Report for
80NSSC20M0261

Unmanned Aerial Systems Research for Public Safety Applications

Task 8: Minimum Display Requirements for UAS Operators Flying BVLOS

Final Report

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The FAA's Center of Excellence for UAS Research
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Alliance for System Safety of UAS through Research Excellence

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03/31/2025

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Table of Acronyms

AC	Advisory Circular
ADS-B	Automatic Dependent Surveillance-Broadcast
APF	Artificial Potential Field
AR	Augmented Reality
ATC	Air Traffic Control
BVLOS	Beyond Visual Line-of-Sight
CFR	Code of Federal Regulations
DAA	Detect-and-Avoid
DAIDALUS	Detect and Avoid Altering Logic for Unmanned Systems
FAA	Federal Aviation Administration
FIMS	Flight Information Management System
GCS	Ground Control Station
GIS	Geographic Information System
HITL	Human-in-the-Loop*
HMI	Human Machine Interface
LAANC	Low Altitude Authorization and Notification Capability
NAS	National Airspace System
NASA-TLX	NASA Task Load Index
NOTAMS	Notices to Air Missions
RFRL	Raspet Flight Research Laboratory
SA	Situational Awareness
SAGAT	Situation Awareness Global Assessment Technique
ScBT	Scenario Based Training
SOAR	Simulated Operations for Aerial Research
UAS	Unmanned Aircraft System
UI	User Interface
USS	UAS Service Supplier
UTM	Uncrewed Traffic Management
UX	User Experience
VTOL	Vertical Take-off-and-Landing

Executive Summary

USRA Task 8: Minimum Display Requirements for UAS Operators Flying Beyond Visual Line-of-Sight

The integration of Unmanned Aircraft Systems (UAS) into the National Airspace System presents significant opportunities for public safety, commercial applications, and governmental operations. However, Beyond Visual Line-of-Sight (BVLOS) operations—where pilots rely entirely on Ground Control Station (GCS) displays—face a critical challenge: the lack of standardized display requirements. This research addresses this gap by establishing minimum display requirements necessary for safe and efficient BVLOS operations.

Current GCS platforms vary significantly in design and functionality, with some incorporating advanced features like multi-sensor data fusion and predictive trajectory indicators, while others rely on basic telemetry. This inconsistency creates variability in operator performance and safety outcomes. The research performed in this task identified critical display requirements across key operational areas and developed a roadmap for validating these requirements through Human-in-the-Loop (HITL) testing.

Analysis Approach

The comprehensive analysis included:

1. A technical survey of existing GCS platforms to identify common features, innovative capabilities, and critical gaps
2. Development of evidence-based display requirements for traffic alerts, contingency management, weather information, and airspace constraints
3. Integration of human factors considerations to optimize situational awareness and reduce cognitive workload
4. Creation of a structured HITL testing methodology to validate display requirements under controlled conditions

Key Findings

The research established minimum display requirements in four critical areas:

1. **Traffic and Alert Displays**: Must provide timely alerting, comprehensive data presentation, intuitive maneuver guidance, and recovery capabilities to support operators in maintaining safe separation.
2. **Contingency Management**: Displays should prioritize system reliability, sensor fusion, and real-time processing to enable effective handling of emergencies such as system failures or communication loss.
3. **Weather Information**: Interfaces must integrate real-time meteorological data with clear visualizations to support flight planning and execution in varying atmospheric conditions.
4. **Airspace and Ground Constraints**: Displays should incorporate advanced mapping tools, regulatory compliance features, and automated deconfliction capabilities to enhance situational awareness.

Human factors analysis revealed that effective displays must prioritize critical information, reduce cognitive workload, and enhance situational awareness through intuitive visualizations and adaptive interfaces.

Recommendations

Based on our findings, we recommend:

1. **Execute the HITL Testing Roadmap**: Validate the proposed display requirements through simulation-based testing using the methodology outlined in this research.
2. **Develop a Reference Implementation**: Create a benchmark GCS display application validated through extensive HITL testing that could serve as an industry standard without mandating standardization.
3. **Establish Collaborative Standards**: Work with industry stakeholders, standards organizations (ASTM, RTCA), and regulatory bodies (Federal Aviation Administration (FAA)) to create a comprehensive framework for GCS display design.
4. **Adopt an Iterative Development Process**: Implement a formal User Interface (UI)/User Experience (UX) development process with continuous HITL testing to refine display requirements based on operator performance data.

This approach could significantly enhance operational safety, reduce development costs for manufacturers, decrease training requirements for operators, and provide regulators with evidence-based certification standards—ultimately facilitating the safe integration of UAS into the National Airspace System (NAS).

1 Introduction

The evolution of Uncrewed Aircraft Systems (UAS) has transformed the aviation industry, enabling a diverse range of applications across both civil and commercial purposes. UAS have demonstrated a wide range of use cases across various fields, such as commercial photography and videography, cargo transportation, disaster response, package delivery, and infrastructure monitoring. The ability to operate in hazardous environments that are inaccessible to crewed aircraft has made them a critical asset in both civilian and governmental contexts. However, as UAS operations continue to expand in scope and complexity, particularly in Beyond Visual Line-of-Sight (BVLOS) operations, there is a need for new guidelines and regulations to support the safe and effective integration of UAS into the National Airspace System (NAS) [1].

BVLOS operations, where pilots rely entirely on the Ground Control Station (GCS) displays and Detect-and-Avoid (DAA) systems to maintain situational awareness, represent one of the more complex and high-risk aspects of UAS deployment. Unlike Visual Line-of-Sight operations, where pilots can directly observe the aircraft and its surroundings, BVLOS operations require advanced technologies to provide real-time telemetry, traffic alerts, and environmental data. These technologies must replicate the situational awareness of a pilot in an aircraft and account for the unique challenges of remote operation. The reliance on GCS displays as the primary interface between the operator and the UAS underscores the critical importance of effective display design in ensuring operational safety and mission success.

Background

The Federal Aviation Administration (FAA) and other regulatory bodies have established a framework of rules and standards to govern UAS operations. Title 14 of the Code of Federal Regulations (CFR), Section 91.113, mandates that all aircraft operators, including UAS pilots, must “see and avoid other aircraft” to maintain “well clear” [2]. While these regulations are well-established for crewed aviation, they pose significant challenges for UAS operators in BVLOS scenarios where direct visual observation is not possible. This requirement can be fulfilled through DAA systems, which provide the necessary information to detect potential conflicts and execute avoidance maneuvers. The rapid evolution of UAS technology and the diverse applications have outpaced the development of GCS user interfaces (UI) and supporting regulations. This has led to a wide variety of GCS display designs, each with differing levels of functionality, usability, and safety considerations.

Existing GCS platforms vary significantly in their capabilities, user interfaces, and methods of presenting information, leading to inconsistencies in operator performance and safety outcomes. For instance, some systems prioritize real-time telemetry and traffic visualization, while others focus on mission planning or data analysis. This lack of standardization creates significant variability in how operators perceive and respond to critical situations, particularly in BVLOS operations where situational awareness is entirely dependent on the information presented on the

GCS display. The absence of standardized display requirements increases the risk of operational errors and the barriers to the broader adoption of BVLOS capabilities.

The Need for Standardized Display Requirements

The FAA's Advisory Circular AC 25.1322-1 emphasizes the importance of effective alerting systems, recommending standardized color schemes, sensory redundancy, and clear prioritization of alerts to support timely and accurate decision-making [3]. These guidelines are critical for ensuring that operators can quickly and accurately interpret alerts, particularly in high-stress or time-sensitive situations. Similarly, ASTM International has developed standards such as ASTM F3442/F3442M-23 [4], which outlines the minimum performance requirements for DAA systems in UAS operations. These standards emphasize the integration of real-time traffic alerts, conflict resolution advisories, and airspace monitoring capabilities within GCS displays. While these guidelines provide a foundation for DAA system design, they do not fully address the unique human factors challenges associated with remote UAS operations.

For example, research by Friedman-Berg et al. [5] demonstrated that the inclusion of predictive elements, such as vector lines indicating the future positions of intruder aircraft, significantly improved operator performance in DAA tasks. Despite these findings, many existing GCS platforms lack these advanced features, relying instead on basic position and direction indicators that provide limited situational awareness. This inconsistency in display design has led to incidents where inadequate information presentation contributed to safety risks, highlighting the need for more uniform standards across GCS platforms.

Human Factors and Display Design Challenges

The design of GCS displays plays a crucial role in ensuring the safety and efficiency of BVLOS operations, as UAS operators rely on the GCS to maintain situational awareness and make critical decisions. This reliance places a significant cognitive burden on operators, particularly in complex or high-traffic environments. Research has shown that poorly designed interfaces can increase cognitive workload, reduce situational awareness, and delay response times, all of which can compromise safety in BVLOS operations.

For example, a study by Vu et al. [6] highlighted the importance of clear and intuitive visualizations in supporting operator performance. The study found that advanced display features, such as color-coded alerts and predictive trajectory indicators, significantly reduced response times and improved decision-making accuracy. Similarly, Fern et al. [7] emphasized the need for integrated displays that combine traffic information, alerting systems, and resolution guidance into a single, cohesive interface. Despite these findings, many existing GCS platforms fail to incorporate these advanced features, resulting in suboptimal performance and increased safety risks.

The lack of consensus on minimum information requirements and display configurations further exacerbates these challenges. While some GCS platforms include advanced features such as predictive trajectory indicators and conflict resolution advisories, others provide only basic position and direction information. This variability not only affects operator performance but also complicates efforts to establish standardized training and certification programs for UAS pilots. Without clear and consistent display requirements, operators may struggle to adapt to different systems, increasing the likelihood of errors and accidents.

Research Objectives

Despite advancements in UAS technology and the increasing prevalence of BVLOS operations, significant gaps remain in the standardization and implementation of GCS display requirements. Existing research emphasizes the importance of displays that present critical information clearly and intuitively—such as intruder aircraft location, alert status, and resolution guidance. However, there is limited consensus on the minimum information requirements, optimal design principles, and human factors considerations specifically tailored for BVLOS displays.

This research addresses these gaps by systematically identifying the minimum display requirements for UAS operators flying BVLOS missions. The primary goal is to establish evidence-based guidelines that enhance situational awareness, reduce cognitive workload, and support timely and adequate decision-making in safety-critical situations. The scope of this research includes:

1. *Surveying Existing UAS Displays:* A comprehensive overview of current GCS platforms, including both open-source and commercial systems, to identify common features, innovative capabilities, and critical gaps in display design.
2. *Defining Display Requirements for Traffic and Alerts:* Developing requirements for presenting critical information such as intruder locations, alert status, and resolution guidance to support DAA tasks.
3. *Developing Contingency Management Display Requirements:* Identifying the information and interface elements necessary to support operators during emergency scenarios, such as system failures or loss of communication.
4. *Determining Weather Information Display Requirements:* An analysis of the necessary weather data and presentation formats to ensure safe BVLOS operations, considering factors such as wind, visibility, and atmospheric threats.
5. *Establishing Airspace and Ground Constraint Display Requirements:* A review of display elements that support compliance with airspace regulations and ground-based restrictions.
6. *Addressing Display Modes and Transitions:* Evaluating the requirements for different display modes, including manual, semi-autonomous, and fully autonomous control, as well as transitions between operational states.

7. *Proposing a Human-in-the-Loop Testing Roadmap:* Outlining a methodology for validating the identified requirements through simulation-based testing and measuring operator workload.

This structured analysis aims to enhance operational safety, improve regulatory compliance, and support the broader integration of UAS into the NAS. By addressing the gaps in current design practices and aligning with regulatory standards, this research will contribute to the development of standardized display requirements that empower operators and ensure the safe and efficient execution of BVLOS missions.

2 Current State of UAS Operator Displays

The rapid growth of UAS technology has outpaced many of the user interfaces that support it, creating both opportunities and challenges for the design of modern GCS displays. Initially rooted in military applications, UAS operator displays have evolved significantly from basic command-line interfaces to sophisticated, multi-modal systems designed to optimize operator performance in increasingly complex environments. As BVLOS operations become more prevalent, the need for standardized GCS displays that effectively integrate diverse data streams, support situational awareness, and manage cognitive workload has become increasingly critical.

Advanced GCS displays must provide real-time telemetry, intuitive traffic visualization, and adaptive alerting systems to enhance safety and efficiency. However, inconsistencies in existing display designs create challenges for operators, particularly in high-risk BVLOS scenarios where situational awareness relies entirely on the information presented on the GCS. While various research efforts have explored human factors considerations and display effectiveness, a lack of consensus remains on standardized display requirements to ensure consistency in operator performance and decision-making.

This section examines the current state of UAS operator displays, analyzing both open-source and commercial GCS platforms to identify common functionalities, innovative features, and critical gaps. By studying how these systems address challenges such as data integration, situational awareness, and cognitive workload management, the findings aim to inform the development of standardized display requirements for modern UAS operations where safety, efficiency, and regulatory compliance are critical factors.

