator" Information Content
Cylinder Head Temperature Indicator	Reciprocating Engine-Powered Airplanes	Subpart F - §23.1305 - (b)	Refer to "Oil Pressure Indicator" Information Content
	Commuter Category Airplanes	Subpart F - §23.1305 - (b)	Refer to "Oil Pressure Indicator" Information Content
Fuel Pressure or Fuel Flow Indicator	Reciprocating Engine-Powered Airplanes	Subpart F - §23.1305 - (b)	§23.1305 - (b): (4) For each pump-fed engine, a means: (i) That continuously indicates, to the pilot, the fuel pressure or fuel flow; or (ii) Refer to "Fuel Pressure or Fuel Flow Warning Device" Refer to "Oil Pressure Indicator" Information Content
Fuel Pressure or Fuel Flow Warning Device	Reciprocating Engine-Powered Airplanes	Subpart F - §23.1305 - (b)	§23.1305 - (b): (4) For each pump-fed engine, a means: (i) Refer to "Fuel Pressure or Fuel Flow Indicator"; or (ii) That continuously monitors the fuel system and warns the pilot of any fuel flow trend that could lead to engine failure.
Manifold Pressure Indicator	Reciprocating Engine-Powered Airplanes	Subpart F - §23.1305 - (b)	Refer to "Oil Pressure Indicator" Information Content

Coolant Temperature Indicator	Reciprocating Engine-Powered Airplanes	Subpart F - §23.1305 - (b)	Refer to "Oil Pressure Indicator" Information Content
Gas Temperature Indicator	Turbine Engine Powered Airplanes & Other Airplanes Mentioned in Subpart F - §23.1303 - (e)(2)	Subpart F - §23.1305 - (c)	Refer to "Oil Pressure Indicator" Information Content
Fuel Flowmeter Indicator	Turbine Engine Powered Airplanes & Other Airplanes Mentioned in Subpart F - §23.1303 - (e)(2)	Subpart F - §23.1305 - (c) Subpart F - §23.1337 - (c)	Refer to "Oil Pressure Indicator" Information Content
Fuel Low Pressure Warning Device	Turbine Engine Powered Airplanes & Other Airplanes Mentioned in Subpart F - §23.1303 - (e)(2)	Subpart F - §23.1305 - (c)	
Fuel Low Level Warning Device	Turbine Engine Powered Airplanes & Other Airplanes Mentioned in Subpart F - §23.1303 - (e)(2)	Subpart F - §23.1305 - (c)	§27.1305 - (l): This device must— (1) Provide a warning to the flightcrew when approximately 10 minutes of usable fuel remains in the tank; and (2) Be independent of the normal fuel quantity indicating system.
Oil Low Pressure Warning Device	Turbine Engine Powered Airplanes & Other Airplanes Mentioned in Subpart F - §23.1303 - (e)(2)	Subpart F - §23.1305 - (c)	
Powerplant Ice Protection System Indicator	Turbine Engine Powered Airplanes & Other Airplanes Mentioned in Subpart F - §23.1303 - (e)(2)	Subpart F - §23.1305 - (c)	§23.1305 - (c): indicate the functioning of the powerplant ice protection system for each engine. §23.1416 - (c): Means to indicate to the flight crew that the pneumatic de-icer boot system is receiving adequate pressure and is functioning normally must be provided. Refer to "Oil Pressure Indicator" Information Content
Fuel Strainer or Filter Indicator	Turbine Engine Powered Airplanes & Other Airplanes Mentioned in Subpart F - §23.1303 - (e)(2)	Subpart F - §23.1305 - (c)	§23.1305 - (c): Indicate the occurrence of contamination of the strainer or filter before it reaches the capacity established in accordance with §23.997(d) Refer to "Oil Pressure Indicator" Information Content
Oil Strainer or Filter Warning Device	Turbine Engine Powered Airplanes & Other	Subpart F - §23.1305 - (c)	§23.1305 - (c): Warn the pilot of the occurrence of contamination of the strainer or filter screen before it reaches the capacity established in accordance

	Airplanes Mentioned in Subpart F - §23.1303 - (e)(2)		with §23.1019(a)(5). §23.1019 - (a): (3) The oil strainer or filter, unless it is installed at an oil tank outlet, must incorporate a means to indicate contamination before it reaches the capacity established in accordance with paragraph (a)(2) of this section.
Heater Performance Indicator	Turbine Engine Powered Airplanes & Other Airplanes Mentioned in Subpart F - §23.1303 - (e)(2)	Subpart F - §23.1305 - (c)	§23.1305 - (c): Indicates the functioning of any heater used to prevent ice clogging of fuel system components. Refer to "Oil Pressure Indicator" Information Content
Thrust Indicator	Turbojet/Turbofan Engine-Powered Airplanes	Subpart F - §23.1305 - (d)	§23.1305 - (d): Indicates thrust or a parameter that can be related to thrust, including a free air temperature indicator if needed for this purpose. Refer to "Oil Pressure Indicator" Information Content
Engine Position Indicating Indicator	Turbojet/Turbofan Engine-Powered Airplanes	Subpart F - §23.1305 - (d)	§23.1305 - (d): Indicates to the flight crew when the thrust reverser, if installed, is in the reverse thrust position. Refer to "Oil Pressure Indicator" Information Content
Torque Indicator	Turbopropeller-Powered Airplanes	Subpart F - §23.1305 - (e)	Part 23 - Special Federal Aviation Regulation No. 23: Indicates power output for each engine. Refer to "Oil Pressure Indicator" Information Content
Propeller Position Indicating Indicator	Turbopropeller-Powered Airplanes	Subpart F - §23.1305 - (e)	§23.1305 - (e): Indicates to the flight crew when the propeller blade angle is below the flight low pitch position, for each propeller. Refer to "Oil Pressure Indicator" Information Content
Fuel Pump Warning Device	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart E - §23.991 - (c)	§23.991 - (c): If both the main pump and emergency pump operate continuously, there must be a means to indicate to the appropriate flight crewmembers a malfunction of either pump.
Fuel Flow Indicator	Turbine Engine Powered Airplanes & Other Airplanes Mentioned in Subpart F - §23.1303 - (e)(2)	Subpart E - §23.955 - (f)	§23.955 - (f): (2) For multiengine airplanes, (ii) The fuel system design must clearly indicate the engine for which fuel in any tank is scheduled.
Pitot Heating System Operation Indicator	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1326	§23.1326: Indicates to the flight crew when the pitot heating system is not operating. The indication system must comply with the following requirements: (a) The indication provided must incorporate an amber light that is in clear view of a flightcrew member. (b) The indication provided must be designed to alert the flight crew if either of the following conditions exist: (1) The pitot heating system is switched “off.” (2) The pitot heating system is switched “on” and any pitot tube heating element is inoperative.

Actuating Device-Control System Alignment Indicator	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1329 - (c)	§23.1329 - (c): Indicates to the pilot the alignment of the actuating device in relation to the control system it operates.
Mode of Operation Indicator	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1329 - (h)	§23.1329 - (h): Indicates to the flight crew the current mode of operation. Selector switch position is not acceptable as a means of indication.
Visual Power Annunciator/Power Indicator	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1331 - (a)	§23.1331: For each instrument that uses a power source, the following apply: (a) Each instrument must have an integral visual power annunciator or separate power indicator to indicate when power is not adequate to sustain proper instrument performance.
Mode of Operation Indicator	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1335	§23.1335: Indicates to the flight crew the current mode of operation (if a flight director system is installed). Selector switch position is not acceptable as a means of indication.
Generator/Alternator Warning Device	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1351 - (c)	§23.1351 - (c): Gives immediate warning to the flight crew of a failure of any generator/alternator.
Ammeter	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1351 - (d)	§23.1351 - (d): Indicates to appropriate flight crewmembers the electric power system quantities essential for safe operation. (1) For normal, utility, and acrobatic category airplanes with direct current systems, an ammeter that can be switched into each generator feeder may be used and, if only one generator exists, the ammeter may be in the battery feeder.
Voltage and Current Indicators	Commuter Category Airplanes	Subpart F - §23.1351 - (d)	§23.1351 - (d): Indicates to appropriate flight crewmembers the electric power system quantities essential for safe operation. (2) For commuter category airplanes, the essential electric power system quantities include the voltage and current supplied by each generator.
Battery Temperature Sensing and Over-Temperature Warning System	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1353 - (g)	
Battery Failure Sensing and Warning System	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1353 - (g)	
Hydraulic System Pressure Indicator	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1435 - (a)	§23.1435 - (a): Indicates the pressure in each hydraulic system which supplies two or more primary functions must be provided to the flight crew.
Terrain Awareness and Warning System	Turbine Engine Powered Airplanes & Other Airplanes Mentioned in	Subpart K - §121.354 - (a)	§121.354 - (a): equipped with an approved terrain awareness and warning system that meets the requirements for Class A equipment in Technical Standard Order (TSO)-C151. The airplane must also include an approved terrain situational awareness display.

	Subpart F - §23.1303 - (e)(2)		
Airborne Windshear Warning and Flight Guidance System, or approved airborne detection and avoidance system, or an approved combination of these systems	Turbine Engine Powered Airplanes & Other Airplanes Mentioned in Subpart F - §23.1303 - (e)(2)	Subpart K - §121.358 - (a)	
Voice Recorder Aural or Visual Device	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1457 - (d)	§23.1457 - (d): Indicates proper operation of the recorder for preflight checking.
	Turbine Engine Powered Airplanes & Other Airplanes Mentioned in Subpart F - §23.1303 - (e)(2)	Subpart K - §121.359	
Flight Recorder Aural or Visual Device	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart F - §23.1459 - (a) Subpart K - §121.343	§23.1459 - (a): Indicates proper recording of data in the storage medium of the recorder for preflight checking. Subpart K - §121.343
Air Intake Door State Indicator	Reciprocating Engine-Powered Airplanes	Subpart E - §23.1091 - (b)	§23.1091 - (b): Indicates to the flight crew when each automatic alternate air door is not closed.
Valve Position	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart E - §23.1141 - (g)	§23.1141 - (g): (g) Powerplant valve controls located in the cockpit must have— (2) For power-assisted valves, a means to indicate to the flight crew when the valve— (i) Is in the fully open or fully closed position; or (ii) Is moving between the fully open and fully closed position.
Stall Warning Device	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart B - §23.207	§23.207: (a) There must be a clear and distinctive stall warning, with the flaps and landing gear in any normal position, in straight and turning flight. (b) The stall warning may be furnished either through the inherent aerodynamic qualities of the airplane or by a device that will give clearly distinguishable indications under expected conditions of flight. However, a visual stall warning device that requires the attention of the crew within the cockpit is not acceptable by itself. (d) When following procedures furnished in accordance with §23.1585, the stall warning must not occur during a takeoff with all engines operating, a takeoff continued with one engine inoperative, or during an approach to

			landing. (f) For acrobatic category airplanes, an artificial stall warning may be mutable, provided that it is armed automatically during takeoff and rearmed automatically in the approach configuration.
Trim Movement Indicator	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart D - §23.677	§23.677: (a) There must be means near the trim control to indicate to the pilot the direction of trim control movement relative to airplane motion. In addition, there must be means to indicate to the pilot the position of the trim device with respect to both the range of adjustment and, in the case of lateral and directional trim, the neutral position. This means must be visible to the pilot and must be located and designed to prevent confusion. The pitch trim indicator must be clearly marked with a position or range within which it has been demonstrated that take-off is safe for all center of gravity positions and each flap position approved for takeoff.
Takeoff Warning Device	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart D - §23.703	§23.703: For all airplanes with a maximum weight more than 6,000 pounds and all jets, unless it can be shown that a lift or longitudinal trim device that affects the takeoff performance of the airplane would not give an unsafe takeoff configuration when selected out of an approved takeoff position, a takeoff warning system must be installed and meet the following requirements: (a) The system must provide to the pilots an aural warning that is automatically activated during the initial portion of the takeoff role if the airplane is in a configuration that would not allow a safe takeoff. The warning must continue until— (1) The configuration is changed to allow safe takeoff, or (2) Action is taken by the pilot to abandon the takeoff roll. (b) The means used to activate the system must function properly for all authorized takeoff power settings and procedures and throughout the ranges of takeoff weights, altitudes, and temperatures for which certification is requested. (c) For the purpose of this section, an unsafe takeoff configuration is the inability to rotate or the inability to prevent an immediate stall after rotation.
Pitching Motion Faults Warning Device	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart D - §23.691 - (c)	§23.691 - (c): In addition to the stall warning required §23.07, a warning that is clearly distinguishable to the pilot under all expected flight conditions without requiring the pilot's attention, must be provided for faults that would prevent the system from providing the required pitching motion.
Wing Flap Position Indicator	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart D - §23.699	§23.699: There must be a wing flap position indicator for— (a) Flap installations with only the retracted and fully extended position, unless— (1) A direct operating mechanism provides a sense of “feel” and position (such as when a mechanical linkage is employed); or (2) The flap position is readily determined without seriously detracting from

			other piloting duties under any flight condition, day or night; and (b) Flap installation with intermediate flap positions if— (1) Any flap position other than retracted or fully extended is used to show compliance with the performance requirements of this part; and (2) The flap installation does not meet the requirements of paragraph (a)(1) of this section.
Landing Gear Position Indicator	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart D - §23.729 - (e)	§23.729 - (e): If a retractable landing gear is used, there must be a landing gear position indicator (as well as necessary switches to actuate the indicator) or other means to inform the pilot that each gear is secured in the extended (or retracted) position. If switches are used, they must be located and coupled to the landing gear mechanical system in a manner that prevents an erroneous indication of either "down and locked" if each gear is not in the fully extended position, or "up and locked" if each landing gear is not in the fully retracted position. §23.1555 - (e): For accessory, auxiliary, and emergency controls— (1) If retractable landing gear is used, the indicator required by §23.729 must be marked so that the pilot can, at any time, ascertain that the wheels are secured in the extreme positions
Landing Gear Warning Devices	All Normal, Utility, Acrobatic, and Commuter Category Airplanes	Subpart D - §23.729 - (f)	§23.729 - (f): For landplanes, the following aural or equally effective landing gear warning devices must be provided: (1) A device that functions continuously when one or more throttles are closed beyond the power settings normally used for landing approach if the landing gear is not fully extended and locked. A throttle stop may not be used in place of an aural device. If there is a manual shutoff for the warning device prescribed in this paragraph, the warning system must be designed so that when the warning has been suspended after one or more throttles are closed, subsequent retardation of any throttle to, or beyond, the position for normal landing approach will activate the warning device. (2) A device that functions continuously when the wing flaps are extended beyond the maximum approach flap position, using a normal landing procedure, if the landing gear is not fully extended and locked. There may not be a manual shutoff for this warning device. The flap position sensing unit may be installed at any suitable location. The system for this device may use any part of the system (including the aural warning device) for the device required in paragraph (f)(1) of this section.

Table 41. 14 CFR 25—Airworthiness standards: Transport category airplanes.