Survey of Existing UAS GCS Displays

The technical survey conducted in this task evaluates current UAS GCS displays to establish a comprehensive understanding of available capabilities, visualization techniques, and operational features relevant to BVLOS operations. The analysis utilized a combination of peer-reviewed research, manufacturer documentation, industry reports, and hands-on evaluation where possible. The objective of this survey was to identify both common capabilities that may represent industry standards and innovative features that could enhance DAA functionality.

It is important to note that this survey is not intended to endorse any specific GCS system. The systems included have not been fully vetted for regulatory compliance, and some may not be suitable for BVLOS or multi-UAS operations without additional modifications or integrations. Instead, this survey serves as a snapshot of the current technological landscape to inform future requirements development.

This survey looked for systems that provide capabilities potentially relevant to BVLOS operations, are commercially or publicly accessible, offer sufficient documentation to enable comprehensive evaluation, and represent diverse approaches to UAS control and visualization. Military-exclusive systems were generally excluded unless they offered civilian variants or technologies with direct civilian applications. It should be noted that this list is not exhaustive, and there are other available systems that are not identified through this survey.

Overview of Surveyed GCS Displays

The GCSs selected for this survey were chosen based on their relevance to UAS operations, available features, industry recognition, and availability of documentation. The selection process prioritized systems used across commercial and research applications. In general, these systems can be categorized into two main groups based on their development approach, target market, and typical use cases.

Open-source systems such as MAVProxy, Mission Planner, APM Planner 2, QGroundControl, and Paparazzi offer significant flexibility and customization capabilities. They typically support a wide range of hardware configurations and provide extensive opportunities for modification. These systems are predominantly utilized in research applications, hobbyist communities, and as development platforms for specialized commercial implementations. Commercial systems such as DJI FlightHub 2, Auterion Mission Control, DroneDeploy Flight App, UgCS, FlytBase, BRINC LiveOps, Lockheed Martin VCSi, Sky-Drones SmartAP, Autel Integrated Command System, and Kongsberg Geospatial IRIS GCS are designed for industrial and professional applications. These platforms serve various sectors, including infrastructure inspection, geological surveying, mapping, remote fleet operations, emergency response, and public safety.

Some systems, such as BRINC LiveOps, are specifically designed for first responders, while others, like Kongsberg Geospatial IRIS GCS, offer specialized BVLOS capabilities. Commercial systems typically feature refined user interfaces, strong integration with proprietary drone ecosystems, enhanced data management capabilities, and, in many cases, advanced situational awareness tools designed for complex operational environments. Many include specialized features tailored to specific industry verticals, emphasizing operational efficiency and safety in professional settings.

Comparative Analysis of UAS GCS Displays

To assess the capabilities of the surveyed GCS displays, a comparative analysis was conducted on visualization and display features and capabilities. The analysis identifies shared and unique functionalities across the surveyed GCS displays.

The goal was to identify shared functionalities across systems and highlight unique or innovative features that distinguish specific platforms. The findings inform the development of display requirements for UAS and DAA systems.

A structured evaluation was performed using a feature matrix, categorizing each GCS based on its approach to visualization, situational awareness, usability, and unique features. The feature matrix, shown in Figure 1, highlights the distribution of capabilities across various surveyed systems. A legend provided in Table 1. Feature Matrix Icon Legend explains the meaning behind the symbols used. Of the 15 UAS GCS reviewed, 10 are included in the table, with the remaining five omitted due to concerns about reliability, defense-specific applications, or insufficient publicly available data. This assessment facilitates a clearer understanding of which visualization elements are commonly implemented in existing GCS systems and which unique features can be leveraged to improve DAA functionality. Each display was evaluated based on the following criteria:

- *Platform* – Describes the platform(s) on which the system natively runs (Windows, Linux, macOS, web-based), excluding mobile applications.
- *Licensing* – Lists the software as open source, software with public source code that is available for modification and redistribution, or enterprise software with licenses available for purchase.
- *Multi-Drone Support* – Labels each GCS as capable of multi-UAS features, able to execute coordinated multi-UAS missions, or developed for control of a fleet of UAS.
- *Geospatial Mission Planning* – Describes 2D, 2.5D, or 3D capabilities of a GCS to perform satellite mapping, flight plan visualization, and geofencing visualization.
- *Payload Control & Data Integration* – Lists the capability to control and analyze data received from onboard payloads natively.
- *In-Flight Reprogramming* – Capabilities to change flight parameters during active missions.
- *Simultaneous Video Feeds* – Support for multiple live video feeds from a single or multiple simultaneously connected UAS.
- *ADS-B Integration* – Capabilities to receive and display Automatic Dependent Surveillance-Broadcast (ADS-B) data for real-time aircraft tracking.
- *Weather Data Integration* – Capabilities to receive, display, and utilize real-time meteorological data.
- *Regulatory Airspace Visualization* – Integrated graphical representation of controlled, restricted, and special-use airspace during flight planning or execution.
- *Primary Flight Display* – Availability of a Primary Flight Display instrument within the GCS.
- *3D Terrain Visualization* – Capabilities to create 3D representations of geographic areas using sensor data and overlay it within the GCS display.

	Mission Planner	QGroundControl	UgCS	DJI FlightHub 2	BRINC LiveOps	Auterion Mission Control	Sky-Drones SmartAP	Autel Integrated Command System	FlytBase	Kongsberg IRIS
Platform Compatibility	Windows	Windows, Linux, macOS	Windows, macOS	Web-Based	Web-Based	Windows, Linux, macOS	Windows, Linux, macOS	Windows	Web-Based	Windows, Linux
Licensing	Open Source	Open Source	$	$	$	$	$	$	$	$
Multi-UAV Support	Capable	Capable	Coordinated	Fleet	Fleet	Capable	Fleet	Coordinated	Fleet	Fleet
Geospatial Mission Planning	2D	3D	3D	2.5D	2D	2D	2D	2D	2D	3D
In-Flight Mission Reconfiguration	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Payload Control & Data Integration	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Simultaneous Video Feeds	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
ADS-B Integration	⚙	✓	✓	✓	✓	✓	✓	-	✓	✓
Weather Data Integration	⚙	⚙	-	✓	✓	-	-	✓	-	-
Regulatory Airspace Visualization	⚙	⚙	-	-	-	-	✓	-	✓	✓
Primary Flight Display	✓	✓	-	-	-	-	✓	-	✓	-
3D Terrain Visualization	-	-	✓	✓	✓	-	-	-	-	✓

Figure 1. Feature Matrix of Surveyed GCS Platforms

Table 1. Feature Matrix Icon Legend

Windows	Linux	macOS	Web-Based	Enterprise Software	Capable With Some Development
				$	⚙

Common Features Across GCS Displays

The GCS platforms surveyed reveal several core functionalities that appear to represent industry standards. These shared capabilities suggest cross-industry agreement on essential visualization and control requirements for effective UAS operation across diverse operational contexts.

Mission Planning and Navigation

Mission planning and waypoint navigation features are included across all surveyed systems. This universal implementation indicates the importance of pre-planned flight paths for operational effectiveness. Systems ranging from command-line interfaces in MAVProxy to sophisticated graphical tools in UgCS enable operators to define various mission parameters. Advanced implementations in platforms like QGroundControl and Mission Planner extend this functionality with geofencing capabilities and automated mission optimization algorithms that calculate efficient routes while considering environmental constraints, streamlining decision-making processes.

The sophistication of planning interfaces varies considerably, with significant differences in operator workload and mission complexity. Open-source systems typically implement functional but visually basic planning tools requiring greater operator expertise, while commercial platforms like Auterion Mission Control and UgCS offer intuitive drag-and-drop interfaces with real-time validation and optimization suggestions [8]. This variation in implementation suggests that while mission planning represents a standard requirement, the quality of planning tools significantly influences operational capabilities and safety margins, particularly for complex BVLOS missions.

Real-time Telemetry and Status Monitoring

All surveyed platforms implement comprehensive telemetry visualization and system status monitoring with varying degrees of sophistication and integration. This universal feature reflects the operational need to maintain continuous awareness of aircraft state, environmental conditions, and system performance. Mission Planner and QGroundControl present critical flight parameters through dedicated heads-up displays with attitude indicator overlays and digital parameter displays, while advanced systems like Kongsberg IRIS GCS integrate this information contextually within 3D visualization environments, as shown in Figure 2.

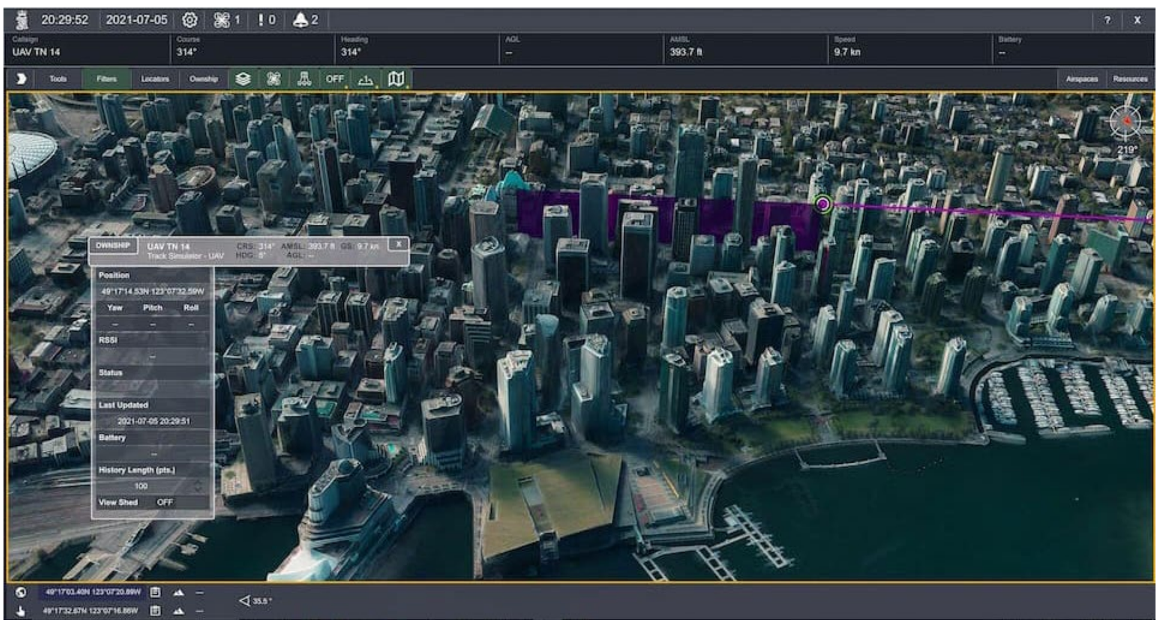

Figure 2. Kongsberg IRIS GCS Flight Monitoring Display [9].

The presentation of telemetry data directly influences an operator's situational awareness and cognitive workload, with significant implications for operational safety. Systems that implement integrated data visualization, where telemetry is contextually presented within spatial representations, demonstrate better human factors characteristics compared to those requiring operators to integrate information from separate displays mentally [7]. The surveyed enterprise systems typically implemented sophisticated alerting hierarchies with graduated warning levels and predictive indicators for parameters approaching critical thresholds. These warnings further enhance proactive risk management compared to simple binary alerting in less advanced systems [10].

Payload Control and Data Integration

Payload integration is present in all surveyed GCS, with enterprise-level systems demonstrating advanced sensor capabilities, while more general-purpose solutions rely on modular UI elements and telemetry overlays. QGroundControl and Mission Planner facilitate payload integration through MAVLink messaging, enabling operators to monitor and control camera gimbals, sensors, and other payloads through customizable telemetry panels [11]. DJI FlightHub 2 and BRINC LiveOps focus on real-time payload management, featuring LiDAR mapping, multiple video feeds, video streaming, and AI-assisted object detection [12], [13].

Higher levels of payload integration enhance situational awareness by allowing operators to interact with sensor data in a georeferenced context rather than relying solely on external telemetry readings. Across the surveyed systems, recently updated GCS are incorporating AI-enhanced payload processing, with enterprise platforms leveraging automation to reduce operator cognitive workload and enhance mission efficiency [7].

Dynamic Mission Adjustment and Operational Flexibility

Real-time mission adaptation capabilities were observed across all surveyed systems, allowing operators to modify flight parameters and waypoints during active missions. Dynamic adjustment provides flexibility during pre-planned missions that may require modifications based on updates to mission objectives or environmental information. Implementations in platforms like UgCS and Kongsberg IRIS GCS include predictive planning tools that suggest adjustments based on observed conditions and operational goals, reducing operator cognitive load during complex replanning tasks [7], [14], [15]. The consistent implementation of dynamic adjustment capabilities indicates recognition of operational unpredictability and the need for responsive control systems rather than rigid execution models.

Multi-UAS Management and Fleet Operations

The surveyed systems offer multi-UAS functionality, enabling simultaneous control and monitoring of multiple aircraft. The survey categorized each GCS into three groups, labeling a GCS as capable of multi-UAS features, able to execute coordinated multi-UAS missions, or developed for controlling a *fleet* of UAS. Systems like Mission Planner, Auterion Mission Control, and QGroundControl are multi-UAS capable but are not designed to operate complex multi-UAS missions [8], [16]. Autel Integrated Command and UgCS can handle more complicated missions, controlling several UAS simultaneously [14], [17]. Systems like Kongsberg IRIS GCS and BRINC LiveOps have been designed to control a large fleet of UAS, providing simultaneous active monitoring and control for each [15], [18]. The implementation of multi-UAS capabilities directly influences operational capacity, complexity, and display organization. Implementations often include maintenance tracking, UAS health monitoring, and live feeds from each UAS.

Cross-platform Compatibility and Deployment Flexibility

The GCS systems surveyed demonstrate an increasing emphasis on cross-platform compatibility. This ability improves platform flexibility and accessibility across diverse operational contexts.

QGroundControl, Auterion Mission Control, APM Planner 2, and Sky-Drones SmartAP all offer native support for Windows, macOS, and Linux operating systems, enabling users to utilize familiar devices and operating systems during missions. Cloud-based implementations, such as FlytBase, Autel Integrated Command, and DJI FlightHub 2, further extend this flexibility by enabling remote access and collaborative operations. The increasing emphasis on deployment flexibility suggests a recognition of diverse operational contexts that require adaptable control solutions rather than fixed infrastructure deployments.

Unique and Innovative Features of GCS Displays

Beyond standard functionalities, several GCS platforms implement distinctive capabilities that address specific operational challenges or enhance situational awareness. These innovative features suggest potential directions for future capability development across the industry.

Advanced Visualization for Enhanced Spatial Awareness

Several platforms implement sophisticated visualization techniques that enhance operator spatial awareness beyond the capabilities of a 2D map display. Examples of further dimensions include 2.5D and 3D representations, adding height and depth, respectively. These implementations provide further context for spatial representations, allowing operators to gain additional visual perspectives on mission objectives. Integration of 2.5D or 3D visualizations in addition to 2D visualizations can greatly enhance information processing and situational comprehension [19]. Advanced display capabilities are particularly valuable for BVLOS operations, where direct visual observation is not possible, and operators must rely entirely on system-provided situational information [20] versus Relative-Position Tasks. Kongsberg IRIS GCS provides fully immersive 3D environments that integrate real-time sensor data with terrain models and infrastructure representations, allowing operators to create and monitor mission plans in a lifelike visual environment.

DJI FlightHub 2 implements a 2.5D approach, as shown in Figure 3, combining elevation data with ortho-mosaic imagery to create terrain visualizations with depth while minimizing computational requirements. The integration of real-time sensor data within these visualizations creates comprehensive operational pictures that reduce the mental workload associated with information integration from disparate [7], [19].

Figure 3. DJI FlightHub 2, 2.5D Base Map and Mission Planning [12].

Detect-and-Avoid Integration for BVLOS Operations

Systems that display air traffic and/or offer avoidance guidance for encounters enhance safety and reduce pilot workload. DAA plays a significant role in enabling BVLOS operations, particularly in scenarios without visual observers or shielded operations. While external displays or separate applications meet current DAA regulations, integration into the GCS provides improved response times during in-flight encounters [20]. While many of the surveyed GCS offer ADS-B monitoring, only FlytBase and Kongsberg IRIS GCS combine this feature with active monitoring capabilities, integrating traffic visualization and conflict detection capabilities. FlytBase integrates third-party systems to provide airspace awareness, advisory, and alert messages to the operator, enabling rapid situation assessment and prioritization. Kongsberg IRIS GCS utilizes the Kongsberg IRIS Terminal to interpret sensor messages from the connected UAS. This capability creates traffic pictures capable of tracking thousands of objects simultaneously and displays them on a single UI [21].

Advanced traffic visualization techniques have a significant impact on operator comprehension and response effectiveness, with more advanced implementations using standardized symbology and graduated alerting hierarchies to enhance situation awareness. The sophisticated DAA implementations in platforms like Kongsberg IRIS GCS and FlytBase specifically address key safety requirements for BVLOS operations, representing critical enabling technologies for regulatory compliance and operational risk management.

Augmented Reality for Contextual Enhancement

Augmented Reality (AR) overlays aim to enhance situational awareness by integrating digital information directly within the GCS visual environment. This approach provides operators with unified operational pictures that offer new information sources or combine existing ones. BRINC LiveOps, shown in Figure 4, implements AR overlays in the UAS live video feed, providing mission-critical information, including building entry points, roadway identifications, and dispatch information.

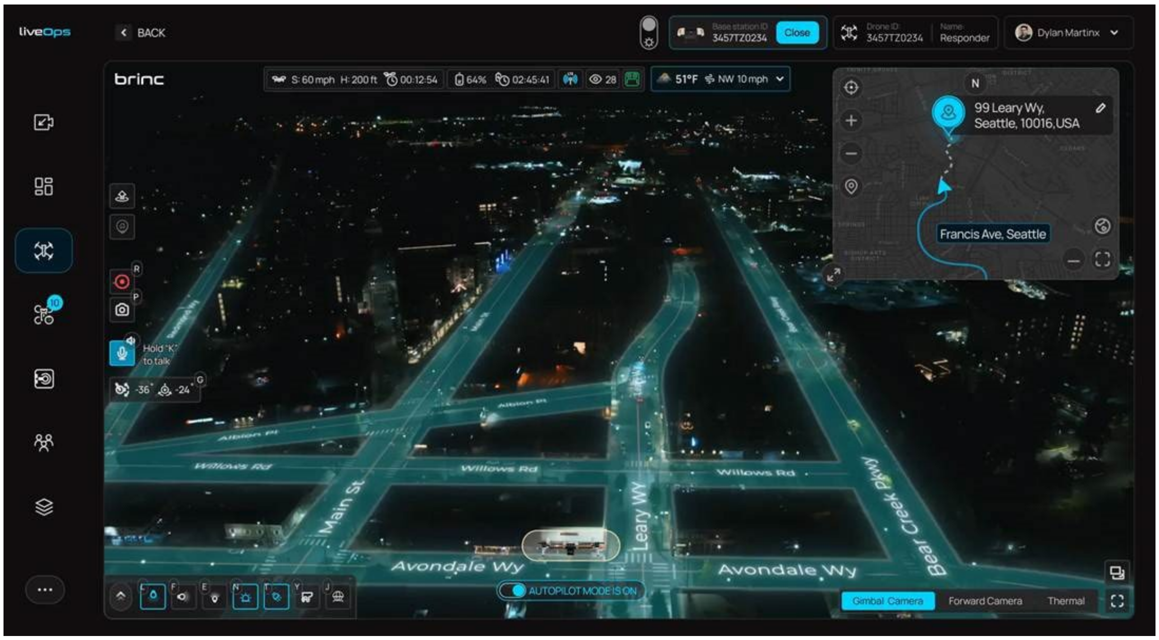

Figure 4. BRINC LiveOps Augmented Reality Street Mapping [13].

Environmental contextualization produced through the AR implementations direct visual associations between digital information and physical environments. While currently limited to specialized platforms, these capabilities suggest potential directions for broader implementation across GCS systems as the technology matures and computational constraints are addressed.

Multi-sensor Integration and Data Fusion

Advanced GCS platforms increasingly implement sophisticated approaches to multi-sensor data integration, transforming diverse data streams into valuable visualizations. UgCS, DJI FlightHub 2, BRINC LiveOps, Kongsberg IRIS GCS, and Lockheed Martin VCSi offer data fusion capabilities specializing in terrain visualization and mapping. Using onboard sensors, these GCSs use visual and LiDAR data to develop and visualize terrain in a 2D or 3D space. GCSs such as BRINC LiveOps offer additional features that allow users to produce 3D maps of indoor structures and evidence.

Additional sensor integration features include Lockheed Martin VCSi's flight prediction capabilities. Using onboard sensing and internal computing, VCSi predicts the future movements of the monitored UAS, including the likelihood of successful object or collision avoidance.

Multi-sensor fusion capabilities significantly enhance operational effectiveness by providing greater environmental awareness compared to the capabilities of individual sensors. Enterprise systems are placing an increased focus on these capabilities, particularly for complex mission scenarios or for BVLOS operations where direct observation is not possible.

Identification of Display Considerations for UAS GCS

Based on the analysis of existing ground control stations, research findings, and current DAA system standards such as F3442/F3442M-23, this section outlines key considerations for BVLOS operations with DAA capabilities [4]. These considerations are informed by a systematic evaluation of operational performance metrics, human factors research, and safety principles across multiple platform implementations.

Human Factors and Design Principles for UAS GCS Displays

Effective UAS GCS display design must strike a balance between operational functionality and human factors considerations to optimize usability while minimizing cognitive fatigue in UAS operators. BVLOS operations introduce unique challenges, necessitating display configurations that enhance an operator's ability to process critical information under time-sensitive conditions.

Information prioritization, ensuring that the most time-sensitive and critical alerts are presented in a manner that captures the operator's attention without introducing distractions, is a foundational principle of display design. Poorly organized and differentiated alert protocol has been shown to hinder timely responses to critical situations [22]. As such, effective GCS displays should employ graduated alerting strategies with standardized color coding, spatial grouping, and appropriate redundancy across sensor modalities (e.g., visual, auditory, or haptic, as needed) to improve operator recognition and response efficiency.

The integration of DAA displays into GCSs further enhances safety by allowing operators to preemptively address hazards rather than reactively responding to alerts. Algorithms such as NASA's Detect and Avoid Altering Logic for Unmanned Systems (DAIDALUS) can be embedded within GCS interfaces to provide real-time conflict detection, enhancing decision support in complex airspace environments [23].

Adaptive interface design is crucial for accommodating the varying complexities of different missions. GCS interfaces should allow operators to toggle between automation levels based on real-time task demands, enabling a seamless transition between highly automated and manual control modes [24]. This adaptability is particularly relevant for multi-UAS operations, where display architectures must efficiently scale to provide situational awareness for multiple aircraft without overwhelming the operator.

Standardized overlays and modular architecture are key considerations for display design. Allowing operators to utilize additional information sources, such as real-time weather data, air traffic information, and terrain mapping, within the primary GCS display reduces the need for operators to cross-reference multiple sources. Current modular frameworks, such as those employed in open-source platforms like PX4, facilitate the integration of third-party tools and the evolution of Beyond Visual Line-of-Sight requirements [25]. Extending module capabilities within current enterprise GCSs could significantly improve decision-making by providing a more comprehensive understanding of the operational environment.

Alignment with Current GCS Design Standards

The development of standardized display requirements for UAS GCS must align with existing regulatory frameworks to ensure safety, interoperability, and compliance with BVLOS operational constraints. One of the most relevant standards in this domain is ASTM F3442/F3442M-23, which outlines visual and operational requirements for DAA systems in UAS operations. This standard emphasizes the importance of integration of real-time traffic alerts, conflict resolution advisories, and airspace monitoring capabilities within GCS displays to support BVLOS safety objectives [4].

The FAA Advisory Circular AC 25.1322-1, which provides guidance on flight crew alerting systems, offers relevant insights into alert prioritization, sensory redundancy, and human-machine interface considerations. The advisory circular highlights best practices for visual and auditory alerting hierarchies, recommending the use of standardized color schemes (red for critical alerts, amber/yellow for cautions) and ensuring that warnings engage at least two sensory modalities to facilitate immediate recognition [3].

Despite these existing guidelines, gaps remain in defining UAS-specific GCS display requirements, particularly in areas such as dynamic airspace visualization, adaptive alerting systems, and contingency management support. While ASTM F3442 establishes minimum performance benchmarks for DAA functionalities, it does not fully address human factors considerations for GCS interface design [4]. Similarly, AC 25.1322-1, though applicable to crewed aircraft, does not explicitly account for the unique cognitive and operational challenges associated with remote UAS control [3]. Emerging research suggests the need for future standardization efforts that incorporate findings from systematic human factors evaluations. This includes refining alert differentiation criteria, establishing best practices for multi-UAS display architectures, and integrating predictive analytics for proactive risk management. Aligning GCS design with these standards will ensure that display configurations comply with regulatory requirements and enhance operator performance.

Functional and Performance Considerations for UAS GCS Displays

To support BVLOS operations efficiently, UAS GCS displays must adhere to functional and performance requirements that ensure reliability, usability, and operational effectiveness. These requirements span multiple dimensions, including readability, responsiveness, informational prioritization, and contingency management.

One of the most critical aspects of display functionality is real-time responsiveness and low latency within visualizations. GCS interfaces must provide immediate feedback on aircraft telemetry, sensor data, and airspace conditions to enable timely and precise decision-making. Latency in displaying critical alerts can significantly impair an operator’s ability to respond to conflicts, particularly in high-traffic airspace.