Indicator/Warning	Required For	Required Based On	Information Represented
Free Air Temperature Indicator	All Transport Category Airplanes	Subpart F - §25.1303 - (a)	
Clock	All Transport Category Airplanes	Subpart F - §25.1303 - (a)	§25.1303 - (a): Displays hours, minutes, and seconds with a sweep-second pointer or digital presentation.
Direction Indicator	All Transport Category Airplanes	Subpart F - §25.1303 - (a)	§23.1321 - (d): Indicates direction of flight §25.1547: (a) A placard meeting the requirements of this section must be installed on, or near, the magnetic direction indicator. (b) The placard must show the calibration of the instrument in level flight with the engines operating. (c) The placard must state whether the calibration was made with radio receivers on or off. (d) Each calibration reading must be in terms of magnetic heading in not more than 45 degree increments.
Airspeed Indicator	All Transport Category Airplanes	Subpart F - §25.1303 - (b)	§25.1323 - (a): Indicates true airspeed (at sea level with a standard atmosphere) with a minimum practicable instrument calibration error when the corresponding pitot and static pressures are applied. §25.1303 - (a): If airspeed limitations vary with altitude, the indicator must have a maximum allowable airspeed indicator showing the variation of V_{MO} with altitude. §25.1563: A placard showing the maximum airspeeds for flap extension for the takeoff, approach, and landing positions must be installed in clear view of each pilot.
Altimeter	All Transport Category Airplanes	Subpart F - §25.1303 - (b)	§25.1325 - (d): Indicates pressure altitude in a standard atmosphere, with a minimum practicable calibration error when the corresponding static pressures are applied.
Rate-Of-Climb Indicator	All Transport Category Airplanes	Subpart F - §25.1303 - (b)	
Gyroscopic Rate-Of-Turn Indicator And Integral Slip-Skid Indicator	All Transport Category Airplanes	Subpart F - §25.1303 - (b)	
Bank And Pitch Indicator	All Transport Category Airplanes	Subpart F - §25.1303 - (b)	
Speed Warning Device	Turbine Engine Powered Airplanes or For Airplanes	Subpart F - §25.1303 - (c)	§25.1303 - (c): Gives effective aural warning (differing distinctively from aural warnings used for other purposes) to the pilots, whenever the speed

	Mentioned in Subpart F - §25.1303 - (c)(1)		exceeds V_{MO} plus 6 knots or M_{MO} + 0.01. The upper limit of the production tolerance for the warning device may not exceed the prescribed warning speed.
Machmeter	All Transport Category Airplanes	Subpart F - §25.1303 - (c)	
Fuel Pressure Warning Means	All Transport Category Airplanes	Subpart F - §25.1305 - (a)	
Fuel Quantity Indicator	All Transport Category Airplanes	Subpart F - §25.1305 - (a) Subpart F - §25.1337 - (b)	§25.1337 - (b): Indicates to the flight crewmembers, the quantity, in gallons or equivalent units, of usable fuel in each tank during flight. In addition— (1) Each fuel quantity indicator must be calibrated to read “zero” during level flight when the quantity of fuel remaining in the tank is equal to the unusable fuel supply determined under §25.959; §25.1553: If the unusable fuel supply for any tank exceeds one gallon, or five percent of the tank capacity, whichever is greater, a red arc must be marked on its indicator extending from the calibrated zero reading to the lowest reading obtainable in level flight. §25.1555 - (c): For powerplant fuel controls— (1) Each fuel tank selector control must be marked to indicate the position corresponding to each tank and to each existing cross feed position; (2) If safe operation requires the use of any tanks in a specific sequence, that sequence must be marked on, or adjacent to, the selector for those tanks; (3) Each valve control for each engine must be marked to indicate the position corresponding to each engine controlled. Refer to "Oil Pressure Indicator" Information Content
Oil Quantity Indicator	All Transport Category Airplanes	Subpart F - §25.1305 - (a) Subpart F - §25.1337 - (d)	§25.1337 - (d): Indicates the quantity of oil in each tank. If an oil transfer or reserve oil supply system is installed, there must be a means to indicate to the flight crew, in flight, the quantity of oil in each tank. §25.1551: Each oil quantity indicating means must be marked to indicate the quantity of oil readily and accurately. Refer to "Oil Pressure Indicator" Information Content
Oil Pressure Indicator	All Transport Category Airplanes	Subpart F - §25.1305 - (a)	§25.1549: For each required powerplant and auxiliary power unit instrument, as appropriate to the type of instrument— (a) Each maximum and, if applicable, minimum safe operating limit must be marked with a red radial or a red line; (b) Each normal operating range must be marked with a green arc or green line, not extending beyond the maximum and minimum safe limits; (c) Each takeoff and precautionary range must be marked with a yellow arc or a yellow line; and (d) Each engine, auxiliary power unit, or propeller speed range that is restricted because of excessive vibration stresses must be marked with red arcs or red lines.

Oil Pressure Warning Means	All Transport Category Airplanes	Subpart F - §25.1305 - (a)	
Oil Temperature Indicator	All Transport Category Airplanes	Subpart F - §25.1305 - (a)	Refer to "Oil Pressure Indicator" Information Content
Fire-Warning Devices	All Transport Category Airplanes	Subpart F - §25.1305 - (a) Subpart E - §25.1203	§25.1305 - (a): Provide visual and audible warning. §25.1203: (a) (2) There is a means to warn the crew in the event that the sensor or associated wiring within a designated fire zone is severed at one point, unless the system continues to function as a satisfactory detection system after the severing; and (3) There is a means to warn the crew in the event of a short circuit in the sensor or associated wiring within a designated fire zone, unless the system continues to function as a satisfactory detection system after the short circuit. (d) There must be means to allow the crew to check, in flight, the functioning of each fire or overheat detector electric circuit. Refer to "Oil Pressure Indicator" Information Content
Augmentation Liquid Quantity Indicator	All Transport Category Airplanes	Subpart F - §25.1305 - (a)	
Carburetor Air Temperature Indicator	Reciprocating Engine-Powered Airplanes	Subpart F - §25.1305 - (b)	Refer to "Oil Pressure Indicator" Information Content
Cylinder Head Temperature Indicator	Reciprocating Engine-Powered Airplanes	Subpart F - §25.1305 - (b)	Refer to "Oil Pressure Indicator" Information Content
Manifold Pressure Indicator	Reciprocating Engine-Powered Airplanes	Subpart F - §25.1305 - (b)	Refer to "Oil Pressure Indicator" Information Content
Fuel Pressure Indicator	Reciprocating Engine-Powered Airplanes	Subpart F - §25.1305 - (b) Subpart F - §25.1337 - (f)	§25.1305 - (b): Indicates the pressure at which the fuel is supplied §25.1337 - (f): Measures fuel pressure, in each system supplying reciprocating engines, at a point downstream of any fuel pump except fuel injection pumps.
Fuel Flowmeter, Or Fuel Mixture Indicator	Reciprocating Engine-Powered Airplanes	Subpart F - §25.1305 - (b) Subpart F - §25.1337 - (c)	Refer to "Oil Pressure Indicator" Information Content
	Turbine Engine Powered Airplanes or For Airplanes Mentioned in Subpart F - §25.1303 - (c)(1)	Subpart F - §25.1305 - (c) Subpart F - §25.1337 - (c)	Refer to "Oil Pressure Indicator" Information Content
	Turbojet Engine Powered Airplanes	Subpart F - §25.1305 - (d) Subpart F - §25.1337 - (c)	Refer to "Oil Pressure Indicator" Information Content

	Turbopropeller-Powered Airplanes	Subpart F - §25.1305 - (e) Subpart F - §25.1337 - (c)	Refer to "Oil Pressure Indicator" Information Content
Tachometer	Reciprocating Engine-Powered Airplanes	Subpart F - §25.1305 - (b)	§25.1305 - (c): Indicates the speed of the rotors with established limiting speeds for each engine.
	Turbine Engine Powered Airplanes or For Airplanes Mentioned in Subpart F - §25.1303 - (c)(1)	Subpart F - §25.1305 - (c)	§25.1305 - (c): Indicates the speed of the rotors with established limiting speeds for each engine.
	Turbojet Engine Powered Airplanes	Subpart F - §25.1305 - (d)	§25.1305 - (c): Indicates the speed of the rotors with established limiting speeds for each engine.
	Turbopropeller-Powered Airplanes	Subpart F - §25.1305 - (e)	§25.1305 - (c): Indicates the speed of the rotors with established limiting speeds for each engine.
Power Output Indicator	Reciprocating Engine-Powered Airplanes	Subpart F - §25.1305 - (b)	§25.1305 - (b): Indicates, to the flight crew (during flight), any change in the power output, for each engine with— (i) An automatic propeller feathering system, whose operation is initiated by a power output measuring system; or (ii) A total engine piston displacement of 2,000 cubic inches or more.
Propeller Reverse Pitch Indicator	Reciprocating Engine-Powered Airplanes	Subpart F - §25.1305 - (b)	§25.1305 - (b): Indicates to the pilot when the propeller is in reverse pitch, for each reversing propeller.
Gas Temperature Indicator	Turbine Engine Powered Airplanes or For Airplanes Mentioned in Subpart F - §25.1303 - (c)(1)	Subpart F - §25.1305 - (c)	Refer to "Oil Pressure Indicator" Information Content
	Turbojet Engine Powered Airplanes	Subpart F - §25.1305 - (d)	Refer to "Oil Pressure Indicator" Information Content
	Turbopropeller-Powered Airplanes	Subpart F - §25.1305 - (e)	Refer to "Oil Pressure Indicator" Information Content
Engine Starter Operation Indicator	Turbine Engine Powered Airplanes or For Airplanes Mentioned in Subpart F - §25.1303 - (c)(1)	Subpart F - §25.1305 - (c)	§25.1305 - (c): Indicates, to the flight crew, the operation of each engine starter that can be operated continuously but that is neither designed for continuous operation nor designed to prevent hazard if it failed. Refer to "Oil Pressure Indicator" Information Content
	Turbojet Engine Powered Airplanes	Subpart F - §25.1305 - (d)	§25.1305 - (c): Indicates, to the flight crew, the operation of each engine starter that can be operated continuously but that is neither designed for continuous operation nor designed to prevent hazard if it failed. Refer to "Oil Pressure Indicator" Information Content
	Turbopropeller-Powered Airplanes	Subpart F - §25.1305 - (e)	§25.1305 - (c): Indicates, to the flight crew, the operation of each engine starter that can be operated continuously but that is neither designed for

			continuous operation nor designed to prevent hazard if it failed. Refer to "Oil Pressure Indicator" Information Content
Powerplant Ice Protection System Indicator	Turbine Engine Powered Airplanes or For Airplanes Mentioned in Subpart F - §25.1303 - (c)(1)	Subpart F - §25.1305 - (c)	§25.1305 - (c): Indicates the functioning of the powerplant ice protection system for each engine Refer to "Oil Pressure Indicator" Information Content
	Turbojet Engine Powered Airplanes	Subpart F - §25.1305 - (d)	§25.1305 - (c): Indicates the functioning of the powerplant ice protection system for each engine Refer to "Oil Pressure Indicator" Information Content
	Turbopropeller-Powered Airplanes	Subpart F - §25.1305 - (e)	§25.1305 - (c): Indicates the functioning of the powerplant ice protection system for each engine Refer to "Oil Pressure Indicator" Information Content
Fuel Strainer Or Filter Indicator	Turbine Engine Powered Airplanes or For Airplanes Mentioned in Subpart F - §25.1303 - (c)(1)	Subpart F - §25.1305 - (c)	§25.1305 - (c): Indicates the occurrence of contamination of the strainer or filter before it reaches the capacity established in accordance with §25.997(d). Refer to "Oil Pressure Indicator" Information Content
	Turbojet Engine Powered Airplanes	Subpart F - §25.1305 - (d)	§25.1305 - (c): Indicates the occurrence of contamination of the strainer or filter before it reaches the capacity established in accordance with §25.997(d). Refer to "Oil Pressure Indicator" Information Content
	Turbopropeller-Powered Airplanes	Subpart F - §25.1305 - (e)	§25.1305 - (c): Indicates the occurrence of contamination of the strainer or filter before it reaches the capacity established in accordance with §25.997(d). Refer to "Oil Pressure Indicator" Information Content
Oil Strainer Or Filter Warning Means	Turbine Engine Powered Airplanes or For Airplanes Mentioned in Subpart F - §25.1303 - (c)(1)	Subpart F - §25.1305 - (c)	§25.1305 - (c): Warns the pilot of the occurrence of contamination of the strainer or filter screen before it reaches the capacity established in accordance with §25.1019(a)(2). §25.1019 - (a): (3) The oil strainer or filter, unless it is installed at an oil tank outlet, must incorporate an indicator that will indicate contamination before it reaches the capacity established in accordance with paragraph (a)(2) of this section.
	Turbojet Engine Powered Airplanes	Subpart F - §25.1305 - (d)	§25.1305 - (c): Warns the pilot of the occurrence of contamination of the strainer or filter screen before it reaches the capacity established in accordance with §25.1019(a)(2). §25.1019 - (a): (3) The oil strainer or filter, unless it is installed at an oil tank outlet, must incorporate an indicator that will indicate contamination before it reaches the capacity established in accordance with paragraph (a)(2) of this section.
	Turbopropeller-Powered Airplanes	Subpart F - §25.1305 - (e)	§25.1305 - (c): Warns the pilot of the occurrence of contamination of the strainer or filter screen before it reaches the capacity established in accordance with §25.1019(a)(2). §25.1019 - (a): (3) The oil strainer or filter, unless it is installed at an oil tank

			outlet, must incorporate an indicator that will indicate contamination before it reaches the capacity established in accordance with paragraph (a)(2) of this section.
Fuel System Heater Operation Indicator	Turbine Engine Powered Airplanes or For Airplanes Mentioned in Subpart F - §25.1303 - (c)(1)	Subpart F - §25.1305 - (c)	§25.1305 - (c): Indicates the proper functioning of any heater used to prevent ice clogging of fuel system components. Refer to "Oil Pressure Indicator" Information Content
	Turbojet Engine Powered Airplanes	Subpart F - §25.1305 - (d)	§25.1305 - (c): Indicates the proper functioning of any heater used to prevent ice clogging of fuel system components. Refer to "Oil Pressure Indicator" Information Content
	Turbopropeller-Powered Airplanes	Subpart F - §25.1305 - (e)	§25.1305 - (c): Indicates the proper functioning of any heater used to prevent ice clogging of fuel system components. Refer to "Oil Pressure Indicator" Information Content
Thrust Indicator	Turbojet Engine Powered Airplanes	Subpart F - §25.1305 - (d)	§25.1305 - (d): Indicates thrust, or a parameter that is directly related to thrust, to the pilot. The indication must be based on the direct measurement of thrust or of parameters that are directly related to thrust. The indicator must indicate a change in thrust resulting from any engine malfunction, damage, or deterioration. Refer to "Oil Pressure Indicator" Information Content
Thrust Reversing Device Position Indicating Indicator	Turbojet Engine Powered Airplanes	Subpart F - §25.1305 - (d)	§25.1305 - (d): Indicates to the flightcrew when the thrust reversing device— (i) Is not in the selected position, and (ii) Is in the reverse thrust position, for each engine using a thrust reversing device. Refer to "Oil Pressure Indicator" Information Content
Rotor System Unbalance	Turbojet Engine Powered Airplanes	Subpart F - §25.1305 - (d)	§25.1305 - (d): Indicates rotor system unbalance. Refer to "Oil Pressure Indicator" Information Content
Torque Indicator	Turbopropeller-Powered Airplanes	Subpart F - §25.1305 - (e)	Part 23 - Special Federal Aviation Regulation No. 23: Indicates power output for each engine. Refer to "Oil Pressure Indicator" Information Content
Propeller Position Indicating Indicator	Turbopropeller-Powered Airplanes	Subpart F - §25.1305 - (e) Subpart F - §25.1337 - (e)	§25.1305 - (e): Indicates to the flight crew when the propeller blade angle is below the flight low pitch position, for each propeller. Refer to "Oil Pressure Indicator" Information Content
Fluid Systems Operation Indicator	Airplanes Equipped With Fluid Systems (Other Than Fuel)	Subpart F - §25.1305 - (f)	§25.1305 - (f): For airplanes equipped with fluid systems (other than fuel) for thrust or power augmentation, an approved means must be provided to indicate the proper functioning of that system to the flight crew. Refer to "Oil Pressure Indicator" Information Content
Radio Communications Systems	All Transport Category Airplanes	Subpart F - §25.1307 - (d)	