Adaptive alert prioritization ensures that high-urgency warnings take precedence over lower-priority notifications. In existing GCS platforms, unclear alert hierarchies are common, necessitating a more structured approach to categorization and differentiation [22].

Standardized overlays play a vital role in enhancing situational awareness by integrating multiple data layers, including real-time traffic visualization, terrain mapping, and weather conditions, into a cohesive display format. Systems like Kongsberg IRIS GCS demonstrate the capabilities of 3D views within UAS GCS, offering significant advantages in spatial awareness and understanding of terrain [19]. However, these views introduce spatial distortions that may hinder relative position judgments, such as distances or altitudes. Implementing toggleable interfaces that allow operators to switch between 2D and 3D perspectives may mitigate these limitations, enabling users to leverage the strengths of each view according to mission criteria.

Contingency management support is often overlooked in existing GCS systems. Although most systems provide manual, pre-flight contingency planning, the lack of real-time emergency landing zone mapping and guidance tools in most surveyed platforms presents a significant risk during system failures. Some progress has been made in addressing this issue; for example, as of 2018, QGroundControl introduced automated emergency replanning capabilities, setting a benchmark for other GCS platforms to follow [25]. However, this feature remains challenging to research and implement due to the complexity of integrating real-time terrain and environmental data. When present, such capabilities significantly enhance mission safety and resilience, providing operators with critical decision-making support during emergencies. Future GCS displays should integrate automated emergency landing site recommendations based on real-time terrain and environmental data, thereby enhancing mission resilience and operational safety.

Modular architecture and interface customization are essential for ensuring scalability and adaptability to a diverse range of mission requirements. The open-source platforms surveyed all incorporated modular architectures, enabling third-party integration and greater customization. This ability allows operators to alter the GCS display to match the mission context.

The survey of existing UAS operator displays revealed that while most current GCS software supports basic mission execution, there are notable gaps in meeting BVLOS-specific safety and situational awareness requirements. Limitations in dynamic airspace visualization, alert prioritization, and contingency management support underscore the need for establishing minimum display requirements and standards [24]. Addressing these gaps through clearly defined display requirements and standardized design principles is essential for improving operational safety and effectiveness in BVLOS UAS operations.

3 Display Requirements for Traffic and Alerts

Avoidance Technology Survey

Avoidance technology enables UAS operations beyond the pilots' line-of-sight. To ensure that the crew can consistently confirm the location of their aircraft, identify potential obstacles, and prevent danger, the technologies involved must meet high precision requirements. These requirements, along with the current BVLOS waiver process, make achieving widespread BVLOS usage challenging. In this section, the available avoidance technology is surveyed. Figure 5 presents a visual summary of the classification of existing avoidance technologies into two basic categories: Perception and Action. Since Perception and Action are necessary for collision avoidance, the chronological order in Figure 5 is from top to bottom.

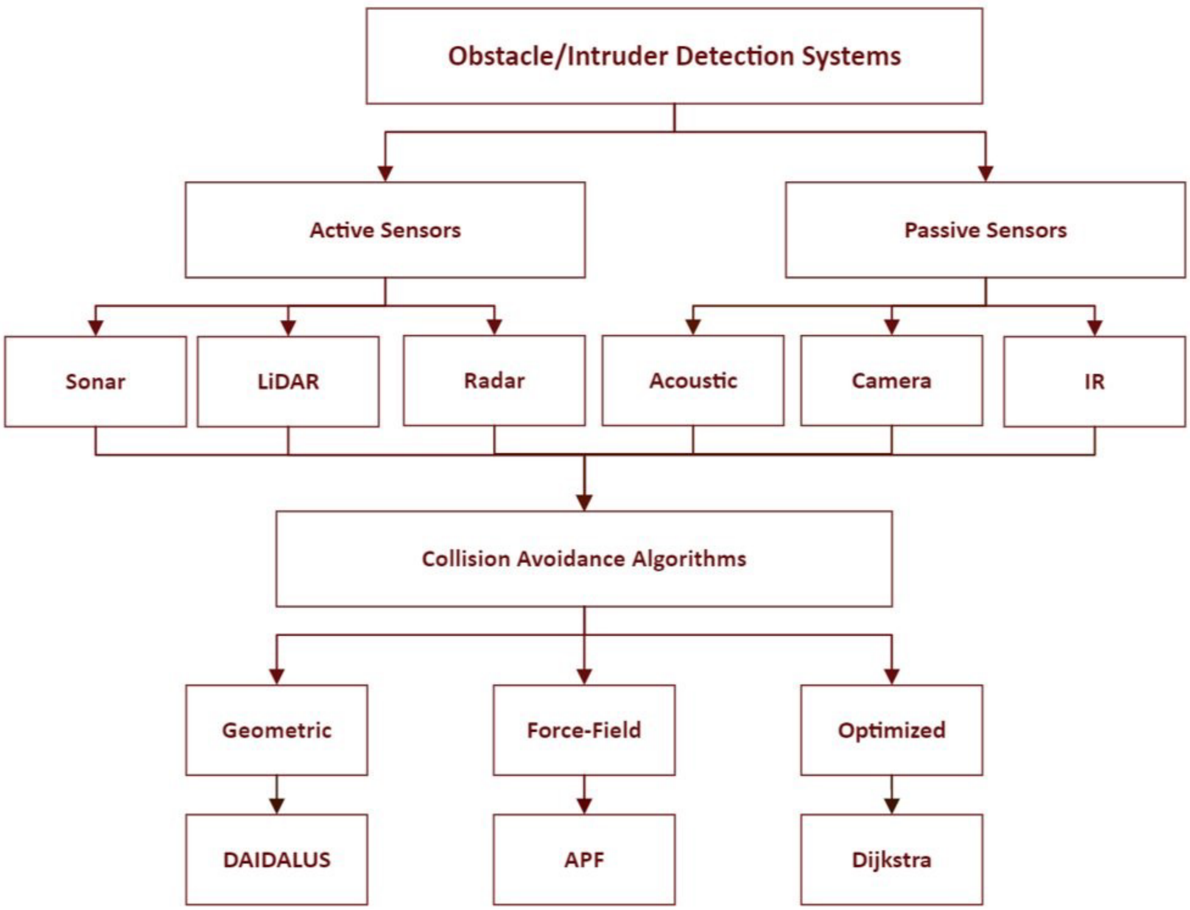

Figure 5. Summary of Collision Avoidance Systems.

Autonomous navigation of a UAS is based on two main aspects: obstacle/intruder detection and collision avoidance. Obstacle detection identifies obstacles and intruders with the help of sensors. There are two types of sensors: passive sensors and active sensors. A passive sensor measures the energy naturally available, such as a camera. The red, green, and blue spectral bands naturally come into the camera. Passive sensors that are commonly used in UAS navigation are optical/visual cameras, thermal/ infrared cameras, and acoustic sensors (see Table 1). An active sensor, on the other hand, sends a signal (energy) into the environment and receives the reflected signal from objects in the environment. For example, a radar sends a signal out to the environment, and the returning signal that is reflected from an object is used to generate a radar return image. Common active sensor types are Radar, LiDAR, and Sonar (see Table 2).

Table 2: Advantages and Disadvantages of Active Sensors

Passive Sensor	Advantages	Disadvantages
Optical/Visual Cameras	• Small and lightweight • Low power consumption • Flexible and easy to mount	• Weather-dependent • Sensitive to lighting and contrast
Thermal/ Infrared Cameras	• Operates in low-light conditions • No contact with components • High mobility	• Expensive • Requires expertise in data interpretation • Prone to image distortion

Table 3: Advantages and Disadvantages of Passive Sensors

Active Sensor	Advantages	Disadvantages
Radar	- Resistant to weather conditions - Detects object motion and speed - Wide range coverage - Operates in all lighting conditions - Penetrates insulators	- Cannot resolve multiple targets - Prone to signal interference - Oversensitive in some cases
LiDAR	- Fast and accurate data collection - Small and lightweight - Economical compared to radar - Detects small objects	- Ineffective in heavy rain or low clouds - Requires expertise to operate - Degraded by high sun angles
Sonar	- Low cost - Unaffected by object transparency	- Ineffective with sound-reflective surfaces

Table 4: Comparison Analysis of Perception Sensors

Sensor	Mode	Accuracy	Weather Condition	Light Sensitivity	Range	Sensor Size	Power Required
Radar	Active	High	Not dependent	No	Long	Large	High
LiDAR	Active	High	Low dependency	No	Medium	Small	Medium
Sonar	Active	Medium	Partial dependency	No	Short	Small	Medium
Acoustic	Passive	Medium	High dependency	No	Medium	Large	Low
Camera	Passive	Medium	High dependency	Yes	Short	Small	Low
Thermal/IR	Passive	Medium	High dependency	No	Medium	Small	Low

The second phase of UAS navigation is collision avoidance. Once sensors detect the intruder, they perform a situational awareness assessment about the presence of that intruder or obstacle. Data provided by sensors is known as collision avoidance factors. These factors are embedded in a cooperative flight algorithm through a GPS position reporting system. The role of this algorithm is to modify the flight path to avoid obstacles while maintaining the optimal path. Collision avoidance algorithms can be categorized into the following primary methods:

Geometric methods: Involve adjusting the positions of nodes to prevent collisions by utilizing both position and velocity data of the UAS and nearby obstacles. This approach typically includes simulating potential trajectories to ensure safe navigation. Geometric approaches rely on analyzing geometric attributes to ensure that the defined minimum distances between agents, e.g., UASs, are not breached. This is accomplished by computing the time to collision by utilizing the distances between the UASs and their velocities. An example of software that uses this type of algorithm is DAIDALUS. DAIDALUS consists of algorithms that utilize a parametric volume, referred to as the well-clear volume, such that aircraft pairs jointly occupying this volume are in a well-clear violation and provide maneuvers for the ownship to maintain or regain well-clear status [26].

Force-field methods: Also known as potential field methods, force-field methods use the pulsive or attractive force field either to repel UAS from an obstacle or to attract it toward a target. One of the standard force-field algorithms is the Artificial Potential Field (APF) [27]. The APF algorithm tackles the following scenarios:

- When the distance between the UAS and the obstacle exceeds the dangerous distance, the repulsion force is zero. Therefore, the robot is moved by the attraction to the target point.
- When the distance between the UAS and the obstacle is less than the safety distance, the repulsion force increases rapidly, and its direction is away from the obstacle.

Optimization-based methods: Aim to find the optimal or near-optimal solutions for path planning and motion characteristics based on geographical coordinates, taking into consideration the environmental conditions. An example of this is the Dijkstra algorithm, which creates a network [28]. Each node of the network is a position that it can UAS move towards in case an obstacle/intruder intervenes in its path.

Traffic and Alert Display Requirements

Enabling Beyond Visual Line-of-Sight operations for UAS is crucial for expanding public and commercial applications, yet it presents significant technical challenges for developers, operators, and regulators. A primary obstacle is that UAS pilots operating from a ground control station are unable to directly "see and avoid" other aircraft—a requirement under Title 14 CFR sections 91.111 and 91.113. This limitation necessitates the development of a dedicated system for BVLOS operations that can detect nearby traffic and display this information to the pilot, thereby supporting their ability to maintain the "DAA well clear" threshold. This capability, known as traffic avoidance, is critical for safe BVLOS operations. The resulting DAA system will be subject to a comprehensive set of requirements that manufacturers must meet to certify their equipment.

The design and evaluation of traffic and alert display systems have been extensively researched by organizations such as NASA Ames and guided by industry standards set forth by RTCA. In fact, studies supporting RTCA SC-228 Minimum Performance Standards and other academic investigations have provided invaluable insights into pilot performance during traffic avoidance scenarios [29]. These references emphasize two critical performance metrics: measured response times and the incidence and severity of losses of DAA well clear. Such metrics are essential, as pilots operate within a limited timeframe to effectively resolve potential conflicts. The resulting body of research underscores the need for displays that offer timely alerts, intuitive maneuver guidance, and seamless integration with ground control systems. The following detailed requirements have been derived to ensure that DAA displays meet these operational and safety objectives.

Timely Alerting and Response Support: The display must immediately and unambiguously signal the onset of a DAA alert [30].

- Alerts should be designed to quickly capture the pilot's attention, given the constrained timeframe dictated by operational rules, alerting thresholds, and encounter geometry.
- The system must clearly initiate the pilot-DAA interaction timeline—from alert issuance to the upload of the final resolution maneuver—ensuring that pilots have the necessary time to respond effectively.

Comprehensive Data Display: The display should continuously present all critical operational data [30].

- Essential information—including intruder locations, relative speeds, directional data, altitudes, and positional metrics—must be updated in real-time.
- The design should support both a broad situational overview and detailed data views, enabling pilots to accurately assess threat levels and make informed decisions.

Maneuver Guidance Functionality: The display must offer maneuver guidance to assist pilots in resolving the potential loss of well-clear scenarios [31].