Radio Navigation Systems	All Transport Category Airplanes	Subpart F - §25.1307 - (e)	
Pitot Heating System Operation Indicator	All Transport Category Airplanes	Subpart F - §25.1326 Subpart F - §125.206 - (a)	§25.1326: indicate to the flight crew when that pitot heating system is not operating. The indication system must comply with the following requirements: (a) The indication provided must incorporate an amber light that is in clear view of a flight crewmember. (b) The indication provided must be designed to alert the flight crew if either of the following conditions exist: (1) The pitot heating system is switched “off”. (2) The pitot heating system is switched “on” and any pitot tube heating element is inoperative.
Command Reference Control Operation Indicator	All Transport Category Airplanes	Subpart F - §25.1329 - (f)	§25.1329 - (f): The function and direction of motion of each command reference control, such as heading select or vertical speed, must be plainly indicated on, or adjacent to, each control if necessary to prevent inappropriate use or confusion.
Autopilot Disengagement Warning	All Transport Category Airplanes	Subpart F - §25.1329 - (j)	§25.1329 - (j): Following disengagement of the autopilot, a warning (visual and auditory) must be provided to each pilot and be timely and distinct from all other cockpit warnings.
Autothrust Function Isengagement Warning	All Transport Category Airplanes	Subpart F - §25.1329 - (k)	§25.1329 - (k): Following disengagement of the autothrust function, a caution must be provided to each pilot.
Inadequate Power Supply Visual Indicators	All Transport Category Airplanes	Subpart F - §25.1331 - (a)	§25.1331 - (a): Indicates when power adequate to sustain proper instrument performance is not being supplied. (For each instrument required by §25.1303(b) that uses a power supply)
Information Loss Visual Indicators	All Transport Category Airplanes	Subpart F - §25.1331 - (a)	§25.1331 - (a): Warns the crew, when such (if an instrument presenting navigation data receives information from sources external to that instrument and loss of that information would render the presented data unreliable) loss of information occurs, that the presented data should not be relied upon.
Battery Temperature Sensing And Over-Temperature Warning System	All Transport Category Airplanes	Subpart F - §25.1353 - (b)	
Battery Failure Sensing And Warning System	All Transport Category Airplanes	Subpart F - §25.1353 - (b)	
Landing Lights Indicators	All Transport Category Airplanes	Subpart F - §25.1383 - (c)	§25.1383 - (c): Indicates to the pilots when the landing lights are extended.
Anti-Ice Or De-Ice System Functioning Warnings	All Transport Category Airplanes	Subpart F - §25.1419 - (c)	§25.1419 - (c) : Caution information, such as an amber caution light or equivalent, must be provided to alert the flightcrew when the anti-ice or de-ice system is not functioning normally.

Ice Detection System	All Transport Category Airplanes	Subpart F - §25.1419 - (e) Subpart F - §25.1420	§27.1419 - (e): Determines the formation of ice on critical parts of the [rotorcraft]. Unless otherwise restricted, the means must be available for nighttime as well as daytime operation.
Hydraulic System Parameters Indicators	All Transport Category Airplanes	Subpart F - §25.1435 - (b)	§25.1435 - (b): Indicates appropriate system parameters, if (i) It performs a function necessary for continued safe flight and landing; or (ii) In the event of hydraulic system malfunction, corrective action by the crew to ensure continued safe flight and landing is necessary;
Terrain Awareness and Warning System	Turbine Engine Powered Airplanes or For Airplanes Mentioned in Subpart F - §25.1303 - (c)(1)	Subpart K - §121.354 - (a)	§121.354 - (a): equipped with an approved terrain awareness and warning system that meets the requirements for Class A equipment in Technical Standard Order (TSO)-C151. The airplane must also include an approved terrain situational awareness display.
Voice Recorder Operation Aural Or Visual Device	All Transport Category Airplanes	Subpart F - §25.1457 - (d)	§25.1457 - (d): Indicates proper operation of the recorder for preflight checking.
	Turbine Engine Powered Airplanes or For Airplanes Mentioned in Subpart F - §25.1303 - (c)(1)	Subpart K - §121.359	
Flight Recorder Operation Aural Or Visual Device	All Transport Category Airplanes	Subpart F - §25.1459 - (a) Subpart K - §121.344 Subpart F - §125.226	§25.1459 - (a): Indicates proper recording of data in the storage medium of the recorder for preflight checking. Subpart K - §121.344 Subpart F - §125.226
Valve Position	All Transport Category Airplanes	Subpart E - §25.1141 - (f)	§25.1141 - (f): For powerplant valve controls located in the flight deck there must be a means: (2) To indicate to the flightcrew: (i) The selected position or function of the valve; and (ii) When the valve has not responded as intended to the selected position or function.
Stall Warning Device	All Transport Category Airplanes	Subpart B - §25.207	§25.207: (a) Stall warning with sufficient margin to prevent inadvertent stalling with the flaps and landing gear in any normal position must be clear and distinctive to the pilot in straight and turning flight. (b) The warning must be furnished either through the inherent aerodynamic qualities of the airplane or by a device that will give clearly distinguishable indications under expected conditions of flight. However, a visual stall warning device that requires the attention of the crew within the cockpit is not acceptable by itself. If a warning device is used, it must provide a warning in each of the airplane configurations prescribed in paragraph (a) of this section at the speed prescribed in paragraphs (c) and (d) of this section. Except for the

			stall warning prescribed in paragraph (h)(3)(ii) of this section, the stall warning for flight in icing conditions must be provided by the same means as the stall warning for flight in non-icing conditions. (c) When the speed is reduced at rates not exceeding one knot per second, stall warning must begin, in each normal configuration, at a speed, VSW, exceeding the speed at which the stall is identified in accordance with §25.201(d) by not less than five knots or five percent CAS, whichever is greater. Once initiated, stall warning must continue until the angle of attack is reduced to approximately that at which stall warning began. (d) In addition to the requirement of paragraph (c) of this section, when the speed is reduced at rates not exceeding one knot per second, in straight flight with engines idling and at the center-of-gravity position specified in §25.103(b)(5), VSW, in each normal configuration, must exceed VSR by not less than three knots or three percent CAS, whichever is greater. (e) In icing conditions, the stall warning margin in straight and turning flight must be sufficient to allow the pilot to prevent stalling (as defined in §25.201(d)) when the pilot starts a recovery maneuver not less than three seconds after the onset of stall warning. When demonstrating compliance with this paragraph, the pilot must perform the recovery maneuver in the same way as for the airplane in non-icing conditions. Compliance with this requirement must be demonstrated in flight with the speed reduced at rates not exceeding one knot per second, with— (1) The most critical of the takeoff ice and final takeoff ice accretions defined in Appendices C and O of this part, as applicable, in accordance with §25.21(g), for each configuration used in the takeoff phase of flight; (2) The most critical of the en route ice accretion(s) defined in Appendices C and O of this part, as applicable, in accordance with §25.21(g), for the en route configuration; (3) The most critical of the holding ice accretion(s) defined in Appendices C and O of this part, as applicable, in accordance with §25.21(g), for the holding configuration(s); (4) The most critical of the approach ice accretion(s) defined in Appendices C and O of this part, as applicable, in accordance with §25.21(g), for the approach configuration(s); and (5) The most critical of the landing ice accretion(s) defined in Appendices C and O of this part, as applicable, in accordance with §25.21(g), for the landing and go-around configuration(s). (f) The stall warning margin must be sufficient in both non-icing and icing conditions to allow the pilot to prevent stalling when the pilot starts a recovery maneuver not less than one second after the onset of stall warning in slow-

			down turns with at least 1.5 g load factor normal to the flight path and airspeed deceleration rates of at least 2 knots per second. When demonstrating compliance with this paragraph for icing conditions, the pilot must perform the recovery maneuver in the same way as for the airplane in non-icing conditions. Compliance with this requirement must be demonstrated in flight with— (1) The flaps and landing gear in any normal position; (2) The airplane trimmed for straight flight at a speed of 1.3 VSR; and (3) The power or thrust necessary to maintain level flight at 1.3 VSR. (g) Stall warning must also be provided in each abnormal configuration of the high lift devices that is likely to be used in flight following system failures (including all configurations covered by Airplane Flight Manual procedures). (h) The following stall warning margin is required for flight in icing conditions before the ice protection system has been activated and is performing its intended function. Compliance must be shown using the most critical of the ice accretion(s) defined in Appendix C, part II, paragraph (e) of this part and Appendix O, part II, paragraph (d) of this part, as applicable, in accordance with §25.21(g). The stall warning margin in straight and turning flight must be sufficient to allow the pilot to prevent stalling without encountering any adverse flight characteristics when: (1) The speed is reduced at rates not exceeding one knot per second; (2) The pilot performs the recovery maneuver in the same way as for flight in non-icing conditions; and (3) The recovery maneuver is started no earlier than: (i) One second after the onset of stall warning if stall warning is provided by the same means as for flight in non-icing conditions; or (ii) Three seconds after the onset of stall warning if stall warning is provided by a different means than for flight in non-icing conditions. (i) In showing compliance with paragraph (h) of this section, if stall warning is provided by a different means in icing conditions than for non-icing conditions, compliance with §25.203 must be shown using the accretion defined in appendix C, part II(e) of this part. Compliance with this requirement must be shown using the demonstration prescribed by §25.201, except that the deceleration rates of §25.201(c)(2) need not be demonstrated.
Trim Movement Indicator	All Transport Category Airplanes	Subpart D - §25.677 - (b)	§25.677 - (b): There must be means adjacent to the trim control to indicate the direction of the control movement relative to the airplane motion. In addition, there must be clearly visible means to indicate the position of the trim device with respect to the range of adjustment. The indicator must be clearly marked with the range within which it has been demonstrated that takeoff is safe for all center of gravity positions approved for takeoff.

Takeoff Warning Device	All Transport Category Airplanes	Subpart D - §25.703	§25.703: A takeoff warning system must be installed and must meet the following requirements: (a) The system must provide to the pilots an aural warning that is automatically activated during the initial portion of the takeoff roll if the airplane is in a configuration, including any of the following, that would not allow a safe takeoff: (1) The wing flaps or leading edge devices are not within the approved range of takeoff positions. (2) Wing spoilers (except lateral control spoilers meeting the requirements of §25.671), speed brakes, or longitudinal trim devices are in a position that would not allow a safe takeoff. (b) The warning required by paragraph (a) of this section must continue until— (1) The configuration is changed to allow a safe takeoff; (2) Action is taken by the pilot to terminate the takeoff roll; (3) The airplane is rotated for takeoff; or (4) The warning is manually deactivated by the pilot. (c) The means used to activate the system must function properly throughout the ranges of takeoff weights, altitudes, and temperatures for which certification is requested.
Landing Gear Position Indicator	All Transport Category Airplanes	Subpart D - §25.729 - (e)	§25.729 - (e): If a retractable landing gear is used, there must be a landing gear position indicator easily visible to the pilot or to the appropriate crew members (as well as necessary devices to actuate the indicator) to indicate without ambiguity that the retractable units and their associated doors are secured in the extended (or retracted) position. The means must be designed as follows: (1) If switches are used, they must be located and coupled to the landing gear mechanical systems in a manner that prevents an erroneous indication of “down and locked” if the landing gear is not in a fully extended position, or of “up and locked” if the landing gear is not in the fully retracted position. The switches may be located where they are operated by the actual landing gear locking latch or device.
Landing Gear Warning Devices	All Transport Category Airplanes	Subpart D - §25.729 - (e)	§25.729 - (e): If a retractable landing gear is used: (2) The flightcrew must be given an aural warning that functions continuously, or is periodically repeated, if a landing is attempted when the landing gear is not locked down. (3) The warning must be given in sufficient time to allow the landing gear to be locked down or a go-around to be made. (4) There must not be a manual shut-off means readily available to the flightcrew for the warning required by paragraph (e)(2) of this section such that it could be operated instinctively, inadvertently, or by habitual reflexive

			action. (5) The system used to generate the aural warning must be designed to minimize false or inappropriate alerts. (6) Failures of systems used to inhibit the landing gear aural warning, that would prevent the warning system from operating, must be improbable. (7) A flightcrew alert must be provided whenever the landing gear position is not consistent with the landing gear selector lever position. §25.1555 - (d): For accessory, auxiliary, and emergency controls— (2) Each visual indicator required by §25.729(e) must be marked so that the pilot can determine at any time when the wheels are locked in either extreme position, if retractable landing gear is used.

Table 42. 14 CFR 27—Airworthiness standards: Normal category rotorcraft.

Indicator/Warning	Required For	Required Based On	Information Represented
Airspeed Indicator	All Normal Category Rotorcrafts	Subpart F - §27.1303 - (a)	§27.1323 - (a): Indicates true airspeed (at sea level with a standard atmosphere) with a minimum practicable instrument calibration error when the corresponding pitot and static pressures are applied. §27.1545: (b) The following markings must be made: (1) A red radial line— (i) For rotocraft other than helicopters, at V_{NE}; and (ii) For helicopters at V_{NE} (power-on). (2) A red cross-hatched radial line at VNE (power-off) for helicopters, if V_{NE} (power-off) is less than V_{NE} (power-on). (3) For the caution range, a yellow arc. (4) For the safe operating range, a green arc.
Altimeter	All Normal Category Rotorcrafts	Subpart F - §27.1303 - (b)	§25.1325 - (d): Indicates pressure altitude in a standard atmosphere, with a minimum practicable calibration error when the corresponding static pressures are applied. AC 23-8C: Measures the difference between a sea level barometer pressure set on the instrument and static pressure, and indicates in units of feet
Magnetic Direction Indicator	All Normal Category Rotorcrafts	Subpart F - §27.1303 - (c)	§23.1321 - (d): Indicates direction of flight §27.1547: (a) A placard meeting the requirements of this section must be installed on or near the magnetic direction indicator. (b) The placard must show the calibration of the instrument in level flight with the engines operating. (c) The placard must state whether the calibration was made with radio receivers on or off. (d) Each calibration reading must be in terms of magnetic heading in not more than 45 degree increments. (e) If a magnetic nonstabilized direction indicator can have a deviation of more than 10 degrees caused by the operation of electrical equipment, the placard must state which electrical loads, or combination of loads, would cause a deviation of more than 10 degrees when turned on.
Fuel Pressure Indicator	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (c)	§23.1305 - (b): (4) For each pump-fed engine, a means: (i) That continuously indicates, to the pilot, the fuel pressure or fuel flow
Fuel Quantity Indicator	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (d) Subpart F - §27.1337 - (b)	§27.1337 - (b): Indicate to the flight crew the quantity of fuel in each tank in flight. In addition— (1) Each fuel quantity indicator must be calibrated to read “zero” during level flight when the quantity of fuel remaining in the tank is equal to the unusable

			fuel supply determined under §27.959. §27.1553: If the unusable fuel supply for any tank exceeds one gallon, or five percent of the tank capacity, whichever is greater, a red arc must be marked on its indicator extending from the calibrated zero reading to the lowest reading obtainable in level flight. §27.1555: (b) For powerplant fuel controls— (1) Each fuel tank selector control must be marked to indicate the position corresponding to each tank and to each existing cross feed position; (2) If safe operation requires the use of any tanks in a specific sequence, that sequence must be marked on, or adjacent to, the selector for those tanks; and (3) Each valve control for any engine of a multiengine rotorcraft must be marked to indicate the position corresponding to each engine controlled. (c) Usable fuel capacity must be marked as follows: (1) For fuel systems having no selector controls, the usable fuel capacity of the system must be indicated at the fuel quantity indicator. (2) For fuel systems having selector controls, the usable fuel capacity available at each selector control position must be indicated near the selector control. Refer to "Oil Pressure Indicator" Information Content
Oil Quantity Indicator	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (i) Subpart F - §27.1337 - (d)	§27.1337 - (d): indicate the quantity of oil in each tank— (1) On the ground (including during the filling of each tank); and (2) In flight, if there is an oil transfer system or reserve oil supply system. §27.1551: Each oil quantity indicator must be marked with enough increments to indicate readily and accurately the quantity of oil. Refer to "Oil Pressure Indicator" Information Content
Oil Pressure Indicator for each Engine	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (h)	27.1549 Powerplant instruments. For each required powerplant instrument, as appropriate to the type of instrument— (a) Each maximum and, if applicable, minimum safe operating limit must be marked with a red radial or a red line; (b) Each normal operating range must be marked with a green arc or green line, not extending beyond the maximum and minimum safe limits; (c) Each takeoff and precautionary range must be marked with a yellow arc or yellow line; (d) Each engine or propeller range that is restricted because of excessive vibration stresses must be marked with red arcs or red lines; and (e) Each OEI limit or approved operating range must be marked to be clearly differentiated from the markings of paragraphs (a) through (d) of this section except that no marking is normally required for the 30-second OEI limit.
Oil Pressure Warning Device	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (g)	§27.1305 - (g): Indicate when the pressure falls below a safe value in each pressure-lubricated main rotor drive gearbox (including any gearboxes

			essential to rotor phasing) having an oil system independent of the engine oil system.
Oil Temperature Warning Device	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (f)	§27.1305 - (f): Indicate when the temperature exceeds a safe value in each main rotor drive gearbox (including any gearboxes essential to rotor phasing) having an oil system independent of the engine oil system.
Oil Temperature Indicator	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (j)	Refer to "Oil Pressure Indicator" Information Content
Gas Temperature Indicator	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (n)	Refer to "Oil Pressure Indicator" Information Content
Carburetor Air Temperature Indicator	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (a)	Refer to "Oil Pressure Indicator" Information Content
Cylinder Head Temperature Indicator	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (b)	Refer to "Oil Pressure Indicator" Information Content
Manifold Pressure Indicator	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (e)	Refer to "Oil Pressure Indicator" Information Content
Fuel Low Level Warning Device	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (l)	§27.1305 - (l): This device must— (1) Provide a warning to the flightcrew when approximately 10 minutes of usable fuel remains in the tank; and (2) Be independent of the normal fuel quantity indicating system.
Fuel Pump Failure Indicator	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (m)	§27.1305 - (m): Indicates to the flightcrew the failure of any fuel pump installed to show compliance with §27.955. Refer to "Oil Pressure Indicator" Information Content
Turboshaft Engine Torque Indicator	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (o)	§27.1305 - (o): Enables the pilot to determine the torque of each turboshaft engine, if a torque limitation is established for that engine under §27.1521(e). Refer to "Oil Pressure Indicator" Information Content
Tachometer	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (k)	§27.1305 - (k): Indicates the r.p.m. of each engine and, as applicable— (1) The r.p.m. of the single main rotor; (2) The common r.p.m. of any main rotors whose speeds cannot vary appreciably with respect to each other; or (3) The r.p.m. of each main rotor whose speed can vary appreciably with respect to that of another main rotor. Refer to "Oil Pressure Indicator" Information Content
Powerplant Ice Protection System Indicator	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (p)	§27.1305 - (p): Indicates the functioning of the powerplant ice protection system. Refer to "Oil Pressure Indicator" Information Content
Fuel Filter Warning Device	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (q)	§27.1305 - (q): Indicates the occurrence of contamination of the filter at the degree established by the applicant in compliance with §27.955. Refer to "Oil Pressure Indicator" Information Content
Oil Strainer or Filter Warning Means	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (r)	§27.1305 - (r): Warns the pilot of the occurrence of contamination of the strainer or filter before it reaches the capacity established in accordance with

			§27.1019(a)(2). §27.1019 - (a): (3) The oil strainer or filter, unless it is installed at an oil tank outlet, must incorporate a means to indicate contamination before it reaches the capacity established in accordance with paragraph (a)(2) of this section.
Fuel System Heater Operation Indicator	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (s)	§27.1305 - (s): Indicates the functioning of any selectable or controllable heater used to prevent ice clogging of fuel system components. Refer to "Oil Pressure Indicator" Information Content
OEI Power Levels Warning Device	Rotorcraft with 30-Second/2-Minute OEI Power Ratings	Subpart F - §27.1305 - (t)	§27.1305 - (t): Alerts the pilot when the engine is at the 30-second and the 2-minute OEI power levels, when the event begins, and when the time interval expires.
Power Usage and Duration at the 30-Second and 2-Minute OEI Levels System Indicators	Rotorcraft with 30-Second/2-Minute OEI Power Ratings	Subpart F - §27.1305 - (u)	§27.1305 - (u): Must be provided for use by ground personnel which— (1) Automatically records each usage and duration of power at the 30-second and 2-minute OEI levels; (4) Has a means to verify proper operation of the system or device. Refer to "Oil Pressure Indicator" Information Content
Ferromagnetic Particles Detection Warning or Caution Devices	All Normal Category Rotorcrafts	Subpart F - §27.1305 - (v)	§27.1305 - (v): Signal to the flight crew when ferromagnetic particles are detected by the chip detector required by §27.1337(e).
Actuating Device-Control System Alignment Indicator	All Normal Category Rotorcrafts	Subpart F - §27.1329 - (b)	§27.1329 - (b): Indicates to the pilot the alignment of the actuating device in relation to the control system it operates.
Mode of Operation Indicator	All Normal Category Rotorcrafts	Subpart F - §27.1329 - (f)	§27.1329 - (f): Indicates to the flight crew the current mode of operation. Selector switch position is not acceptable as a means of indication.
Mode of Operation Indicator	All Normal Category Rotorcrafts	Subpart F - §27.1335	§27.1335: Indicates to the flight crew the current mode of operation (if a flight director system is installed). Selector switch position is not acceptable as a means of indication.
Electric Power System Essential Quantities	All Normal Category Rotorcrafts	Subpart F - §27.1351	§27.1351: Indicates to appropriate crewmembers the electric power system quantities essential for safe operation of the system
Battery Temperature Sensing and Over-Temperature Warning System	All Normal Category Rotorcrafts	Subpart F - §27.1353 - (g)	
Battery Failure Sensing and Warning System	All Normal Category Rotorcrafts	Subpart F - §27.1353 - (g)	
Ice Detection System	All Normal Category Rotorcrafts	Subpart F - §27.1419 - (e)	§27.1419 - (e): Determines the formation of ice on critical parts of the rotorcraft. Unless otherwise restricted, the means must be available for nighttime as well as daytime operation.
Voice Recorder Operation Aural or Visual Device	All Normal Category Rotorcrafts	Subpart F - §27.1457 - (d)	§27.1457 - (d): Indicates proper operation of the recorder for preflight checking.

Flight Recorder Operation Aural or Visual Device	All Normal Category Rotorcrafts	Subpart F - §27.1459 - (a)	§23.1459 - (a): Indicates proper recording of data in the storage medium of the recorder for preflight checking.
Valve Position	All Normal Category Rotorcrafts	Subpart E - §27.1141 - (d)	§27.1141 - (d): Controls of powerplant valves required for safety must have— (2) For power-assisted valves, a means to indicate to the flight crew when the valve— (i) Is in the fully open or fully closed position; or (ii) Is moving between the fully open and fully closed position.
Landing Gear Position Indicator	All Normal Category Rotorcrafts	Subpart D - §27.729 - (e)	§27.729 - (e): Indicates to the pilot when the gear is secured in the extreme positions. §27.1555: (d) For accessory, auxiliary, and emergency controls— (1) Each essential visual position indicator, such as those showing rotor pitch or landing gear position, must be marked so that each crewmember can determine at any time the position of the unit to which it relates; and (e) For rotorcraft incorporating retractable landing gear, the maximum landing gear operating speed must be displayed in clear view of the pilot.
Landing Gear Warning Devices	All Normal Category Rotorcrafts	Subpart D - §27.729 - (g)	§27.729 - (g): Functions continuously when the rotorcraft is in a normal landing mode and the landing gear is not fully extended and locked. A manual shutoff capability must be provided for the warning device and the warning system must automatically reset when the rotorcraft is no longer in the landing mode.

Table 43. 14 CFR 29—Airworthiness standards: Transport category rotorcraft.

Indicator/Warning	Required For	Required Based On	Information Represented
Free Air Temperature Indicator	All Transport Category Rotorcraft	Subpart F - §29.1303 - (e)	
Clock	All Transport Category Rotorcraft	Subpart F - §29.1303 - (d)	§29.1303 - (d): Displays hours, minutes, and seconds with a sweep-second pointer or digital presentation.
Magnetic Direction Indicator	All Transport Category Rotorcraft	Subpart F - §29.1303 - (c)	§23.1321 - (d): Indicates direction of flight §29.1547: (a) A placard meeting the requirements of this section must be installed on or near the magnetic direction indicator. (b) The placard must show the calibration of the instrument in level flight with the engines operating. (c) The placard must state whether the calibration was made with radio receivers on or off. (d) Each calibration reading must be in terms of magnetic heading in not more than 45 degree increments.
Airspeed Indicator	All Transport Category Rotorcraft	Subpart F - §29.1303 - (a)	§29.1303 - (a): For Category A rotorcraft with V_{NE} less than a speed at which unmistakable pilot cues provide overspeed warning, a maximum allowable airspeed indicator must be provided. If maximum allowable airspeed varies with weight, altitude, temperature, or r.p.m., the indicator must show that variation. §29.1545: (a) Each airspeed indicator must be marked as specified in paragraph (b) of this section, with the marks located at the corresponding indicated airspeeds. (b) The following markings must be made: (1) A red radial line— (i) For rotorcraft other than helicopters, at V_{NE}; and (ii) For helicopters, at a V_{NE} (power-on). (2) A red, cross-hatched radial line at V_{NE} (power-off) for helicopters, if V_{NE} (power-off) is less than V_{NE} (power-on). (3) For the caution range, a yellow arc. (4) For the safe operating range, a green arc.
Altimeter	All Transport Category Rotorcraft	Subpart F - §29.1303 - (b)	§25.1325 - (d): Indicates pressure altitude in a standard atmosphere, with a minimum practicable calibration error when the corresponding static pressures are applied. AC 23-8C: Measures the difference between a sea level barometer pressure set on the instrument and static pressure, and indicates in units of feet

Rate-of-Climb Indicator	All Transport Category Rotorcraft	Subpart F - §29.1303 - (i)	
Gyroscopic Rate-of-Turn Indicator and Integral Slip-Skid Indicator	All Transport Category Rotorcraft	Subpart F - §29.1303 - (g)	
Bank And Pitch Indicator	All Transport Category Rotorcraft	Subpart F - §29.1303 - (f)	
Gyroscopic Direction Indicator	All Transport Category Rotorcraft	Subpart F - §29.1303 - (h)	
Speed Warning Device	Category A Rotorcraft	Subpart F - §29.1303 - (j)	§29.1303 - (j): For Category A rotorcraft, a speed warning device when VNE is less than the speed at which unmistakable overspeed warning is provided by other pilot cues. The speed warning device must give effective aural warning (differing distinctively from aural warnings used for other purposes) to the pilots whenever the indicated speed exceeds VNE plus 3 knots and must operate satisfactorily throughout the approved range of altitudes and temperatures.
Fuel Quantity Indicator	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a) Subpart F - §29.1337 - (b)	§29.1337 - (b): Indicates to the flight crew members the quantity, in gallons or equivalent units, of usable fuel in each tank during flight. In addition— (1) Each fuel quantity indicator must be calibrated to read “zero” during level flight when the quantity of fuel remaining in the tank is equal to the unusable fuel supply determined under §29.959; §29.1553: If the unusable fuel supply for any tank exceeds one gallon, or five percent of the tank capacity, whichever is greater, a red arc must be marked on its indicator extending from the calibrated zero reading to the lowest reading obtainable in level flight. §29.1555: (b) For powerplant fuel controls— (1) Each fuel tank selector valve control must be marked to indicate the position corresponding to each tank and to each existing cross feed position; (2) If safe operation requires the use of any tanks in a specific sequence, that sequence must be marked on, or adjacent to, the selector for those tanks; and (c) Usable fuel capacity must be marked as follows: (1) For fuel systems having no selector controls, the usable fuel capacity of the system must be indicated at the fuel quantity indicator. (2) For fuel systems having selector controls, the usable fuel capacity available at each selector control position must be indicated near the selector control.
Low Fuel Warning Device	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	§29.1305 - (a): 4) A low fuel warning device for each fuel tank which feeds an engine. This device must— (i) Provide a warning to the crew when approximately 10 minutes of usable fuel remains in the tank; and (ii) Be independent of the normal fuel quantity indicating system.