- Guidance can be provided in various forms: informative (data only), suggestive (multiple maneuver options), or directive (a single recommended maneuver).
- Empirical studies have indicated that suggestive guidance—particularly through continuous "banding" displays—improves pilot performance by presenting multiple viable resolution options [30].
- The system should seamlessly integrate these guidance cues within the overall UI, ensuring clarity without overwhelming the pilot.

Integration with GCS Interfaces: The DAA display must be seamlessly integrated with existing GCS vehicle control interfaces [30].

- Integration should enable the automatic transfer of recommended maneuvers into the navigation interface, thereby minimizing the manual workload for pilots.
- This feature is critical for ensuring that directive guidance tools operate efficiently, allowing pilots to accept and execute maneuvers promptly.

Recovery Guidance Capability: In scenarios where a loss of DAA well clear becomes imminent, the display must provide additional recovery guidance [30].

- The recovery guidance should offer clear instructions for regaining safe separation, whether through horizontal or vertical maneuvers.
- Guidance should be delivered via both textual commands and intuitive graphical cues (such as directional arrows), ensuring pilots can quickly interpret and act on the information provided.
- This capability is vital during severe encounters where standard guidance may be insufficient to restore safe conditions.

Feedback and Performance Monitoring: The display system should facilitate the capture of performance metrics related to pilot responses [30].

- Metrics such as measured response times across different stages of the pilot-DAA timeline must be monitored to assess display effectiveness.
- The system should record the frequency, severity, and context of any losses of DAA well clear, enabling continuous refinement of display features and informing future design improvements.

- This feedback loop is essential to ensure the display remains aligned with evolving operational requirements and safety standards.

4 Contingency Management Display Requirements

To maintain a safe and dependable operation, contingencies of avoidance technologies for UAS should be properly examined. These are some crucial aspects to assess:

System Reliability

The avoidance technology must be highly dependable to prevent failures in all circumstances where prevention is feasible. To ensure the system's dependability, the system should be tested under diverse operating scenarios. Critical considerations of contingencies for system reliability for UASs would be:

Redundancy: Redundancy is one of the most crucial factors for system dependability. This means that if the primary avoidance system fails, backup measures should be in place. A backup sensor or numerous backup sensors should be available if the primary avoidance system only relies on a single sensor to ensure that the UAS can avoid obstacles even if one sensor fails. Redundancy can be incorporated at various system levels, including hardware, software, and communication [32], [33], [34].

Fail-safe mechanisms: are a different backup plan for system dependability. If the primary avoidance system fails, these procedures will take over and direct the UAS to safety. For instance, the fail-safe mechanism may activate and direct the UAS to a safe landing area if the UAS loses contact with the ground control station or the primary avoidance system malfunctions [32], [33], [34].

Constant monitoring and maintenance: It is critical to have a continuous monitoring and maintenance program in place to guarantee system dependability. The avoidance system and its parts must undergo routine testing, inspections, and maintenance. The reliability of a system can be increased by regularly calibrating sensors, upgrading software and firmware, and replacing worn-out or damaged parts [32], [33], [34].

Sensor Fusion

Sensor fusion combines data from various sensors, such as radar, lidar, and cameras, to increase the precision of obstacle monitoring and detection. This can help decrease false warnings and improve the efficiency of the avoidance system [32], [33].

Sensor diversity: Using multiple types of sensors is an essential safety measure for sensor fusion. Various sensors should be employed to provide different types of data, enhancing obstacle identification and tracking. For example, a UAS might combine lidar and radar sensors to provide precise distance measurements and identify obstacles under various weather and illumination conditions [32], [33]. Another example would be a set of cameras with various fields of view that can provide a more comprehensive view of the surroundings. This can aid in reducing blind spots and enhancing obstacle recognition and tracking in general [32], [33].

Sensor calibration: Sensor accuracy is critical for BVLOS operations. To guarantee that each sensor's data is precise and reliable, each one needs to be calibrated correctly. This is crucial for precise obstacle tracking and recognition and for cutting down on false alarms [32], [33].

Data integration: The sensor data should be merged in real-time to present a complete view of the UAS's environment. This can be accomplished via advanced data processing methods, such as sensor fusion algorithms, which pool the information from many sensors to enable more precise obstacle monitoring and detection [32], [33].

Tests and validation: To ensure the sensor fusion system is accurate and reliable, the system should be verified and tested under various operating scenarios. This includes its ability to detect and track obstacles in different conditions, such as varying lighting and weather [32], [33].

Real-Time Processing

To swiftly identify and react to obstacles, the avoidance system should be able to process sensor data in real-time. This is important for preventing crashes and other risky circumstances [32], [33].

Efficient computing resources: Real-time processing requires efficient computing resources to handle sensor data quickly and provide timely input to the UAS's control system. Instead of relying on full-scale high-performance computing systems, practical solutions such as optimized processors or specialized hardware like field-programmable gate arrays or graphics processing units (GPUs) can be employed. These systems are designed to balance performance and power consumption, making them suitable for UAS applications.

Task Prioritization: Prioritizing processing tasks is essential for real-time operations to ensure that the most critical functions are completed first. For example, obstacle recognition and tracking should take precedence over less time-sensitive tasks like data storage or image compression.

Algorithm optimization: Real-time processing demands practical algorithms that can quickly and adequately handle sensor data. The algorithms utilized for obstacle recognition and tracking should be improved to reduce processing time and increase accuracy.

System reliability: Backup and redundancy systems should be implemented to ensure the UAS can continue functioning if the primary processing system fails. However, instead of requiring multiple full-scale processing systems, lightweight backup systems or failover mechanisms can be used to maintain critical functions like obstacle detection and tracking. This approach minimizes the need for excessive hardware while ensuring reliability.

Testing and validation: To assure the correctness and dependability of real-time processing systems, they should be thoroughly tested and verified under various operating scenarios. To make the system handle sensor data reliably and promptly in all circumstances, this may entail testing the system in various settings, such as various lighting or weather conditions.

Human-Machine Interface

The system should have an intuitive user interface that enables the operator to swiftly check the status of the avoidance system and take appropriate action.

Design for usability: The human machine interface (HMI) needs to be simple to use and intuitive so that operators can rapidly comprehend and analyze the data the system provides. Considerations for the design include user experience, ergonomics, and learning facilitation.

Effective communication: The HMI should enable the operator and the UAS to communicate effectively. These can include tools that warn operators of impending obstructions or other problems, like clear and succinct displays, audio alerts, and haptic feedback.

Backup and redundancy mechanisms: These should be in place for HMI systems to ensure the UAS can still function even if the primary HMI system fails. For instance, in the event of a malfunction, the operator can be given crucial information using backup displays or sensors.

Integration with other systems: To provide a complete image of the UAS's environment, the HMI should be integrated with other systems, such as the obstacle detection and tracking system. This can guarantee that the operator gets all the information required to decide on the UAS's flight path and avoid obstacles in an informed manner.

Testing and validation: To guarantee the HMI's efficacy and dependability, it should be rigorously tested and validated under various operating situations. To ensure that the system can be utilized effectively and efficiently in all circumstances, it may entail testing with various operators and settings.

Environment

The avoidance system should function in various weather and environmental circumstances, such as rain, fog, and low light.

Weather conditions: The performance of UASs and the efficacy of avoidance technologies can be affected by weather conditions such as wind, rain, snow, and fog. UAS pilots should monitor the weather and modify their activities as necessary.

Terrain and topography: Both the performance of UASs and the capacity of avoidance technologies to identify obstacles are impacted by the terrain and topography of the operating environment. When preparing their operations and choosing avoidance technology, operators should consider the topography and terrain.

Wildlife and other natural dangers: Because they can endanger UASs, wildlife and other natural dangers, including trees, power lines, and waterways, must be taken into consideration by avoidance technology.

Civil Environment: Developed cities and towns can pose difficulties for UAS operations and avoidance techniques because of structures, busy streets, and crowded airspace.

5 Display Requirements for Weather Information

Evaluation of Weather Information Display Requirements: Regulatory Gaps and Limitations

The FAA has established comprehensive regulations to ensure the safe operation of UAS as their use expands in both commercial and recreational sectors. To facilitate the integration of small UAS (sUAS) into the NAS while maintaining safety, the FAA implements specific operational limitations outlined in 14 CFR Part 107 [35]. These regulations govern key aspects of sUAS operations, including the required distance between the operator and the aircraft, altitude limitations, and maximum ground speed. A summary of these critical operational restrictions is provided in Table 5.

The dynamic nature of aviation environments necessitates a more refined approach to operational safety. Weather, in particular, plays a critical role in the efficiency and safety of UAS operations. This section focuses on examining how the comprehensive presentation of weather data on the GCS can significantly enhance sUAS operational safety. By leveraging advanced weather information systems, operators can make more informed decisions, anticipate potential hazards, and maintain greater situational awareness throughout their missions. This aligns with the FAA's broader objectives for UAS integration and traffic management in the NAS.

Table 5: Operational Limitations for sUAS Adapted from the FAA Part 107 [35]

Regulation	**Limitation**
Max Weight (14 CFR 107.3 “Small unmanned aircraft”)	55-lbs
Max Groundspeed (14 CFR 107.51(a)	100 mph/87 Knots
Max Altitude (14 CFR 107.51(b))	400ft above ground level or within 400ft radius of a structure.
Max allowed distance from operator (14 CFR 107.31(a))	Must maintain a VLOS with vision unaided, except for the use of corrective lenses
Min weather visibility (14 CFR 107.51(c))	3 miles from operator
Allowed area of operation (14 CFR 107.41)	Class A: Prohibited Class B, C, D, and E: Air Traffic Controller (ATC) authorization needed Class G: No ATC authorization needed
Time restrictions	From Official sunrise to official sunset
Number of operators per sUAS	One operator per sUAS. Operator may use a visual observer

While the FAA proposes a minimum visibility, it does not address other weather conditions that may interfere with operations, such as high sustained winds, gusting winds, or winds aloft. The relatively small size of these aircraft make it difficult for them to operate and be controlled under strong wind conditions. The wind will also impact the relative ground speed, whether it be a headwind or a tailwind. The wind will impact range as well, as sUAS spend more battery life opposing wind direction.

In 2018, RTCA produced DO-367, a document outlining weather radar requirements primarily for larger UAS [36]. These requirements define standards in four main areas: weather and ground mapping radar, forward-looking wind shear detection, forward-looking turbulence detection, and atmospheric threat awareness. While these requirements were developed with larger UAS in mind, they provide valuable guidance that can be adapted for sUAS operations, particularly as technology advances and miniaturization continues to improve the feasibility of incorporating sophisticated weather detection capabilities in smaller platforms. An overview of these requirements can be seen in Table 6.

Table 6: RTCA Minimum Operational Performance Standards for Airborne Weather Radar [36]

Weather and Ground Mapping Radar	The airborne weather radar display should provide sufficient and clear information to inform the operators of weather conditions and allow for rapid interpretation. The position of a target should be displayed within 3 degrees of its true position, with zero pitch and roll. The data should be displayed with a minimum of 0.5 nautical miles or 15% of the minimum range selected by the user. At minimum, the reflectivity data should be updated twice every 20 seconds. The reflectivity data rage resolution should be at least 3 nautical miles or 5 percent of the displayed range. The azimuth coverage displayed should be at least 40 degrees of the longitudinal axis of the UAS. The display should provide range indicators.

Forward-Looking Windshear Detection	The azimuth coverage sector of the windshear detection mode should be at least 25 degrees in either direction of the longitudinal axis of the aircraft. For a threat within the azimuth coverage sector, A windshear warning should be issued at least 3378 feet.
Forward-Looking Turbulence Detection	A graphical output of 25 degrees on either side of the longitudinal axis of the aircraft or the aircraft track should display the radar-detected turbulence that presents a hazard to the aircraft.
Atmospheric Threat Awareness (Optional)	The system should have a graphical output indicating potential threats at 25 degrees on either side of the longitudinal axis or aircraft track. The range of the atmospheric threat awareness system should be sufficient to provide the operators with timely information.

While airborne weather radar systems, as specified by RTCA DO-367 [36], may be impractical for most current sUAS platforms due to size, weight, power, and cost constraints, the underlying requirements for weather information display remain relevant. For sUAS operations, particularly BVLOS, alternative approaches to obtaining this critical weather information include:

1. Ground-based weather radar networks (e.g., NEXRAD)
2. Satellite-based weather monitoring systems
3. Commercial weather data services
4. Localized weather stations and sensors
5. Atmospheric modeling and prediction services

These alternatives can provide comparable weather awareness without the need for onboard radar systems. The relative advantages and limitations of these approaches are summarized in Table 7.