Oil Quantity Indicator	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a) Subpart F - §29.1337 - (d)	§29.1337 - (d): Indicates the quantity of oil— (1) In each tank; and (2) In each transmission gearbox. Refer to "Oil Pressure Indicator" Information Content
Oil Pressure Indicator	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	§29.1549 Powerplant instruments. For each required powerplant instrument, as appropriate to the type of instruments— (a) Each maximum and, if applicable, minimum safe operating limit must be marked with a red radial or a red line; (b) Each normal operating range must be marked with a green arc or green line, not extending beyond the maximum and minimum safe limits; (c) Each takeoff and precautionary range must be marked with a yellow arc or yellow line; (d) Each engine or propeller range that is restricted because of excessive vibration stresses must be marked with red arcs or red lines; and (e) Each OEI limit or approved operating range must be marked to be clearly differentiated from the markings of paragraphs (a) through (d) of this section except that no marking is normally required for the 30-second OEI limit.
Oil Pressure Warning Device	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	§29.1305 - (a): Indicates when the oil pressure falls below a safe value for each pressure-lubricated gearbox.
Oil Temperature Indicator	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	Refer to "Oil Pressure Indicator" Information Content
Oil Temperature Warning Device	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	§29.1305 - (a): Indicates unsafe oil temperatures in each main rotor drive gearbox, including gearboxes necessary for rotor phasing;
Carburetor Air Temperature Indicator	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	Refer to "Oil Pressure Indicator" Information Content
Cylinder Head Temperature Indicator	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	Refer to "Oil Pressure Indicator" Information Content
Manifold Pressure Indicator	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	Refer to "Oil Pressure Indicator" Information Content
Fuel Pressure Indicator	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	§25.1305 - (b): Indicates the pressure at which the fuel is supplied §25.1337 - (f): Measures fuel pressure, in each system supplying reciprocating engines, at a point downstream of any fuel pump except fuel injection pumps. Refer to "Oil Pressure Indicator" Information Content
Fuel Pump Failure Indicator	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	§29.1305 - (a): Indicates to the flightcrew the failure of any fuel pump installed to show compliance with §29.955; Refer to "Oil Pressure Indicator" Information Content
Gas Producer Rotor Tachometer	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	

Autorotation Tachometer	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	§29.1305 - (a): A tachometer for each engine that, if combined with the applicable instrument required by paragraph (a)(14) of this section, indicates rotor r.p.m. during autorotation. Refer to "Oil Pressure Indicator" Information Content
Tachometer	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	§29.1305 - (a): indicate, as applicable— (i) The r.p.m. of the single main rotor; (ii) The common r.p.m. of any main rotors whose speeds cannot vary appreciably with respect to each other; and (iii) The r.p.m. of each main rotor whose speed can vary appreciably with respect to that of another main rotor; Refer to "Oil Pressure Indicator" Information Content
Free Power Turbine Tachometer	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	
Gas Temperature Indicator	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	
Turbine Engine Power Indicator	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	§29.1305 - (a): Indicates power for each turbine engine
Powerplant Ice Protection System Indicator	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	§29.1305 - (a): Indicates the functioning of the powerplant ice protection system
Fuel Filter Contamination Indicator	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	§29.1305 - (a): Indicates the occurrence of contamination of the filter to the degree established in compliance with §29.955;
Oil Strainer or Filter Warning Means	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	§29.1305 - (a): Warns the pilot of the occurrence of contamination of the strainer or filter before it reaches the capacity established in accordance with §29.1019(a)(2); §29.1019 - (a): (3) The oil strainer or filter, unless it is installed at an oil tank outlet, must incorporate a means to indicate contamination before it reaches the capacity established in accordance with paragraph (a)(2) of this section.
Fuel System Heater Operation Indicator	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	§29.1305 - (a): Indicates the functioning of any selectable or controllable heater used to prevent ice clogging of fuel system components; Refer to "Oil Pressure Indicator" Information Content
OEI Power Levels Warning Device	Rotorcraft with 30-Second/2-Minute OEI Power Ratings	Subpart F - §29.1305 - (a)	§29.1305 - (a): Alerts the pilot when the engine is at the 30-second and 2-minute OEI power levels, when the event begins, and when the time interval expires. Refer to "Oil Pressure Indicator" Information Content
Power Usage and Duration at the 30-Second and 2-Minute OEI Levels System Indicators	Rotorcraft with 30-Second/2-Minute OEI Power Ratings	Subpart F - §29.1305 - (a)	§29.1305 - (a): For each turbine engine utilizing 30-second/2-minute OEI power, a device or system must be provided for use by ground personnel which— (iv) Has a means to verify proper operation of the system or device. Refer to "Oil Pressure Indicator" Information Content

Auxiliary Power Units Warning Devices	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	§29.1305 - (a): An individual indicator, warning or caution device, or other means to advise the flightcrew that limits are being exceeded, if exceeding these limits can be hazardous, for— (i) Gas temperature; (ii) Oil pressure; and (iii) Rotor speed.
Ferromagnetic Particles Detection System Indicator	All Transport Category Rotorcraft	Subpart F - §29.1305 - (a)	§29.1305 - (a): Signals to the flightcrew when ferromagnetic particles are detected by the chip detector required by §29.1337(e);
Individual Oil Pressure Indicator for each Engine	Category A Rotorcraft	Subpart F - §29.1305 - (b)	
	Category B Rotorcraft	Subpart F - §29.1305 - (c)	
Independent Fuel Pressure Warning Device	Category A Rotorcraft	Subpart F - §29.1305 - (b)	
Fire Warning Indicators	Category A Rotorcraft	Subpart F - §29.1305 - (b)	§29.1203 - (d): There must be means to allow crewmembers to check, in flight, the functioning of each fire detector system electrical circuit.
	Category B Rotorcraft	Subpart F - §29.1305 - (c)	§29.1203 - (d): There must be means to allow crewmembers to check, in flight, the functioning of each fire detector system electrical circuit.
Radio Communications Systems	All Transport Category Rotorcraft	Subpart F - §29.1307	
Actuating Device-Control System Alignment Indicator	All Transport Category Rotorcraft	Subpart F - §29.1329 - (b)	§29.1329 - (b): Indicates to the pilot the alignment of the actuating device in relation to the control system it operates.
Mode of Operation Indicator	All Transport Category Rotorcraft	Subpart F - §29.1329 - (f)	§29.1329 - (f): Indicates to the pilots the current mode of operation. Selector switch position is not acceptable as a means of indication.
Inadequate Power Supply Visual Indicators	All Transport Category Rotorcraft	Subpart F - §29.1331 - (a)	§29.1331 - (a): A visual means integral with each instrument to indicate when the power adequate to sustain proper instrument performance is not being supplied.
Mode of Operation Indicator	All Transport Category Rotorcraft	Subpart F - §29.1335	§29.1335: Indicates to the flight crew the current mode of operation (if a flight director system is installed). Selector switch position is not acceptable as a means of indication.
Generating System Essential Quantities (Such as Voltage and Current)	All Transport Category Rotorcraft	Subpart F - §29.1351	§29.1351 - (a): Indicates to appropriate crewmembers the generating system quantities essential for the safe operation of the system, such as the voltage and current supplied by each generator.
Battery Temperature Sensing and Over-Temperature Warning System	All Transport Category Rotorcraft	Subpart F - §29.1353 - (c)	

Battery Failure Sensing and Warning System	All Transport Category Rotorcraft	Subpart F - §29.1353 - (c)	
Hydraulic Power System Pressure Indicators	All Transport Category Rotorcraft	Subpart F - §29.1435 - (a)	§29.1435 - (a): Indicates the pressure in each main hydraulic power system.
Voice Recorder Operation Aural or Visual Device	All Transport Category Rotorcraft	Subpart F - §29.1457 - (d)	§29.1457 - (d): Indicates proper operation of the recorder for preflight checking.
Flight Recorder Operation Aural or Visual Device	All Transport Category Rotorcraft	Subpart F - §29.1459 - (a)	§29.1459 - (a): Indicates proper recording of data in the storage medium of the recorder for preflight checking.
Valve Position	All Transport Category Rotorcraft	Subpart E - §29.1141 - (f)	§29.1141 - (f): Controls of powerplant valves required for safety must have— (2) For power-assisted valves, a means to indicate to the flight crew when the valve— (i) Is in the fully open or fully closed position; or (ii) Is moving between the fully open and fully closed position.
Landing Gear Position Indicator	All Transport Category Rotorcraft	Subpart D - §29.729 - (e)	§29.729 - (e): Indicates to the pilot when the gear is secured in the extreme positions. §29.1555: (d) For accessory, auxiliary, and emergency controls— (1) Each essential visual position indicator, such as those showing rotor pitch or landing gear position, must be marked so that each crewmember can determine at any time the position of the unit to which it relates; and (2) Each emergency control must be red and must be marked as to method of operation. (e) For rotorcraft incorporating retractable landing gear, the maximum landing gear operating speed must be displayed in clear view of the pilot.
Landing Gear Warning Devices	All Transport Category Rotorcraft	Subpart D - §29.729 - (g)	§29.729 - (g): Functions continuously when the rotorcraft is in a normal landing mode and the landing gear is not fully extended and locked. A manual shutoff capability must be provided for the warning device and the warning system must automatically reset when the rotorcraft is no longer in the landing mode.

Table 44. 14 CFR 31—Airworthiness standards: Manned free balloons.

Indicator/Warning	Required For	Required Based On	Information Represented
Altimeter	All Manned Free Balloons	Subpart F - §31.85 - (a)	§25.1325 - (d): Indicates pressure altitude in a standard atmosphere, with a minimum practicable calibration error when the corresponding static pressures are applied. AC 23-8C: Measures the difference between a sea level barometer pressure set on the instrument and static pressure, and indicates in units of feet
Rate-of-Climb Indicator	All Manned Free Balloons	Subpart F - §31.85 - (a)	
Fuel Quantity Gauge	Hot Air Balloons	Subpart F - §31.85 - (b)	§31.85 - (b): Indicates to the crew the quantity of fuel in each cell during flight. The means must be calibrated in appropriate units or in percent of fuel cell capacity
Envelope Temperature Indicator	Hot Air Balloons	Subpart F - §31.49 - (e) Subpart F - §31.85 - (b)	§31.49 - (e): Indicates the maximum envelope skin temperatures occurring during operation. The indicator must be readily visible to the pilot and marked to indicate the limiting safe temperature of the envelope material. If the markings are on the cover glass of the instrument, there must be provisions to maintain the correct alignment of the glass cover with the face of the dial.
Compass	Captive Gas Balloons	Subpart F - §31.85 - (c)	AC 43.13-1B: Used to determine direction on the Earth's surface. A magnetic compass utilizes the Earth's magnetic field to establish direction.

Table 45. 14 CFR 33—Airworthiness standards: Aircraft engines.

Indicator/Warning	Required For	Required Based On	Information Represented
Rotor System Unbalance Indicator	Turbojet Engine	Subpart B - §33.29 - (b)	§33.29 - (b): Indicates rotor system unbalance.
OEI Power Levels Warning Device	Rotorcraft Turbine Engine Having a 30-Second OEI Rating and a 2-Minute OEI Rating	Subpart B - §33.29 - (c)	§33.29 - (c): (1) Alerts the pilot when the engine is at the 30-second OEI and the 2-minute OEI power levels, when the event begins, and when the time interval expires; (3) Alerts maintenance personnel in a positive manner that the engine has been operated at either or both of the 30-second and 2-minute OEI power levels, and permit retrieval of the recorded data; and
Oil Strainer or Filter Contamination Indicator/Warning Device	All Aircraft Engines	Subpart E - §33.71 - (b)	§33.71 - (b): Indicate contamination before it reaches the capacity established in accordance with paragraph (b)(3) of this section.
Oil Quantity Indicator	All Aircraft Engines	Subpart E - §33.71 - (c)	§23.1337 - (d): Indicates the quantity of oil in each tank

Table 46. 14 CFR 91—General operating and flight rules.

Indicator/Warning	Required For	Required Based On	Information Represented
Airspeed Indicator	All Operations and Flight Rules	Subpart C - §91.205 - (b)	Refer to: Part 23: Airspeed Indicator Part 25: Airspeed Indicator Part 27: Airspeed Indicator Part 29: Airspeed Indicator
Altimeter	All Operations and Flight Rules	Subpart C - §91.205 - (b)	§25.1325 - (d): Indicates pressure altitude in a standard atmosphere, with a minimum practicable calibration error when the corresponding static pressures are applied. AC 23-8C: Measures the difference between a sea level barometer pressure set on the instrument and static pressure, and indicates in units of feet
Magnetic Direction Indicator	All Operations and Flight Rules	Subpart C - §91.205 - (b)	Refer to: Part 23: Magnetic Direction Indicator Part 25: Direction Indicator Part 27: Magnetic Direction Indicator Part 29: Magnetic Direction Indicator
Tachometer for Each Engine	All Operations and Flight Rules	Subpart C - §91.205 - (b)	Refer to: Part 23: Tachometer Indicator Part 25: Tachometer Part 27: Tachometer Part 29: Autorotation Tachometer Part 29: Tachometer
Oil Pressure Gauge for Each Engine Using Pressure System	All Operations and Flight Rules	Subpart C - §91.205 - (b)	Refer to: Part 23: Oil Pressure Indicator
Temperature Gauge for Each Liquid-Cooled Engine	All Operations and Flight Rules	Subpart C - §91.205 - (b)	
Oil Temperature Gauge for Each Air-Cooled Engine	All Operations and Flight Rules	Subpart C - §91.205 - (b)	Refer to: Part 23: Oil Temperature Indicator
Manifold Pressure Gauge for Each Altitude Engine	All Operations and Flight Rules	Subpart C - §91.205 - (b)	Refer to: Part 23: Manifold Pressure Indicator
Fuel Gauge Indicating the Quantity of Fuel in each Tank	All Operations and Flight Rules	Subpart C - §91.205 - (b)	Refer to: Part 23: Fuel Quantity Indicator Part 25: Fuel Quantity Indicator

			Part 27: Fuel Quantity Indicator Part 29: Fuel Quantity Indicator Part 31: Fuel Quantity Gauge
Landing Gear Position Indicator, if the Aircraft Has a Retractable Landing Gear	All Operations and Flight Rules	Subpart C - §91.205 - (b)	Refer to: Part 23: Landing Gear Position Indicator Part 25: Landing Gear Position Indicator Part 27: Landing Gear Position Indicator Part 29: Landing Gear Position Indicator
Emergency Locator Transmitter	All Operations and Flight Rules	Subpart C - §91.205 - (b)	
Two-Way Radio Communication and Navigation Equipment	Visual Flight Rules	Subpart K - §121.347 Subpart K - §121.349	
	Instrument Flight Rules	Subpart C - §91.205 - (d) Subpart K - §121.349	
	Category II Operations	Subpart C - §91.205 - (f)	
	Category III Operations	Subpart C - §91.205 - (g)	
	Night Vision Goggle Operations	Subpart C - §91.205 - (h)	
Gyroscopic Rate-of-Turn Indicator	Instrument Flight Rules	Subpart C - §91.205 - (d)	
	Category II Operations	Subpart C - §91.205 - (f)	
	Category III Operations	Subpart C - §91.205 - (g)	
Slip-Skid Indicator	Instrument Flight Rules	Subpart C - §91.205 - (d)	
	Category II Operations	Subpart C - §91.205 - (f)	
	Category III Operations	Subpart C - §91.205 - (g)	
Sensitive Altimeter Adjustable for Barometric Pressure	Instrument Flight Rules	Subpart C - §91.205 - (d) Subpart K -	

		§121.325 - (b)	
	Category II Operations	Subpart C - §91.205 - (f)	
	Category III Operations	Subpart C - §91.205 - (g)	
Clock	Instrument Flight Rules	Subpart C - §91.205 - (d)	§91.205 - (d): Displays hours, minutes, and seconds with a sweep-second pointer or digital presentation.
	Category II Operations	Subpart C - §91.205 - (f)	§91.205 - (d): Displays hours, minutes, and seconds with a sweep-second pointer or digital presentation.
	Category III Operations	Subpart C - §91.205 - (g)	§91.205 - (d): Displays hours, minutes, and seconds with a sweep-second pointer or digital presentation.
Gyroscopic Pitch and Bank Indicator (Artificial Horizon)	Instrument Flight Rules	Subpart C - §91.205 - (d)	
	Category II Operations	Subpart C - §91.205 - (f)	
	Category III Operations	Subpart C - §91.205 - (g)	
	Night Vision Goggle Operations	Subpart C - §91.205 - (h)	
Gyroscopic Direction Indicator (Directional Gyro or Equivalent)	Instrument Flight Rules	Subpart C - §91.205 - (d)	
	Category II Operations	Subpart C - §91.205 - (f)	
	Category III Operations	Subpart C - §91.205 - (g)	
Two Localizer and Glide Slope Receiving Systems with Basic ILS Displays (*)	Category II Operations	Subpart C - §91.205 - (f)	
Communications System	Category II Operations	Subpart C - §91.205 - (f)	
Marker Beacon Receiver, that provides distinctive aural and visual indications of the outer and the middle markers	Category II Operations	Subpart C - §91.205 - (f)	

Two Gyroscopic Pitch and Bank Indicating Systems (*)	Category II Operations	Subpart C - §91.205 - (f)	
Two Gyroscopic Direction Indicating Systems (*)	Category II Operations	Subpart C - §91.205 - (f)	
Two Airspeed Indicators	Category II Operations	Subpart C - §91.205 - (f)	
Two Sensitive Altimeters Adjustable for Barometric Pressure	Category II Operations	Subpart C - §91.205 - (f)	
Two Vertical Speed Indicators	Category II Operations	Subpart C - §91.205 - (f)	
Flight Control Guidance System (*)	Category II Operations	Subpart C - §91.205 - (f)	
Marker Beacon Receiver, providing aural and visual indications of the inner marker or a radio altimeter	Category II Operations	Subpart C - §91.205 - (f)	
Warning systems for immediate detection by the pilot of system faults in items above with (*), if installed for use in Category III operations, the radio altimeter and autothrottle system	Category II Operations	Subpart C - §91.205 - (f)	
Night Vision Goggles	Night Vision Goggle Operations	Subpart C - §91.205 - (h)	
Radar Altimeter	Night Vision Goggle Operations	Subpart C - §91.205 - (h)	
Airborne Weather Radar Equipment for any transport category airplane (except C-46 type airplanes) or a nontransport category airplane IFR or night VFR conditions	Visual Flight Rules	Subpart K - §121.357 - (c)	
	Instrument Flight Rules	Subpart K - §121.357 - (c)	

Table 47. 14 CFR 91—General operating and flight rules (airspace).