Table 7: Comparison of Weather Information Sources for sUAS Operations

Weather Information Source	**Advantages**	**Limitations**	**Cost Considerations**
Ground-based radar networks	Wide coverage area, Established infrastructure, Regular updates	Limited resolution for microclimate detection, Update intervals may be too long for rapidly changing conditions	Lower cost, Often publi'cly available

Satellite-based systems	Global coverage, Multiple data parameters, Broader weather pattern visibility	Lower resolution, Latency issues, Limited low-altitude detail	Moderate to high cost for specialized data
Commercial weather services	Integrated data sources, Customized for aviation, API availability	Subscription required, Varying quality between providers	Recurring subscription costs
Local weather stations	Hyperlocal Data, Real-time updates, Custom deployable	Limited range, Requires maintenance, Network gaps	Initial setup costs, Ongoing maintenance
Atmospheric modeling	Predictive capabilities, Customizable to mission needs	Accuracy diminishes with forecast length, Computation intensive	Varies based on complexity and provider

BVLOS operations introduce an added complication with the necessity for extensive contingency planning, making it essential to have weather analysis capability for both the current flight path of the aircraft and the contingency or lost-link flight path. This capability would allow the UAS operators to be aware of whether the contingency flight path is feasible in the event of a lost-link scenario, allowing them the potential to switch the contingency flight path to a safer path.

Additionally, without first-hand visual observation of weather conditions like cloud cover or visibility, the DAA system may face limitations. Sensors such as LiDAR and RGB cameras depend on visibility and may not perform effectively in low-visibility conditions. Therefore, it is beneficial to establish display requirements that inform the flight crew when certain onboard sensors are compromised. This enables them to recognize when sensor performance is degraded and, if necessary, switch to a more suitable onboard scanning system to maintain situational awareness and prevent collisions.

Weather Information Display Requirements for BVLOS Operations

In BVLOS operations, accurate and timely weather information is critical for ensuring flight safety, operational efficiency, and regulatory compliance. Unlike traditional line-of-sight operations, BVLOS missions often cover long distances, traverse diverse weather conditions, and require real-time decision-making to mitigate environmental risks. Adverse weather, such as high winds, turbulence, precipitation, and low visibility, can significantly impact UAS performance, navigation, and mission success.

To address these challenges, BVLOS weather displays must provide comprehensive situational awareness by integrating real-time and predictive weather data, graphical overlays, automated alerts, and customizable settings. These displays should enable operators to assess weather risks, optimize flight paths, and respond proactively to changing conditions. Furthermore, compliance with regulatory standards ensures safe and efficient UAS operations.

The following outlines the minimum display requirements for weather information in BVLOS operations, detailing essential features, regulatory considerations, and best practices to enhance operational safety and effectiveness:

Real-Time and Predictive Weather Data: The display must provide real-time and forecasted weather conditions along the BVLOS flight path, including wind speed, turbulence, gusts, precipitation intensity, lightning activity, temperature, humidity, visibility, and cloud cover. To ensure accurate situational awareness, integration with ground-based weather stations, satellite feeds, and UAS-specific weather models is essential.

Graphical and Text-Based Representation: Weather data should be presented through graphical overlays on 3D flight maps, enabling operators to assess conditions quickly. Weather severity should be clearly indicated using standardized symbology and visualization techniques consistent with aviation standards [37], [38]. The display should incorporate standard aviation weather symbols and color conventions as used in aviation weather products by the National Weather Service's Aviation Weather Center. Additionally, text-based weather reports, such as Meteorological Aerodrome Report and Terminal Aerodrome Forecast, should be integrated for reference and validation.

*Multi-Range and High-Resolution Displa*y: The system should support multiple range settings for near-field, en-route, and destination weather monitoring. High-resolution, zoomable weather layers must be available to distinguish microclimate variations that could impact flight safety and operational efficiency.

Automated Alerts and Rerouting Recommendations: Real-time audio and visual alerts should notify operators of weather hazards that may affect BVLOS operations. Automated, weather-based rerouting suggestions must be incorporated to ensure safe mission execution by recommending alternate flight paths when adverse conditions arise.

Overlay Capabilities for Enhanced Situational Awareness: Weather data should be integrated with other operational layers, including flight paths, terrain data, airspace restrictions, and infrastructure coverage zones. This allows operators to assess wind effects over different terrains, comply with controlled airspace regulations, and optimize flight routes for specific BVLOS applications such as cargo delivery or infrastructure inspections.

Data Latency and Update Frequency: To maintain real-time accuracy, weather data should refresh every 30 seconds to 1 minute. The system should display the time of the last update to ensure operators are aware of data reliability and can make informed decisions accordingly.

Regulatory and Operational Compliance Consideration: Weather display systems must align with FAA BVLOS waiver requirements under Part 107 and Part 135, ensuring they meet the minimum standards for long-range UAS operations. While ASTM F38 UAS weather standards are an effective means of ensuring compliance with regulations, they are not the only method for achieving compliance. Integration with Unmanned Traffic Management (UTM) systems for real-time weather updates can also contribute to meeting regulatory requirements. Additionally, access to authoritative weather sources such as the National Oceanic and Atmospheric Administration and the National Weather Service must be incorporated, particularly for emergency response operations where rapid situational assessments are critical.

6 Airspace and Ground Constraint Requirements

Display Requirements for Airspace and Ground Constraint Management in UAS

The safe and efficient operation of UAS requires effective management of both airspace and ground constraints, which are critical to ensuring compliance with regulatory requirements and mitigating potential risks. UAS operate in a highly dynamic and complex environment, where airspace restrictions, no-fly zones, and ground conditions are subject to frequent changes. BVLOS flights operate in an even more complex environment due to the increased distances and the absence of direct visual monitoring of the UAS. These factors, coupled with evolving regulatory frameworks, present challenges for operators in maintaining situational awareness and adjusting flight paths as needed.

User display interfaces play a critical role in supporting BVLOS operations by providing operators with the comprehensive, up-to-date information needed to avoid collisions, stay within regulatory boundaries, and ensure compliance with operational restrictions. These displays need to integrate real-time data from various sources, including regulatory bodies, weather services, and traffic management systems, to ensure that operators can make informed decisions at all times, even when visual contact with the UAS is not possible. Key considerations for these display systems in BVLOS operations include:

Airspace Visualization:

- Real-Time Airspace Mapping: Displays should offer up-to-date representations of controlled and uncontrolled airspace, highlighting areas such as temporary flight restrictions, no-fly zones, and other regulated regions. This feature assists operators in planning and adjusting flight paths to avoid restricted areas [39].
- Integration with Regulatory Data: Incorporating data from regulatory bodies, such as the FAA, enhances situational awareness. For instance, UAS Facility Maps indicate maximum altitudes around airports where the FAA may authorize Part 107 UAS operations without additional safety analysis, aiding operators in understanding airspace limitations [40].

Ground Constraint Awareness:

- Geofencing Capabilities: Implementing geofencing within display systems prevents UAS from entering predefined restricted zones, such as critical infrastructure areas or sensitive locations, thereby ensuring compliance with operational boundaries.
- Real-Time Ground Data Integration: Incorporating real-time data on ground conditions, including weather updates and terrain information, allows operators to make informed decisions about flight planning and adjustments. This integration enhances safety by accounting for dynamic ground constraints.

Compliance with Operational Regulations:

- Altitude and Airspeed Monitoring: Displays should continuously present current altitude and airspeed metrics, ensuring operators adhere to legal limits. For example, under FAA Part 107 regulations, the maximum allowable altitude is 400 feet above ground level, and operations are prohibited over people not involved in the operation [40].

Human Factors Considerations:

- Intuitive UI: Designing displays with user-friendly interfaces reduces cognitive load, minimizes the risk of operator error, and enhances overall mission effectiveness. Human factors evaluations have highlighted the importance of UI design in UAS operations [41].

  Customizable Display Settings: Allowing operators to tailor display settings, such as data overlays and alert thresholds, ensures that critical information is prominently presented according to individual preferences and mission requirements [42].

Integration with Traffic Management Systems:

- Incorporating UTM data into display systems enables operators to receive real-time traffic alerts and airspace status updates, facilitating safe coordination with other UAS and manned aircraft. This integration supports dynamic flight planning and conflict resolution.

Compliance with Remote Identification (Remote ID) Requirements:

- With the implementation of Remote ID regulations, display systems should indicate the UAS's identification, location, and performance information. This feature enhances transparency and safety by allowing other airspace users to be aware of the UAS's presence and intentions [43].

Analysis of Key Platforms for Managing Airspace and Ground Constraints in UAS Operations

UAS operate in a complex environment where airspace regulations and ground constraints must be carefully managed to ensure safety, compliance, and operational efficiency. As UAS technology continues to evolve and the applications expand across various industries, the operational demands placed on these systems have increased. Advanced situational awareness and automated compliance tools have been developed by various groups to display real-time airspace mapping, environmental monitoring, automated flight planning, and regulatory compliance. This integration enables operators to manage UAS operations safely and efficiently, even in complex environments.

Below is a detailed analysis of key platforms—DJI FlightHub 2, ArcGIS, AirMatrix, AstraUTM, and UASidekick—that address airspace and ground constraint requirements. Various regulatory bodies such as the FAA and the International Civil Aviation Organization have implemented frameworks that define operational boundaries and risk assessment protocols. The following section examines how different management platforms currently integrate these requirements and support airspace deconfliction, mission planning, and monitoring processes.

DJI FlightHub 2

DJI FlightHub 2 is a cloud-based operations management platform for UAS. The platform includes sensor feed monitoring capabilities where multiple users can view flights. It features a mapping functionality that displays airspace constraints, including temporary flight restrictions and no-fly zones. The platform contains annotation functions where users can mark points and define corridors. It displays weather data and UAV health metrics. The system tracks UAV usage and maintenance information [12].

ArcGIS

ArcGIS, developed by Esri, is a geographic information system (GIS) platform for spatial data visualization and analysis. The system can render maps that include airspace classifications. It can incorporate data from various sources including regulatory and weather information. The platform has functions for spatial analysis that can be applied to identifying areas with specific characteristics. While primarily developed for GIS applications beyond aviation, the system contains capabilities applicable to displaying data relevant to UAS operations [44].

AirMatrix

AirMatrix is a web-based platform for low-level airspace display. The system shows regulated airspace, no-fly zones, and other constraint data. It connects with the FAA's Low Altitude Authorization and Notification Capability (LAANC) system for processing authorizations. The platform utilizes computational methods for operational functions and displays data for the altitude range of 0 to 1,500 feet. The system contains mapping functions and regulatory integration components applicable to airspace management [45], [46].

AstraUTM

AstraUTM is an Uncrewed Traffic Management (UTM) platform by Astra with UAS airspace integration capabilities. The system includes flight planning interfaces and displays data on airspace and traffic. The platform shows airspace limitations and no-fly zones for planning and during operations. It connects with the FAA's LAANC system for airspace authorization processing. The platform contains functionalities applicable to various operation types in different environments [45], [47].

UASidekick

UASidekick is available as both a web and mobile application focused on UAS operations and regulatory processes. The system displays weather data, flight planning tools, and drone management functions. It connects with the FAA's LAANC system for requesting airspace authorizations. The platform includes functions for submitting flight plans and Notices to Air Missions (NOTAMS). It contains features for accessing regulatory information and standardizing operational procedures [45], [48].

7 Display Modes and Transitions

UAS operate in complex and dynamic environments, requiring user interfaces to adapt to varying display modes to ensure safe operations. These display modes must provide operators with the necessary information to manage the UAS across different control modes, phases of flight, operational states, and conflict scenarios. This section outlines the requirements for UAS display modes, integrating insights from regulatory guidelines and research on human-machine interaction.

UAS Display Modes

UAS display requirements are designed to address specific mission needs and operational scenarios across a wide range of conditions. These requirements ensure that operators receive appropriate information based on how the UAS navigates and interacts with its environment. The goal is to provide intuitive, context-sensitive displays capable of supporting safe and efficient UAS operations regardless of the level of autonomy or control mode in use. Proper display design considers not only the UAS's current state but also external factors such as airspace management, conflict resolution, and system-to-system communications.

Autonomous Control Modes

In Waypoint Mode, the UAS autonomously follows a series of predefined waypoints. The interface must display the UAS's current position, the next waypoint, and overall progress along the route to help operators maintain situational awareness. This includes showing the estimated time and distance to the next waypoint, as well as any deviations from the planned path. Highlighting these deviations is critical for identifying potential issues, such as environmental factors or system malfunctions, that may require corrective action [40]. Waypoint Mode is particularly valuable for missions requiring precise navigation, such as mapping or surveillance, where operators need to monitor progress while allowing the system to handle detailed navigation tasks.

Point and Click Mode represents a hybrid approach that combines elements of autonomous operation with real-time operator guidance. Unlike predefined Waypoint Mode, Point and Click enables operators to designate new navigation points during flight by interacting directly with a map display. The interface must show the current UAS position, the operator-designated point, and the projected path between them. Display requirements include clear visualization of the commanded point, estimated time to reach the point, and system feedback confirming the UAS has acknowledged and accepted the new navigation command. This mode is particularly valuable for dynamic missions requiring adaptive navigation, such as evolving search operations or responding to moving targets, where predefined waypoints would be insufficient.

When operating in Altitude Hold Mode, the UAS maintains a specific altitude while allowing the operator to control other parameters, such as roll, pitch, and yaw. The interface needs to provide real-time telemetry data, including altitude, speed, and heading, along with mission status and progress. This information allows operators to focus on directional control while the system manages vertical positioning. Alerts and warnings must be prominently displayed to notify the operator of any deviations or system issues, enabling prompt identification and correction of problems such as altitude drift due to environmental factors [40].

Manual Control Modes

Manual control modes, such as joystick and throttle control, require the interface to provide real-time feedback on telemetry data to support precise operator input. These modes are essential in scenarios requiring detailed operator control, such as navigating through confined spaces or responding to emergency situations. The display must adjust to show appropriate control parameters and provide visual feedback that correlates with physical controller inputs. This tight coupling between operator actions and display feedback is crucial for maintaining precise control and effective decision-making, especially in time-sensitive situations where automated modes may not be appropriate.

Operator Interaction Levels

Operator control modes define the level of involvement required during UAS operations, each with specific interface requirements. During in-the-loop mode, operators maintain direct manual control over the UAS, typically using joystick or throttle inputs. The interface must prioritize critical information such as real-time video feeds, comprehensive telemetry data, and immediate alerts to support rapid decision-making. This high-engagement mode is typically employed in complex or high-risk scenarios where human judgment is essential, such as search-and-rescue missions that require adaptable responses to changing conditions [49].

When operating in on-the-loop mode, the operator supervises the mission while the UAS functions autonomously under autopilot control. The display should emphasize overall mission progress and system performance, with options for operator intervention clearly available. This supervisory role requires displays that summarize system status while highlighting exceptions or situations requiring human judgment. On-the-loop mode is commonly employed for routine operations such as agricultural surveys or infrastructure inspections where predictable flight patterns and sensor operations can be effectively automated [50].

In automated mode, the UAS operates independently with minimal operator involvement. Despite this autonomy, the interface must still display mission status, alerts, and warnings to maintain operator awareness of the UAS's performance. Emergency intervention options must remain accessible to allow the operator to assume control if needed. This mode supports long-duration missions or multi-UAS operations where continuous, direct control would be impractical, yet the display must maintain sufficient information flow to keep operators engaged and ready to respond when necessary [40].

Flight Phases and Display Requirements

UAS operations progress through distinct phases of flight, each requiring specific interface elements. During takeoff, displays must emphasize altitude, vertical speed, and immediate surroundings to support safe initial ascent. This critical phase needs a clear indication of system readiness and performance parameters to allow operators to abort if necessary. As the UAS transitions to the climb phase, the interface should highlight altitude progress toward cruise height, along with speed, heading, and estimated time to reach the target altitude. This information allows operators to monitor progress and adjust when environmental factors like headwinds affect climb performance [35].

During the cruise, the UAS travels at a relatively consistent altitude and speed toward waypoints. Displays during this phase emphasize navigation information, including distance to target waypoints and estimated arrival times, helping operators monitor progress and ensure the UAS remains on course for mission objectives [50]. As the UAS enters the descent phase, the interface returns focus to vertical navigation, showing altitude reduction rates and approach paths. Finally, during landing, displays must present detailed telemetry and landing progress information, enabling operators to monitor the descent and touchdown with sufficient detail to ensure safety during this high-risk phase [49].

UTM Operational States

UAS operations within UTM systems involve three main operational states that require distinct interface approaches. During pre-flight, the interface must support comprehensive planning and preparation by displaying the UAS's status and readiness, current weather conditions, airspace restrictions, and any regulatory constraints affecting the mission. This information is crucial for proper flight planning and risk assessment, allowing operators to make informed decisions about mission feasibility before launch. Effective pre-flight displays reduce operational risks by ensuring operators understand both system capabilities and external constraints.

The in-flight operation represents the core of UAS activity, during which the aircraft executes its mission while airborne. The interface during this state must provide comprehensive situational awareness through real-time telemetry, mission progress indicators, and alert systems. Critical parameters like altitude, speed, heading, and battery/fuel status need to always be clearly visible. This continuous information flow enables operators to maintain awareness of normal operations while quickly identifying abnormal situations requiring intervention, supporting both mission success and flight safety.

Post-flight analysis requires interfaces that summarize completed mission data and system performance. Displays during this operational state should present flight summaries, including performance metrics, anomalies encountered, and mission accomplishment status. The FAA requires UAS operators to maintain accurate flight records [40], and post-flight displays support this requirement while providing valuable feedback for improving future operations. By presenting comprehensive mission data after landing, these displays facilitate operational improvement through systematic review and analysis.

Special Display Scenarios

Conflict scenarios occur when a UAS encounters obstacles, other aircraft, or restricted airspace during flight. The interface must immediately alert operators to potential conflicts while providing essential details about the nature, location, and severity of the situation. Beyond simply identifying conflicts, displays must present resolution options appropriate to the UAS's capabilities and operator's authority level. After conflict resolution, the interface should transition back to normal operation displays while providing confirmation that the conflict has been successfully addressed. This transition helps operators reestablish situational awareness and continue the mission with minimal disruption [3].

Effective communication between UAS operators and with UAS Service Supplier / Flight Information Management System (USS/FIMS) requires dedicated interface elements. Messaging functionality should support both routine coordination and emergency communications, with incoming messages displayed prominently without obscuring critical flight information. Communication with USS/FIMS provides essential updates on airspace conditions, temporary flight restrictions, and other operational constraints that may affect ongoing missions. By integrating communication capabilities within the primary display system, operators can maintain coordination with other airspace users while focusing on their primary mission tasks [50].

8 Human-in-the-Loop Testing Roadmap

Human-in-the-loop (HITL) testing of GCS displays for BVLOS operations presents several key challenges. Safety is a primary concern, as evaluating novel display concepts in real-world flight environments can introduce unnecessary risks [51]. Controlling environmental variables, sensor clutter, and airspace management further complicates live testing scenarios. Cost considerations can also pose a significant barrier to the extensive flight testing required to systematically test and evaluate different UAS displays. Additionally, the needed resources to conduct repeated trials under varying operational conditions often exceed the capabilities of many research and development programs. These challenges underscore the need for controlled testing environments that mitigate operational risks while enabling rigorous evaluation.

Simulation-Based Testing

Simulation-based testing offers a solution to the challenges associated with validating UAS displays. By conducting HITL trials in a simulated environment, researchers can systematically assess display performance while controlling for extraneous variables and minimizing safety risks [51]. This approach allows for the manipulation of specific parameters to isolate the effects of display characteristics on operator performance. Simulation environments such as DAAMSim provide a structured framework for evaluating DAA system requirements, enabling the assessment of various sensor models, conflict prediction mechanisms, and human factors elements essential for system validation [52].

Simulation also enables the creation of repeatable test scenarios, allowing for the collection of consistent performance data across multiple subjects and trials. Standards such as ASTM F3442/F3442M-23 define performance thresholds for DAA systems and outline compliance verification methods, including simulation-based testing as a critical validation technique [4]. This repeatability enhances the reliability of the testing results and facilitates the identification of key performance drivers. Simulation platforms can also provide comprehensive data collection capabilities, enabling the automated capture of quantitative performance metrics in addition to subjective feedback.

Simulated Operations for Aerial Research Platform

Mississippi State University's Raspet Flight Research Laboratory (RFRL) has developed the Simulated Operations for Aerial Research (SOAR) platform to address the challenges associated with HITL testing of UAS displays. This open-source simulation environment provides researchers with a testing framework for evaluating various GCS and DAA displays that replicate real-world scenarios under controlled conditions to mitigate the safety risks, environmental variability, and cost constraints of live flight testing.

SOAR's architecture aligns with established DAA simulation frameworks like DAAMSim [52], incorporating interconnected modules for encounter design, sensor modeling, conflict prediction, and resolution. The platform enables systematic assessment of various display configurations, particularly focusing on information levels and presentation formats that have been shown to significantly impact pilot response metrics. Research by Fern et al. [7], [53], demonstrated that advanced information displays can result in faster pilot response times compared to basic displays when responding to traffic alerts, highlighting the importance of display design considerations in DAA systems.

SOAR was designed to adapt to different operational contexts and UAS configurations. The platform can accommodate various vehicle types, such as quadcopters, hexacopters, and both standard and Vertical Take-off-and-Landing (VTOL) fixed-wing vehicles across different airspace configurations and operational scenarios. This flexibility enables researchers to evaluate display effectiveness under conditions that closely approximate real-world operations while maintaining experimental control.

For HITL evaluations, SOAR enables the ability to measure pilot performance metrics across different display configurations. Previous research has established standardized metrics for evaluating pilot-DAA interaction through an eight-stage response timeline that captures detection, determination, and execution functions [7]. Similar evaluation approaches have been validated in other studies examining DAA display configurations and their effects on pilot performance, particularly in assessing how information presentation and display location impact pilot response times and decision-making capabilities. The platform includes a standalone RFRL-DAA application that integrates with the simulation environment to provide DAA functionality, including alerts and notifications for manual control interventions to maintain well-clear. This application serves as a foundation for future research and development that would implement all the requirements identified in this report and undergo rounds of HITL testing.

SOAR provides a standardized platform for assessing compliance with minimum DAA display requirements. This approach aligns with ASTM industry standards for DAA system performance [4]. Data can be extracted from this simulation with minimum software development to inform the development of industry standards and best practices. This approach aligns with the ongoing research and regulatory efforts on small UAS DAA requirements to ensure the safe integration of BVLOS UAS into the national airspace system [54].

Additional technical details regarding SOAR's implementation architecture, component technologies, and integration protocols are provided in Appendix A. This supplemental information includes specifications of the underlying simulation engines, communication mechanisms, and hardware requirements for researchers interested in implementing the platform for their HITL testing applications.

Proposed HITL Assessments

Experimental Design

Evaluating UAS displays through HITL simulation testing requires careful consideration of experimental design principles to ensure valid and reliable results. The selection of appropriate experimental design methods is crucial for generating meaningful data that can inform display requirements and safety standards for BVLOS operations. This section outlines four key methodological considerations for conducting rigorous HITL display evaluations: within-subjects design approach, counterbalancing strategies, sample size determination, and fatigue management.

Within-Subjects Design

Individual differences among pilots, including variations in expertise, decision-making styles, and risk tolerance, can introduce significant variability in experimental results. This variability may mask the true effects of display design changes and compromise the validity of research findings. To address this challenge, a within-subjects design approach is recommended, where each participant is exposed to all display variations [51].

This experimental method effectively minimizes the impact of individual differences by allowing direct comparisons of each pilot's performance across different display configurations, thereby isolating the effects of display changes from underlying participant variability [51]. This approach is particularly valuable when evaluating subtle differences between interface designs that might otherwise be obscured by between-subject variation [55].

Counterbalancing Strategies

Within-subjects designs need careful counterbalancing to control order effects, such as learning, fatigue, or adaptation, which can influence participant performance. The presentation order of test conditions must be systematically managed, so these effects are evenly distributed across all configurations being evaluated.

A fundamental challenge in counterbalancing is that the number of possible presentation orders increases factorially with the number of conditions. For example, testing five variations of a single independent variable would require 120 ($5! = 5 \times 4 \times 3 \times 2 \times 1$) unique presentation orders to achieve complete counterbalancing. When testing multiple independent variables simultaneously, this challenge becomes even more pronounced. For instance, with two independent variables each having five variations, the total number of conditions is $5 \times 5 = 25$, and complete counterbalancing would require $25! = 1.55 \times 10^{25}$ unique presentation orders. This exponential growth makes complete counterbalancing impractical for most human factors studies [56].

To address these limitations while maintaining experimental control, a Latin Square Design provides an efficient alternative. This design is commonly used in human factors research to counterbalance the orders of treatments across participants [56]. In a Latin Square Design, each variable's variation appears exactly once in each row and column of the design matrix. This method lets each participant encounter all the variations of both variables while controlling for order effects.

It is important to note that Latin Square Designs have limitations. This design assumes little to no interaction effects between the variables being tested and requires careful consideration when applied to complex multi-factorial experiments. Alternative approaches such as Balanced Incomplete Block Designs or Williams Designs may be considered for specific experimental requirements [57].

Figure 6 below illustrates a Latin Square Design for counterbalancing two independent variables (Variable #1 and Variable #2) across participants. Each participant (represented by a unique color) evaluates one row of the matrix, ensuring that all combinations of Variable #1 and Variable #2 are tested across the study. This design minimizes order effects and participant variability while requiring only five test cards per participant.