Indicator/Warning	Required For	Required Based On	Information Represented
ATC Transponder and Altitude Reporting Equipment	Class A	Subpart C - §91.215 - (b)	§91.215: (a): All airspace: U.S.-registered civil aircraft. For operations not conducted under part 121 or 135 of this chapter, ATC transponder equipment installed must meet the performance and environmental requirements of any class of TSO-C74b (Mode A) or any class of TSO-C74c (Mode A with altitude reporting capability) as appropriate, or the appropriate class of TSO-C112 (Mode S). (b) All airspace. Unless otherwise authorized or directed by ATC, no person may operate an aircraft in the airspace described in paragraphs (b)(1) through (b)(5) of this section, unless that aircraft is equipped with an operable coded radar beacon transponder having either Mode 3/A 4096 code capability, replying to Mode 3/A interrogations with the code specified by ATC, or a Mode S capability, replying to Mode 3/A interrogations with the code specified by ATC and intermode and Mode S interrogations in accordance with the applicable provisions specified in TSO C-112, and that aircraft is equipped with automatic pressure altitude reporting equipment having a Mode C capability that automatically replies to Mode C interrogations by transmitting pressure altitude information in 100-foot increments.
	Class B	Subpart C - §91.215 - (b)	§91.215: (a): All airspace: U.S.-registered civil aircraft. For operations not conducted under part 121 or 135 of this chapter, ATC transponder equipment installed must meet the performance and environmental requirements of any class of TSO-C74b (Mode A) or any class of TSO-C74c (Mode A with altitude reporting capability) as appropriate, or the appropriate class of TSO-C112 (Mode S). (b) All airspace. Unless otherwise authorized or directed by ATC, no person may operate an aircraft in the airspace described in paragraphs (b)(1) through (b)(5) of this section, unless that aircraft is equipped with an operable coded radar beacon transponder having either Mode 3/A 4096 code capability, replying to Mode 3/A interrogations with the code specified by ATC, or a Mode S capability, replying to Mode 3/A interrogations with the code specified by ATC and intermode and Mode S interrogations in accordance with the applicable provisions specified in TSO C-112, and that aircraft is equipped with automatic pressure altitude reporting equipment having a Mode C capability that automatically replies to Mode C interrogations by transmitting pressure altitude information in 100-foot increments.

	Class C	Subpart C - §91.215 - (b)	§91.215: (a): All airspace: U.S.-registered civil aircraft. For operations not conducted under part 121 or 135 of this chapter, ATC transponder equipment installed must meet the performance and environmental requirements of any class of TSO-C74b (Mode A) or any class of TSO-C74c (Mode A with altitude reporting capability) as appropriate, or the appropriate class of TSO-C112 (Mode S). (b) All airspace. Unless otherwise authorized or directed by ATC, no person may operate an aircraft in the airspace described in paragraphs (b)(1) through (b)(5) of this section, unless that aircraft is equipped with an operable coded radar beacon transponder having either Mode 3/A 4096 code capability, replying to Mode 3/A interrogations with the code specified by ATC, or a Mode S capability, replying to Mode 3/A interrogations with the code specified by ATC and intermode and Mode S interrogations in accordance with the applicable provisions specified in TSO C-112, and that aircraft is equipped with automatic pressure altitude reporting equipment having a Mode C capability that automatically replies to Mode C interrogations by transmitting pressure altitude information in 100-foot increments.
Altitude Alerting System, or device which alert the pilot upon approaching a preselected by a sequence of both aural and visual signals	All Airspace	Subpart C - §91.219 - (b)	§91.219 - (b): (1) Alerts the pilot— (i) Upon approaching a preselected altitude in either ascent or descent, by a sequence of both aural and visual signals in sufficient time to establish level flight at that preselected altitude; or (ii) Upon approaching a preselected altitude in either ascent or descent, by a sequence of visual signals in sufficient time to establish level flight at that preselected altitude, and when deviating above and below that preselected altitude, by an aural signal; (2) Provide the required signals from sea level to the highest operating altitude approved for the airplane in which it is installed; (3) Preselect altitudes in increments that are commensurate with the altitudes at which the aircraft is operated; (4) Be tested without special equipment to determine proper operation of the alerting signals; and (5) Accept necessary barometric pressure settings if the system or device operates on barometric pressure. However, for operation below 3,000 feet AGL, the system or device need only provide one signal, either visual or aural, to comply with this paragraph. A radio altimeter may be included to provide the signal if the operator has an approved procedure for its use to determine DA/DH or MDA, as appropriate.
Extended Squitter Automatic Dependent	Class A	Subpart C - §91.225 - (a)	§91.225 - (a): (1) Meets the performance requirements in TSO-C166b, Extended Squitter Automatic Dependent Surveillance-Broadcast (ADS-B)

Surveillance-Broadcast (ADS-B)			Operating on the Radio Frequency of 1090 Megahertz (MHz); and (2) Meets the requirements of §91.227.
Traffic Information Service-Broadcast (TIS-B) Equipment	Class A	Subpart C - §91.225 - (a)	§91.225 - (a): (1) Meets the performance requirements in Traffic Information Service-Broadcast (TIS-B) Equipment Operating on the Radio Frequency of 1090 Megahertz (MHz); and (2) Meets the requirements of §91.227.
Universal Access Transceiver (UAT) Automatic Dependent Surveillance-Broadcast (ADS-B) Equipment	Class B	Subpart C - §91.225 - (d)	§91.225 - (b): (1) Meets the performance requirements in— (i) TSO-C166b; or (ii) TSO-C154c, Universal Access Transceiver (UAT) Automatic Dependent Surveillance-Broadcast (ADS-B) Equipment Operating on the Frequency of 978 MHz; (2) Meets the requirements of §91.227.
	Class C	Subpart C - §91.225 - (d)	§91.225 - (b): (1) Meets the performance requirements in— (i) TSO-C166b; or (ii) TSO-C154c, Universal Access Transceiver (UAT) Automatic Dependent Surveillance-Broadcast (ADS-B) Equipment Operating on the Frequency of 978 MHz; (2) Meets the requirements of §91.227.
The length and width of the aircraft	All Airspace	Subpart C - §91.227 - (d) and for above items	
An indication of the aircraft's latitude and longitude	All Airspace	Subpart C - §91.227 - (d) and for above items	
An indication of the aircraft's barometric pressure altitude	All Airspace	Subpart C - §91.227 - (d) and for above items	
An indication of the aircraft's velocity	All Airspace	Subpart C - §91.227 - (d) and for above items	
An indication if TCAS II or ACAS is installed and operating in a mode that can generate resolution advisory alerts	All Airspace	Subpart C - §91.227 - (d) and for above items	

If an operable TCAS II or ACAS is installed, an indication if a resolution advisory is in effect	All Airspace	Subpart C - §91.227 - (d) and for above items	
An indication of the Mode 3/A transponder code specified by ATC	All Airspace	Subpart C - §91.227 - (d) and for above items	
An indication of the aircraft's call sign that is submitted on the flight plan, or the aircraft's registration number, except when the pilot has not filed a flight plan, has not requested ATC services, and is using a TSO-C154c self-assigned temporary 24-bit address	All Airspace	Subpart C - §91.227 - (d) and for above items	
An indication if the flightcrew has identified an emergency, radio communication failure, or unlawful interference	All Airspace	Subpart C - §91.227 - (d) and for above items	
An indication of the aircraft's "IDENT" to ATC	All Airspace	Subpart C - §91.227 - (d) and for above items	
An indication of the aircraft assigned ICAO 24-bit address, except when the pilot has not filed a flight plan, has not requested ATC services, and is using a TSO-C154c self-assigned temporary 24-bit address	All Airspace	Subpart C - §91.227 - (d) and for above items	
An indication of the aircraft's emitter category	All Airspace	Subpart C - §91.227 - (d)	

		and for above items	
An indication of whether an ADS-B In capability is installed	All Airspace	Subpart C - §91.227 - (d) and for above items	
An indication of the aircraft's geometric altitude	All Airspace	Subpart C - §91.227 - (d) and for above items	
An indication of the Navigation Accuracy Category for Position (NACP)	All Airspace	Subpart C - §91.227 - (d) and for above items	
An indication of the Navigation Accuracy Category for Velocity (NACV)	All Airspace	Subpart C - §91.227 - (d) and for above items	
An indication of the Navigation Integrity Category (NIC)	All Airspace	Subpart C - §91.227 - (d) and for above items	
An indication of the System Design Assurance (SDA) and	All Airspace	Subpart C - §91.227 - (d) and for above items	
An indication of the Source Integrity Level (SIL)	All Airspace	Subpart C - §91.227 - (d) and for above items	

Table 48. 14 CFR 121—Operational requirements for domestic, flag, and supplemental operations.

Indicator/Warning	Required For	Required Based On	Information Represented
Airspeed Indicating System	Domestic, Flag, And Supplemental Operations	Subpart K - §121.305 - (a)	Refer to: Part 23: Airspeed Indicator Part 25: Airspeed Indicator Part 27: Airspeed Indicator Part 29: Airspeed Indicator
Sensitive Altimeter	Domestic, Flag, And Supplemental Operations	Subpart K - §121.305 - (b)	§25.1325 - (d): Indicates pressure altitude in a standard atmosphere, with a minimum practicable calibration error when the corresponding static pressures are applied. AC 23-8C: Measures the difference between a sea level barometer pressure set on the instrument and static pressure, and indicates in units of feet
Sweep-Second Hand Clock	Domestic, Flag, And Supplemental Operations	Subpart K - §121.305 - (c)	§25.1303 - (a): Displays hours, minutes, and seconds with a sweep-second pointer or digital presentation.
Free-Air Temperature Indicator	Domestic, Flag, And Supplemental Operations	Subpart K - §121.305 - (d)	
Gyroscopic Bank and Pitch Indicator (Artificial Horizon)	Domestic, Flag, And Supplemental Operations	Subpart K - §121.305 - (e)	
Gyroscopic Rate-of-Turn Indicator Combined With An Integral Slip-Skid Indicator (Turn-And-Bank Indicator)	Domestic, Flag, And Supplemental Operations	Subpart K - §121.305 - (f)	
Gyroscopic Direction Indicator (Directional Gyro Or Equivalent)	Domestic, Flag, And Supplemental Operations	Subpart K - §121.305 - (g)	
Magnetic Compass	Domestic, Flag, And Supplemental Operations	Subpart K - §121.305 - (h)	AC 43.13-1B: Used to determine direction on the Earth's surface. A magnetic compass utilizes the Earth's magnetic field to establish direction.
Vertical Speed Indicator (Rate-Of-Climb Indicator)	Domestic, Flag, And Supplemental Operations	Subpart K - §121.305 - (i)	
On turbojet powered airplane, in addition to two gyroscopic bank and pitch indicators (artificial horizons) for use at the	Domestic, Flag, And Supplemental Operations	Subpart K - §121.305 - (j)	

pilot stations, a third such instrument is installed			
Carburetor Air Temperature Indicator for each Engine.	Domestic, Flag, And Supplemental Operations	Subpart K - §121.307 - (a)	Refer to: Part 25: Carburetor Air Temperature Indicator
Cylinder Head Temperature Indicator for each Air-Cooled Engine.	Domestic, Flag, And Supplemental Operations	Subpart K - §121.307 - (b)	
Fuel Pressure Indicator for each Engine.	Domestic, Flag, And Supplemental Operations	Subpart K - §121.307 - (c)	Refer to: Part 23: Fuel Pressure or Fuel Flow Indicator Part 25: Fuel Pressure Indicator Part 27: Fuel Pressure Indicator
Fuel flowmeter or Fuel mixture Indicator for each engine not equipped with an automatic altitude mixture control.	Domestic, Flag, And Supplemental Operations	Subpart K - §121.307 - (d)	Refer to: Part 23: Fuel Flowmeter Indicator
Fuel Quantity Indicator, for each fuel tank	Domestic, Flag, And Supplemental Operations	Subpart K - §121.307 - (e)	Refer to: Part 23: Fuel Quantity Indicator Part 25: Fuel Quantity Indicator Part 27: Fuel Quantity Indicator Part 29: Fuel Quantity Indicator Part 31: Fuel Quantity Gauge
Manifold Pressure Indicator for each Engine.	Domestic, Flag, And Supplemental Operations	Subpart K - §121.307 - (f)	Refer to: Part 23: Manifold Pressure Indicator
Oil Pressure Indicator for each Engine.	Domestic, Flag, And Supplemental Operations	Subpart K - §121.307 - (g)	Refer to: Part 23: Oil Pressure Indicator
Oil Quantity Indicator for each oil tank when a transfer or separate oil reserve supply is used.	Domestic, Flag, And Supplemental Operations	Subpart K - §121.307 - (h)	Refer to: Part 23: Oil Quantity Indicator Part 25: Oil Quantity Indicator Part 27: Oil Quantity Indicator Part 29: Oil Quantity Indicator
Oil-In Temperature Indicator for each engine.	Domestic, Flag, And Supplemental Operations	Subpart K - §121.307 - (i)	Refer to: Part 23: Oil Temperature Indicator
Tachometer for each engine.	Domestic, Flag, And Supplemental Operations	Subpart K - §121.307 - (j)	Refer to: Part 23: Tachometer Indicator Part 25: Tachometer Part 27: Tachometer

			Part 29: Autorotation Tachometer Part 29: Tachometer
Independent Fuel Pressure Warning Device for each engine or a master warning device for all engines with a means for isolating the individual warning circuits from the master warning device.	Domestic, Flag, And Supplemental Operations	Subpart K - §121.307 - (k)	
Propeller Reverse Pitch Indicator, for each reversible propeller	Domestic, Flag, And Supplemental Operations	Subpart K - §121.307 - (l)	§121.307 - (l): Indicates to the pilot when the propeller is in reverse pitch, that complies with the following: (1) The device may be actuated at any point in the reversing cycle between the normal low pitch stop position and full reverse pitch, but it may not give an indication at or above the normal low pitch stop position. (2) The source of indication must be actuated by the propeller blade angle or be directly responsive to it.
Power Supply Adequacy Indicator	Domestic, Flag, And Supplemental Operations	Subpart K - §121.313 - (d)	§121.313 - (d): Indicates the adequacy of the power being supplied to required flight instruments.
Airframe Ice Detection System	Domestic, Flag, And Supplemental Operations	Subpart K - §121.321 - (a)	
Collision Avoidance Systems + Mode S transponder for Turbine-powered airplane of more than 33,000 pounds maximum certificated takeoff weight	Domestic, Flag, And Supplemental Operations	Subpart K - §121.356 - (a)	§121.356 - (a): (1) An appropriate class of Mode S transponder that meets Technical Standard Order (TSO) C-112, or a later version, and one of the following approved units: (i) TCAS II that meets TSO C-119b (version 7.0), or takeoff weight a later version. (ii) TCAS II that meets TSO C-119a (version 6.04A Enhanced) that was installed in that airplane before May 1, 2003. If that TCAS II version 6.04A Enhanced no longer can be repaired to TSO C-119a standards, it must be replaced with a TCAS II that meets TSO C-119b (version 7.0), or a later version. (iii) A collision avoidance system equivalent to TSO C-119b (version 7.0), or a later version, capable of coordinating with units that meet TSO C-119a (version 6.04A Enhanced), or a later version.
Collision Avoidance Systems + Mode S transponder for Piston-powered airplane of more than 33,000 pounds	Domestic, Flag, And Supplemental Operations	Subpart K - §121.356 - (c)	§121.356 - (c): (1) TCAS I that meets TSO C-118, or a later version, or (2) A collision avoidance system equivalent to maximum TSO C-118, or a later version, or (3) A collision avoidance system and Mode S transponder that meet paragraph (a)(1) of this section.

maximum certificated takeoff weight			
Airborne Weather Radar Equipment for any transport category airplane (except C-46 type airplanes) or a nontransport category airplane	Domestic, Flag, And Supplemental Operations	Subpart K - §121.357 - (a)	

Table 49. 14 CFR 125—Certification and operations: Airplanes having a seating capacity of 20 or more passengers or a maximum payload capacity of 6,000 pounds or more; and rules governing persons on board such aircraft.

Indicator/Warning	Required For	Required Based On	Information Represented
Two-Way Radio Communication Equipment	Airplanes Having A Seating Capacity of 20 or more Passengers or a Maximum Payload Capacity of 6,000 Pounds or more	Subpart F - §125.203 - (a)	
Navigation Equipment	Airplanes Having A Seating Capacity of 20 or more Passengers or a Maximum Payload Capacity of 6,000 Pounds or more	Subpart F - §125.203 - (b)	
Vertical Speed Indicator	Airplanes Having A Seating Capacity of 20 or more Passengers or a Maximum Payload Capacity of 6,000 Pounds or more	Subpart F - §125.205 - (a)	
Free-Air Temperature Indicator	Airplanes Having A Seating Capacity of 20 or more Passengers or a Maximum Payload Capacity of 6,000 Pounds or more	Subpart F - §125.205 - (b)	
Power Failure Warning Device or Vacuum Indicator	Airplanes Having A Seating Capacity of 20 or more Passengers or a Maximum Payload Capacity of 6,000 Pounds or more	Subpart F - §125.205 - (d)	§125.205 - (d): Shows the power available for gyroscopic instruments from each power source;
Airspeed Indicating System with Heated Pitot Tube or Equivalent Means	Airplanes Having A Seating Capacity of 20 or more Passengers or a Maximum Payload	Subpart F - §125.205 - (i)	Refer to: Part 23: Airspeed Indicator Part 25: Airspeed Indicator

	Capacity of 6,000 Pounds or more		Part 27: Airspeed Indicator Part 29: Airspeed Indicator
Sensitive Altimeter	Airplanes Having A Seating Capacity of 20 or more Passengers or a Maximum Payload Capacity of 6,000 Pounds or more	Subpart F - §125.205 - (j)	§25.1325 - (d): Indicates pressure altitude in a standard atmosphere, with a minimum practicable calibration error when the corresponding static pressures are applied. AC 23-8C: Measures the difference between a sea level barometer pressure set on the instrument and static pressure, and indicates in units of feet
Power Supply Adequacy Indicator	Airplanes Having A Seating Capacity of 20 or more Passengers or a Maximum Payload Capacity of 6,000 Pounds or more	Subpart F - §125.213 - (d)	§125.213 - (d): Indicates the adequacy of the power being supplied to required flight instruments.
Collision Avoidance Systems + Mode S Transponder for Turbine-powered airplane of more than 33,000 pounds maximum certificated takeoff weight	Airplanes Having A Seating Capacity of 20 or more Passengers or a Maximum Payload Capacity of 6,000 Pounds or more	Subpart F - §125.224 - (a)	§125.224 - (a): (1) An appropriate class of Mode S transponder that meets Technical Standard Order (TSO) C-112, or a later version, and one of the following approved units: (i) TCAS II that meets TSO C-119b (version 7.0), or a later version. (ii) TCAS II that meets TSO C-119a (version 6.04A Enhanced) that was installed in that airplane before May 1, 2003. If that TCAS II version 6.04A Enhanced no longer can be repaired to TSO C-119a standards, it must be replaced with a TCAS II that meets TSO C-119b (version 7.0), or a later version. (iii) A collision avoidance system equivalent to TSO C-119b (version 7.0), or a later version, capable of coordinating with units that meet TSO C-119a (version 6.04A Enhanced), or a later version.
Collision Avoidance Systems + Mode S Transponder for Piston-powered airplane of more than 33,000 pounds maximum certificated takeoff weight	Airplanes Having A Seating Capacity of 20 or more Passengers or a Maximum Payload Capacity of 6,000 Pounds or more	Subpart F - §125.224 - (b)	§125.224 - (b): (1) TCAS I that meets TSO C-118, or a later version, or (2) A collision avoidance system equivalent to TSO C-118, or a later version, or (1)(3) A collision avoidance system and Mode S transponder that meet paragraph (a)(1) of this section.
Flight Data Recorder that must be able to determine predefined information	Airplanes Having A Seating Capacity of 20 or more Passengers or a Maximum Payload Capacity of 6,000 Pounds or more	Subpart F - §125.225 Subpart F - §125.226	

Cockpit Voice Recorder (Turbine engine powered or large pressurized airplane with four reciprocating engines)	Airplanes Having A Seating Capacity of 20 or more Passengers or a Maximum Payload Capacity of 6,000 Pounds or more	Subpart F - §125.227 - (a)	§125.227 - (c): The cockpit voice recorder required by this section must also meet the following standards: (1) The requirements of part 25 of this chapter in effect after October 11, 1991. (2) After September 1, 1980, each recorder container must— (i) Be either bright orange or bright yellow;

15. APPENDIX D9: OPERATIONAL CONTROL STATION REVIEW FORM

Control Station Background Information	
Reviewer(s):	Date:
Company:	Control Station Name:
Type(s) of unmanned aircraft (UA) on which the responses are based:	
Type of unmanned aircraft system (UAS): Fixed Control Station Ship-Based Motor Vehicle-Based Hand-Held Air-Based Other: Other details about the control station (e.g., mobile integrated structure, tent, laptop on table, command center):	
Nature of Operations: Military Civil Commercial Other: What typical mission profiles and associated flight segments are flown with this control station?	
What crew members are necessary? What are their responsibilities? What are the similarities/differences in the displays, controls, and/or other equipment located for each in the control station?	

What physical input device(s) are available to the pilot-in-command? Where are they located with respect to the pilot-in-command's normal position in the control station?   What displays are included in the control station and where are they located relative to the pilot's normal position and field of view in the control station?   Was the control station designed to look similar to the cockpit of a manned aircraft?   Is it necessary for the RPIC to have visual line of sight of the UAS during takeoff and landing?

Please describe a normal operation using the control station.
Planning   Pre-taxi   Taxi Out   Takeoff

Climb Out   Cruise   Descent   Approach

Landing   Taxi In   Post Taxi

Aviating the UA
What information is presented on the control station displays to support aviating tasks? What information would you consider to be "nice to have" versus "need to have" for aviating the UA? How does information change as a function of the automation mode and/or the phase of flight? What information is always displayed vs. what information requires manipulation to access?

How is the content organized on the display(s)? For example, are there overlays that can be displayed or filtered? What design features support interpretation of the information relevant for aviating the UA (e.g., shapes, colors, spatial position)?
What automation capabilities are available to the pilot to support aviating the UA? How often and under what conditions are the automation capabilities used?

Navigating the UA
What information is presented on the control station displays supporting navigation? What information would you consider to be "nice to have" versus "need to have" for navigation? How does information change as a function of the automation mode and/or the phase of flight? What information is always displayed vs. what information requires manipulation to access?

How is the content organized on the display(s)? For example, are there overlays that can be displayed or filtered? What design features support interpretation of the information relevant for navigation (e.g., shapes, colors, spatial position)?
What automation capabilities are available to the pilot to support navigation? How often and under what conditions are the automation capabilities used?

Communication with VO and/or ATC
Regarding pilot-in-command interactions with ATC and/or VO, are communication capabilities built in or assumed to be external to the workstation (i.e., installed or handheld)?

Systems Management
How does the crew plan for contingencies, both pre-flight and during the flight? How does the control station identify off-normal operations and attract the pilot's attention? How does the control station design ensure an equivalent level of safety in terms of handling an emergency situation? And how is this enabled (e.g., autonomously, pilot input) and presented to the pilot?

Design Philosophy/Strategy
Describe the process used for making control station design decisions.   What “lessons learned” from the design of prior control stations did you use in the design for this control station?

16. APPENDIX D10: UAS ACCIDENT ANALYSIS SUPPLEMENTAL MATERIAL

The following are NTSB recommendations based on the accident. A-07-065 through A-07-069 are for the FAA and A-07-070 through A-07-086 for the Customs and Border Protection (CBP).

A-07-065: Require that unmanned aircraft transponders provide beacon code and altitude information to air traffic control and to aircraft equipped with traffic collision avoidance systems at all times while airborne by ensuring that the transponder is powered via the emergency or battery bus.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-065

A-07-066: Require that all conversations, including telephone conversations, between unmanned aircraft (UA) pilots and air traffic control, other UA pilots, and other assets that provide operational support to unmanned aircraft system operations, be recorded and retained in accordance with Federal Aviation Administration Orders 7210.3 and 8020.11.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-066

A-07-67: Require periodic operational reviews between the unmanned aircraft system (UAS) operations teams and local air traffic control facilities, with specific emphasis on face-to-face coordination between working-level controllers and unmanned aircraft pilot(s), to clearly define responsibilities and actions required for standard and nonstandard UAS operations. These operational reviews should include, but not be limited to, discussion on lost-link profiles and procedures, the potential for unique emergency situations and methods to mitigate them, platform-specific aircraft characteristics, and airspace management procedures.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-067

A-07-68: Require that established procedures for handling piloted aircraft emergencies be applied to unmanned aircraft systems.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-068

A-07-69: Require that all unmanned aircraft system operators report to the Federal Aviation Administration, in writing within 30 days of occurrence, all incidents and malfunctions that affect safety; require that operators are analyzing these data in an effort to improve safety; and evaluate these data to determine whether programs and procedures, including those under air traffic control, remain effective in mitigating safety risks.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-069

A-07-70: Require General Atomics Aeronautical Systems, Inc., to modify the unmanned aircraft system to ensure that inadvertent engine shutdowns do not occur.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-070

A-07-71: Require General Atomics Aeronautical Systems, Inc., to modify the unmanned aircraft system to provide adequate visual and aural indications of safety-critical faults, such as engine-out conditions and console lockups, and present them in order of priority, based on the urgency for pilot awareness and response.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-071

A-07-72: Review the U.S. Customs and Border Protection's methods of developing lost-link mission profiles to ensure that lost-link mission profile routes minimize the potential safety impact to persons on the ground, optimize the ability to recover the data link, and, in the absence of data-link recovery, provide the capability to proceed to a safe zone for a crash landing.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-072

A-07-73: Following completion of the action requested in Safety Recommendation A-07-72, require that pilots be trained concerning the expected performance and flightpath of the unmanned aircraft during a lost-link mission.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-073

A-07-74: Require that the unmanned aircraft system be modified to ensure that the transponder continues to provide beacon code and altitude information to air traffic control even if an engine shuts down in flight and that the pilot is provided a clear indication if transponder function is lost for any reason.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-074

A-07-75: Review all unmanned aircraft system (UAS) functions and require necessary design changes to the UASs that the U.S. Customs and Border Protection operates to ensure that electrical power is available for an appropriate amount of time to all systems essential to unmanned aircraft control following loss of engine power.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-075

A-07-76: Develop a means of restarting the unmanned aircraft (UA) engine during the lost-link emergency mission profile that does not rely on line-of-sight control, for example, through an autonomous capability in the unmanned aircraft system's control system or through use of control functions enabled via a backup satellite communication system available to the pilot on the ground.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-076

A-07-77: Participate in periodic operational reviews between the unmanned aircraft system operations team and local air traffic control facilities, with specific emphasis on face-to-face coordination between the working-level controller and unmanned aircraft (UA) pilot(s), to clearly define responsibilities and actions required for standard and nonstandard UA operations. These operational reviews should include, but not be limited to, discussion on lost-link profiles and procedures, the potential for unique emergency situations and methods to mitigate them, platform-specific aircraft characteristics, and airspace management procedures.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-077

A-07-78: Require that all conversations, including telephone conversations, between unmanned aircraft (UA) pilots and air traffic control, other UA pilots, and other assets that provide operational support to UA operations, be recorded and retained to support accident investigations.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-078

A-07-79: Identify and correct the causes of the console lockups.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-079

A-07-80: Implement a documented maintenance and inspection program that identifies, tracks, and resolves the root cause of systemic deficiencies and that includes steps for in-depth troubleshooting, repair, and verification of functionality before returning aircraft to service. https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-080

A-07-81: Require that aviation engineering and maintenance experts oversee the definition of maintenance tasks, establishment of inspection criteria, and the implementation of such programs. Also, ensure oversight of contractor(s) implementing such programs.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-081

A-07-82: Develop minimum equipment lists and dispatch deviation guides for the U.S. Customs and Border Protection's unmanned aircraft system operations.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-082

A-07-83: Assess the spare-parts requirements for U.S. Customs and Border Protection's unmanned aircraft operations to ensure the availability of parts critical to unmanned aircraft launch, as defined by the minimum equipment list.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-083

A-07-84: Revise U.S. Customs and Border Protection's pilot training program to ensure pilot proficiency in executing emergency procedures.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-084

A-07-85: Require that a backup pilot or another person who can provide an equivalent level of safety as a backup pilot be readily available during the operation of an unmanned aircraft system.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-085

A-07-86: Develop a safety plan, which ensures that hazards to the National Airspace System and persons on the ground introduced by the U.S. Customs and Border Protection's (CBP) unmanned aircraft system (UAS) operation are identified and that necessary actions are taken to mitigate the corresponding safety risks to the public over the life of the program. The plan should include, as a minimum, design requirements, emergency procedures, and maintenance program requirements to minimize the safety impact of UAS malfunctions in flight, continuous monitoring of the CBP's unmanned aircraft operation, analysis of malfunctions and incidents, and lessons learned from other operators of similar UAS designs.

https://www.ntsb.gov/publications/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-086

NTSB reports removed from analysis

The following reports have the term "unmanned" but were removed from the analysis. The reason for the matched with "unmanned" is described as well as the rationale for the removal.

1. CEN17LA057 (Event date 12/16/2016): removed because it is not relevant as the aircraft was a Stinson 108. The match was because the "departure airport was unmanned."
2. DCA16WA229 (Event date 9/28/2016): removed because the analysis is not completed. Only information available is "The Australian Transport Safety Bureau (ATSB) has notified the NTSB of an incident involving a Pulse Vapor 55 unmanned helicopter that occurred on September 28, 2016. The NTSB has appointed a U.S. Accredited Representative to assist the ATSB's investigation under the provisions of ICAO Annex 13 as the State of Manufacturer and Design of the unmanned helicopter."
3. WPR15LA242 (Event date 8/13/2015): removed by it involves a manned aircraft. The match was because the airplane was registered to and being operated by Unmanned Systems, Inc.

4. ERA15MA259A (Event date 7/7/2015): This fatal accident did not include a UA (it involved an F-16 and a Cessna). It was retrieved because the F16 pilot had flight experience including with the MQ-1B (Predator) and the MQ-9 (Reaper).
5. ERA15MA259B (Event date 7/7/2015): See ERA15MA259A
6. WPR15LA034 (Event date 11/5/2014): removed by it involves a manned aircraft. The match was because the airplane was registered to and being operated by Unmanned Systems, Inc.
7. CEN14WA536 (Event date 10/04/2013): removed because it involves manned helicopter. The match was because the helicopter made an emergency landing on the unmanned and decommissioned oil rig.
8. ERA13LA042 (Event date 10/28/2012): removed because it involves manned aircraft. The match was due to the air traffic controller reporting that prior to the accident, he was obtaining flight strips from the unmanned flight data position.
9. OPS11IA401 (Event date 3/23/2011): removed because it involves manned aircraft. The match was due to the tower being unmanned.
10. WPR10FA131 (Event date 2/8/2010): removed because it involves manned aircraft. The match was due to the pilot and the passenger also being MQ-1 pilots
11. ERA10CA083 (Event date 11/28/2009): removed because it involves manned helicopter. The match was due to the pilot's failure to secure the collective control prior to departing the helicopter which resulted in an unwanted unmanned departure
12. CEN10FA028 (Event date 10/26/2009): removed because it involves manned aircraft. The match was due to a Global Hawk UAV in the sector with an unusual route in its flight plan that the controller believed was incorrect
13. WPR10FA005 (Event date 10/4/2009): removed because it involves manned aircraft. The match was due an unmanned weather reporting facility (Remote Automated Weather Station (RAWS))
14. DFW08FA053 (Event date 12/20/2007): removed because it involves manned helicopter. The match was due an unmanned offshore platform
15. NYC07LA017 (Event date 10/31/2006): removed because it involves a towing operation. The match was due an unmanned B757 in tow.
16. DFW07LA006 (Event date 10/18/2006): Removed because it involves a manned experimental glider. The match was due to a statement about the flight test research being part of the development of a UAV from a carbon fiber.
17. ATL07CA003 (Event date 10/8/2006): Removed because it involves hand-propping an airplane’s engine. The airplane taxied unmanned.
18. DFW06FAMS1 (Event date 10/6/2005): Removed because it involves a manned helicopter. The match was due an unmanned offshore platform.
19. LAX05LA208 (Event date 6/17/2005): Removed because it involves a manned aircraft. The match was due to an unmanned pump.
20. ATL04LA074 (Event date 2/7/2004): Removed because it involves a run-away manned airplane. The airplane taxied unmanned.
21. LAX03CA272 (Event date 8/31/2003): It is unclear why this report was returned with the query.

22. SEA03LA130 (Event date 7/5/2003): Removed because it involves a manned aircraft. The match was due an unmanned public airstrip.
23. ATL03LA013 (Event date 10/31/2002): Removed because it involves a run-away manned airplane. The airplane taxied unmanned.
24. ATL03FA008 (Event date 10/23/2002): Removed because it involves a manned airplane. The match was due to the wreckage being compared to a UAV.
25. LAX01FA252 (Event date 7/21/2001): Removed because it involves a run-away helicopter. The unmanned helicopter performed a dynamic rollover.
26. NYC01LA165 (Event date 7/3/2001): Removed because it involves a run-away manned airplane. The airplane taxied unmanned
27. LAX01FA071 (Event date 1/9/2001): Removed because it involves a run-away airship. The blimp became airborne unmanned
28. CHI01LA066 (Event date 1/8/2001): Removed because it involves a unmanned nine-passenger service van that hit an aircraft
29. MIA01LA055 (Event date 1/5/2001): removed because it involves manned helicopter. The match was due to the pilot's failure to secure the collective which resulted in an unwanted unmanned departure
30. FTW99LA215 (Event date 8/10/1999): removed because the match was due to the helicopter knocking into a parked, unmanned helicopter
31. FTW99FA192 (Event date 7/17/1999): removed because the match was due to an unmanned fueling site
32. ATL99LA103 (Event date 7/3/1999): removed because the match was due to an unmanned balloon that caught fire, drifted, and collided into a single family dwelling
33. IAD99FA008 (Event date 10/27/1998): removed because the match was due to a parked unmanned pickup truck
34. FTW98LA336 (Event date 7/27/1998): removed because the match was due to taxiing into a parked unmanned aircraft
35. FTW98LA353 (Event date 7/27/1998): removed because the match was due to an aircraft rolling backward into an unmanned, parked aircraft
36. FTW98LA257 (Event date 6/5/1998): removed because the match was due to a statement that the employer discontinued flight testing of an unmanned vehicle
37. ANC98LA045 (Event date 5/6/1998): removed because the match was due to an aircraft striking an unmanned, parked helicopter
38. FTW98LA149 (Event date 3/11/1998): removed because the match was due to an unmanned runaway golf cart
39. FTW98FA089 (Event date 1/9/1998): removed because the match was due to a crew parachuting from a balloon that then flew unmanned
40. NYC98LA031 (Event date 11/23/1997): removed because the match was due to a pilot failing to set the airplane controls prior to hand propping and thus the aircraft departed unmanned
41. BFO96LA009 (Event date 10/12/1995): removed because the match was due to a balloon inadvertently departing unmanned

42. LAX95LA121 (Event date 2/26/1995): removed because the match was due to a balloon inadvertently departing unmanned
43. MIA94LA190 (Event date 8/7/1994): removed because the match was due to a manned pilot walking into the propeller of the aircraft (then unmanned) he was walking around
44. BFO94LA083 (Event date 6/1/1994): removed because the match was due to a pilot parachuting from a glider that then flew unmanned
45. NYC94LA051 (Event date 3/3/1994): removed because the match was due to a pilot failing to tie down adequately the airplane prior to hand propping and thus the aircraft taxied unmanned
46. FTW94LA021 (Event date 10/29/1993): removed because it involves manned helicopter. The match was due an unmanned offshore platform
47. NYC93LA149 (Event date 8/9/1993): removed because the match was due to a pilot hand propping an aircraft that subsequently taxied unmanned
48. FTW91LA026 (Event date 12/25/1990): removed because the match was due to a pilot hand propping an aircraft that subsequently taxied unmanned
49. DEN90LA073 (Event date 3/9/1990): removed because the match was due the mention of an unmanned airport
50. MIA89LA163 (Event date 5/30/1989): removed because the match was due to a pilot hand propping an aircraft that subsequently taxied unmanned
51. DEN85LA080 (Event date 2/17/1985): removed because the match was due the mention of an unmanned tower
52. MKC84LA248 (Event date 8/12/1984): removed because the match was due to the colliding with parked, unmanned aircraft
53. MKC84LA183 (Event date 6/24/1984): removed because the match was due to a pilot hand propping an aircraft that subsequently taxied unmanned
54. FTW84FA189 (Event date 4/4/1984): removed because the match was due the mention of an unmanned rig
55. NYC76DNC17 (Event date 9/5/1975): removed because the match was due the mention of an unmanned airport
56. SEA70DWD09 (Event date 4/16/1970): removed because the match was due to a pilot hand propping an aircraft that subsequently taxied unmanned

UAS Accident Analysis Papers Reviewed

Overview of recommendations and interventions from the literature:

R1. Crewmember selection criteria and associated procedures
R2. Crewmember aeromedical screening
R3. Training tool development (e.g., simulators)
R4. Training curriculum and program development
R5. Display design (information content and representation)
R6. Automation and control interface/mode design
R7. Job/procedure design
R8. Organizational culture emphasizing commitment to safety

R9. UAS crewmember career development and growth opportunities
R10. Physical control station design/layout

1. Schmidt, J., & Parker, R. (1995). Development of UAV mishap human factors database. Presented at the AUVSI 1995 Conference, Washington, DC, July 10–14, 1995

   Causes for 170 Pioneer UAV mishaps/incidents for 1986-1993:

Causal Factor	**Potential Recommendations**
Failure/latency in recognizing in-flight emergency	R3,R4,R5,R6
Failure to apply emergency procedures in a timely or correct manner	R3,R4,R5,R6,R7
Lack of proficiency in launching and landing the UA	R3,R4,R5,R6,R7
Personnel illness	R1,R2
Spatial disorientation	R5
Poor crew coordination	R3,R4
Low proficiency due to poor training	R3,R4
Eye sight	R1,R2
Crew station design	R5,R6,R10

   Recommendations

   - Establish personnel aeromedical screening/monitoring guidelines (R2)
   - Create better personnel selection procedures and tests (R1)
   - Develop UAS crew coordination training program (R4)
   - Develop better training tools and training requirements (R3)
   - Create a tailored aviation physiology training program (R4)
   - Enhance human-system integration in design (R5,R6)

2. Seagle, J. (1997). Unmanned aerial vehicle mishaps: A human factors analysis (master's thesis). Embry-Riddle Aeronautical University Extended Campus Norfolk, VA.

Classification: predecessor to HFACS

Recommendations:

- Establishment of aircrew selection criteria (R1)
- Establishment of simulator and training programs (R3,R4)
- Requirement of annual flight physicals (R2)
- Increased automation in difficult operations (e.g., landing, adverse weather) (R6)
- Establishment of dedicated training pipeline and career path for crew members (R4,R9)

3. Ferguson, M. G. (1999). Stochastic modeling of naval unmanned aerial vehicle mishaps: Assessment of potential intervention strategies. Retrieved from http://www.dtic.mil/dtic/tr/fulltext/u2/a371104.pdf

Study uses Seagle's predecessor to HFACS to categorize mishaps

Recommendations:

- Use of simulators (R3)
- Implementation of improved aircrew coordination training (R4)
- Improvements to crew resource management (R7)
- Unit leaders should have operational experience (R7,R8)
- Establishment of dedicated training pipeline and career path for crew members (R9)

4. Manning, S. D., Rash, C. E., LeDuc, P. A., Noback, R. K., & McKeon, J. (2004). The Role of human causal factors in U.S. Army unmanned aerial vehicle accidents. Retrieved from http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA421592

   Two approaches to categorizing mishaps:

   - HFACS
   - Army accident investigation and reporting (Department of the Army Pamphlet 385-40)

   Recommendations:

   - Develop training programs that focus on addressing the items in the HFACS taxonomy (R4)

5. Williams, K. W. (2004). A summary of unmanned aircraft accident/incident data: Human factors implications. Retrieved from http://www.dtic.mil/get-tr-doc/pdf?AD=ADA460102

Mishap classification:

Classification		**Potential Recommendations**
Human factors	Alerts/alarms	R6
	Display design	R5
	Procedural error	R7
	Skill-based error	R3,R4,R5,R6
	Other	N/A
Non-human factors	Maintenance	N/A
	Aircraft	N/A

	Unknown	N/A

Recommendations: No recommendations provided

6. Asim, M., Ehsan, D. N., & Rafique, K. (2005). Probable causal factors in UAV accidents based on human factor analysis and classification systems. History, 1905, 5.

Classification:

Classification	**Potential Recommendations**
Fatigue	R5,R6,R7
Workload	R3,R4,R5,R6,R7
Situation awareness	R3,R4,R5,R6
Crew coordination	R4
Training	R3,R4
Ergonomics	R10

Proposed model for making recommendations according to HFACS:

- Organizational influences
    - Culture change (R8)
    - Commitment from high-level management (R8)
    - Process improvements (R7,R9)
- Unsafe supervision
    - Extensive training (R3,R4)
    - System of checks and balances (R7)
    - Leadership workshops (R8,R9)
- Precondition for unsafe acts
    - Improvements to man-machine interface (R5,R6,R10)
    - Improve environmental and operating conditions (R10)
- Unsafe acts
    - Refresher trainings (R4)
    - Enhancement of pilot ability to respond (R3,R4,R5,R6)
    - Improve ergonomics (R10)

7. Tvaryanas, A. P., Thompson, W. T., & Constable, S. H. (2005). Human factors in remotely piloted aircraft operations: HFACS analysis of 221 mishaps over 10 years. Aviation, Space, and Environmental Medicine, 77(7), 724–731.

8. Tvaryanas, A. P., Thompson, B. T., & Constable, S. H. (2005). US military unmanned aerial vehicle mishaps: assessment of the role of human factors using HFACS. 311th Performance Enhancement Directorate, US Air Force, Brooks AFB, TX.

    Classification: HFACS

    Recommendations:

    - Evaluate and optimize UAV operator selection and training criteria (R1)
    - Evaluate and optimize the control station with regard to basic human-systems integration principles (R5,R6,R10)
    - Improve technical publications, checklists, and initial operator training programs to include a specific curriculum emphasis on crew resource management (R3,R4)
    - Improve job and workstation design (R7,R10)
    - Assess manpower requirements (R7)
    - Develop empirically-based training programs and formal procedures and guidance (R4)
    - Address failures in organizational culture, management, and acquisition processes (R8)
    - Utilize simulation systems for crew training, especially for challenging, off-nominal situations (R3)

9. Yildiz, S., & Oncu, M. (2014). An analysis of human causal factors in Unmanned Aerial Vehicle (UAV) accidents (Doctoral dissertation, Monterey, California: Naval Postgraduate School).

    Classification: HFACS

    Recommendations: No recommendations provided

10. Rash, C. E., LeDuc, P. A., & Manning, S. D. (2006). Human factors in US military unmanned aerial vehicle accidents. Human Factors of Remotely Operated Vehicles, 7, 117-131.

    Classification:

    - HFACS
    - Army accident investigation and reporting (Department of the Army Pamphlet 385-40)

    Recommendations: no recommendations provided

11. Taranto, M. T. (2013). A human factors analysis of USAF remotely piloted aircraft mishaps (Master's thesis, Monterey, California: Naval Postgraduate School).

Classification: HFACS

Recommendations: no recommendations provided

Department of the Army Pamphlet 385-40

http://www.campbell.army.mil/Installation/Documents/DA%20PAM%20385-40%20Army%20Accident%20Investigations%20and%20Reporting.pdf

What happened?	Why did it happen?	Potential Recommendations
Human mistake/error	Individual failure	R7,R8
	Leader failure	R7,R8
Material failure	Training failure	R3,R4
	Standards failure	R4,R7,R8
Environmental factor	Support failure	R1,R3,R5,R6