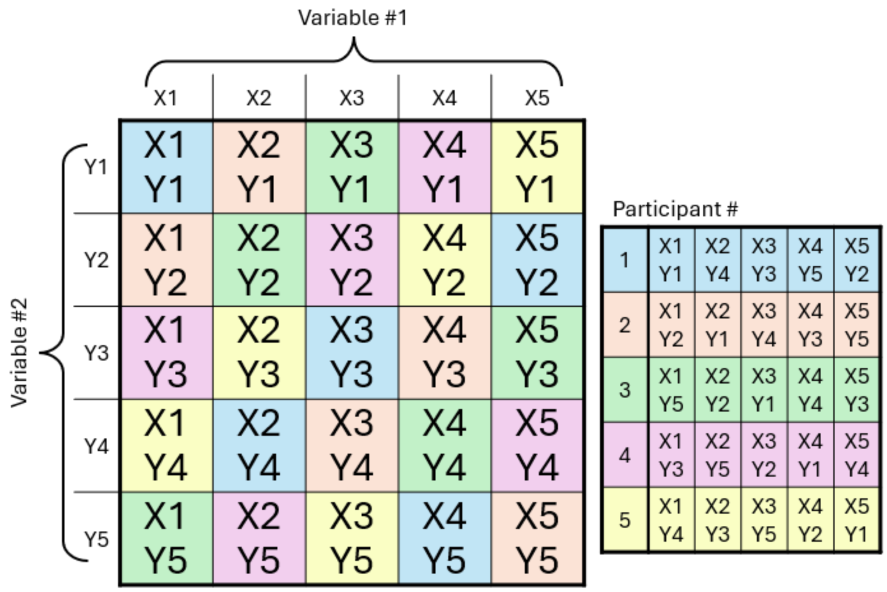

Figure 6. Latin Square Design for Counterbalancing Two Variables Across Participants.

In Figure 6, the rows represent the levels of Variable 2, and the columns represent the levels of Variable 1. Each cell in the matrix corresponds to a unique combination of the two variables, and the color coding indicates the participant assigned to that row. This ensures that each participant evaluates all five levels of Variable 1 and Variable 2 in a balanced and counterbalanced manner.

Randomization Protocol

Beyond the structural counterbalancing provided by the Latin Square Design, a randomization protocol is recommended as a standard experimental practice [58]. In this approach, the specific order of test conditions for each participant is randomized within the constraints of the Latin Square structure. For example, participant 1 might evaluate the conditions in the sequence:

$$X1 \rightarrow X2 \rightarrow X3 \rightarrow X4 \rightarrow X5$$

While another participant might evaluate them in the sequence:

$$X3 \rightarrow X5 \rightarrow X1 \rightarrow X4 \rightarrow X2$$

This randomization ensures that any potential learning or fatigue effects are evenly distributed across the study.

By combining the Latin Square Design with a randomized order of exposure, researchers are able to isolate the effects of display configurations on performance without confounding variables introduced by presentation order or participant variability.

Sample Size Considerations

Determining the appropriate sample size is essential for obtaining reliable and valid results in HITL evaluations. Insufficient sample sizes can lead to two types of statistical errors: identifying effects that are not truly present (Type I errors) or failing to detect meaningful differences between display configurations (Type II errors) [59]. Statistical power analysis provides a systematic method for calculating the minimum number of participants required to detect an effect with a specified level of confidence [59]. This process considers three key factors: the expected effect size, the significance level, and the desired statistical power [59].

The expected effect size refers to the magnitude of the difference anticipated between conditions. Larger effect sizes require fewer participants, while smaller effect sizes demand larger samples to achieve statistical significance [60]. Similarly, the degree of variation between display configurations significantly influences sample size requirements. For displays with substantial differences, as few as 3-5 participants may be sufficient to identify major effects. However, for displays with subtle differences, such as minor iconography changes, more participants and trials will be needed to determine statistically significant effects [61]. For example, Nielsen and Landauer [62] demonstrated that 5 to 10 participants per iteration are typically sufficient to uncover up to 85% of major usability issues in usability testing. This recommendation applies to both within-subjects and between-subjects designs, as it is based on problem discovery rates rather than comparative statistical analysis.

The significance level, typically set at 0.05, represents the probability of a false positive, or Type I error, where an effect is identified when none actually exists. A lower significance level (e.g., 0.01) reduces the likelihood of false positives but requires a larger sample size to maintain statistical power. Conversely, a higher significance level (e.g., 0.10) increases the risk of false positives but allows for smaller sample sizes. In HITL evaluations, the standard significance level of 0.05 strikes a balance between these trade-offs, ensuring that results are both reliable and practical to obtain [63].

The desired statistical power, usually set at 80% or higher, reflects the likelihood of correctly identifying a true effect, or avoiding a Type II error. Higher statistical power reduces the risk of failing to detect meaningful differences between conditions but requires larger sample sizes. For example, increasing power to 90% instead of 80% can significantly raise participant requirements, especially for small effect sizes. Statistical power is influenced by the effect size, sample size, and significance level, making it a critical factor in experimental design. In HITL evaluations, maintaining a power of at least 80% ensures that researchers can confidently detect true effects while keeping participant numbers manageable [60], [63].

Comparative evaluations, however, often require larger sample sizes. Sauro and Lewis [61] recommend 20-30 participants per group for between-subjects designs, where each participant experiences only one display configuration. This larger sample size accounts for individual differences between groups. Using within-subjects designs, where participants experience multiple configurations, with comparative display evaluations can reduce sample size requirements by 30-50% because each participant serves as their own control, minimizing variability [55]. For within-subjects' comparative evaluations, a sample size of 10-20 participants is typically sufficient, assuming moderate to high correlation between repeated measures. By carefully considering effect size, significance level, statistical power, and the degree of display variation, researchers can design experiments that reliably assess how display configurations influence operator performance while optimizing resources.

On the other hand, Sauro and Lewis [61] recommend that comparative display evaluations need a sample of 20-30 participants per group when each participant experiences only one display configuration. This larger sample size is necessary to account for individual differences between groups. Using within-subjects designs with comparative display evaluations can reduce the sample size by approximately 30-50% compared to between-subjects designs because each participant serves as their own control, thereby reducing data variability [55]. For comparative display evaluations using a within-subjects approach (as recommended in this framework), a sample size of approximately 10-20 participants will typically provide adequate statistical power, assuming moderate to high correlation between repeated measures.

This approach enables the experimental design to be both scientifically robust and feasible, allowing researchers to reliably determine how variations in display configurations influence operator performance while maximizing the efficiency of the testing process.

Managing Fatigue in Extended Testing Sessions

Extended testing sessions in complex operational environments can lead to participant fatigue, which may degrade performance and compromise the validity of research findings. Fatigue typically manifests as slower reaction times, reduced attention, and inconsistent performance, all of which can skew experimental results [64]. To address this challenge, a temporal design structure should be implemented. A temporal design structure is a methodical framework for organizing the timing, duration, and frequency of testing sessions to optimize data quality while minimizing fatigue effects.

HITL testing of UAS displays should limit each scenario to 5-10 minutes, which aligns with research on cognitive task duration and mental fatigue induction [65]. Systematic rest intervals should include 2-minute breaks between scenarios and 10–15-minute breaks after every 3-5 scenarios, consistent with findings that a 20-30 minute break improves test performance by approximately 1.7% of a standard deviation in cognitive assessment research [66]. Daily testing limits should not exceed 4 hours of testing per day, based on studies showing increased subjective fatigue and performance degradation in cognitive test sessions longer than 3.5 hours [67]. Session distribution should spread testing across multiple days rather than conducting all tests in a single extended session to prevent cumulative fatigue effects [66].

Circadian considerations should also be incorporated by scheduling complex tasks during periods of peak alertness to account for circadian rhythm effects, as research indicates cognitive performance declines by approximately 0.9% of a standard deviation for each hour later in the day [66].

Research consistently demonstrates that shorter, distributed testing sessions yield more reliable data than longer, continuous sessions. Studies on distributed practice in aviation tasks show that breaking evaluations into multiple shorter sessions significantly enhances performance and reduces cognitive strain [68]. These structured breaks allow participants to recover mentally and physically, maintaining consistent performance throughout the testing period [69]. By implementing these temporal design principles, researchers can ensure that observed performance differences are attributed to the experimental variables being tested rather than fatigue-related artifacts. This approach is particularly important in studies involving complex operational tasks, such as evaluating UAS displays, where sustained attention and decision-making are critical to performance outcomes.

Human Factors Metrics

Evaluating human-machine interfaces for UAS operations requires a structured, evidence-based approach to effectively measure operator performance across varying display configurations. This is particularly critical for BVLOS operations, where operators must rely entirely on display information to maintain situational awareness and make safety-critical decisions. This framework of human factors metrics provides the foundation for a systematic assessment of display effectiveness, allowing researchers to identify design elements that meet performance standards and those requiring improvement. This framework integrates multiple measurements—from quantitative performance indicators to qualitative cognitive assessments—enabling a holistic evaluation of how information presentation affects operator capability in complex operational environments. The metrics outlined in this section progress from fundamental performance measures (response times) through cognitive assessments (workload, situation awareness) to decision quality and error analysis. Each category provides complementary insights into different aspects of the human-machine interaction, collectively informing the development of the minimum operational performance standards for UAS displays. By applying this structured evaluation approach, designers and regulators can ensure that interface requirements are grounded in empirical evidence of operational effectiveness.

Response Time Metrics

Response time metrics serve as primary indicators of the efficiency and effectiveness of information acquisition from visual displays [70]. These measures quantify the speed with which operators detect, interpret, and respond to relevant information presented on the display. In the context of UAS operations, critical response time metrics include notification time, initial response time, initial edit time, total edit time, and total response time [53]. Notification time represents the duration between the onset of a potential conflict and the operator's initial awareness of the situation. This metric directly reflects the effectiveness of alert notifications in capturing operator attention during concurrent tasks. Initial response time captures the interval between conflict detection and the initiation of resolution action, providing insight into the clarity of information presentation and decision support features. Edit times reflect the duration of resolution input, highlighting the intuitiveness and efficiency of control interfaces. Total response time encompasses the entire process from detection to resolution execution, serving as a comprehensive measure of interface effectiveness in time-critical scenarios. Faster response times across these metrics generally indicate more efficient information processing and decision-making, providing a buffer of safety in time-critical situations [53].

When implementing response time measurements in HITL testing, careful consideration must be given to the operational context and task complexity. Response time benchmarks should be established based on realistic operational scenarios and safety margins, recognizing that the fastest response is not always the optimal one if it compromises decision quality or creates secondary conflicts.

Cognitive Workload Assessment

Cognitive workload assessment represents a critical dimension in display evaluation, as it directly impacts operator performance and situational awareness in UAS operations. Displays that present information in a clear, intuitive manner can significantly reduce mental workload, freeing attentional resources for other critical tasks and improving overall operational safety [71].

However, measuring cognitive workload poses significant challenges due to its multidimensional nature and the limitations of subjective assessment techniques. The operator's experience of workload encompasses multiple factors, including the complexity of information processing, time pressure, and the interaction between concurrent task demands.

The NASA Task Load Index (NASA-TLX) has emerged as a widely validated tool for quantifying operator workload across various domains, including aviation [72]. This multi-dimensional rating scale captures the relative contributions of six workload factors:

Mental demand: The level of cognitive activity required

Physical demand: The physical effort involved in task execution

Temporal demand: The time pressure experienced during operations

Performance: The operator's perception of task success

Effort: The work required to achieve the desired performance level

Frustration: The stress and irritation experienced during the task

By administering the NASA-TLX after each test scenario, researchers can gain valuable insights into the operator's subjective experience and identify display configurations that optimize workload management. These assessments can be complemented by performance-based workload measures, such as secondary task performance, which provides a more objective indicator of residual attentional capacity.

When implementing workload assessments in HITL simulation studies, consistency in measurement timing and administration is essential to ensure valid comparisons across display configurations. Baseline measurements should be established to account for individual differences in workload perception and management strategies. The relationship between workload levels and performance outcomes should be carefully analyzed to identify optimal workload ranges that balance engagement and overload for UAS operators.

Situational awareness (SA) is a critical determinant of operator performance in complex, dynamic systems like UAS [71]. Displays that effectively convey relevant information about the aircraft's state, environment, and potential threats can enhance operator SA, enabling proactive decision-making and risk management [51]. However, measuring SA is a complex challenge that requires a multi-faceted approach. Subjective measures, such as the Situation Awareness Rating Technique, provide insight into operators' perceived understanding of the situation but may be influenced by individual biases and meta-cognitive limitations. Objective measures, such as the Situation Awareness Global Assessment Technique (SAGAT), offer a more direct assessment of SA by comparing operators' perceptions to ground truth data at discrete points during a scenario [73].

In the SAGAT approach, the simulation is paused at random intervals and operators are asked to report their understanding of key situational elements without access to the displays. This technique enables researchers to identify gaps between the operator's mental model and the actual system state, providing a more direct measure of SA. However, SAGAT administration requires careful scenario design and timing to minimize disruption to the natural flow of the task. Combining subjective and objective SA measures can provide a comprehensive assessment of how display configurations impact operator understanding and projection of future states. Decision quality metrics offer additional insight into the effectiveness of display information in supporting optimal choices in complex situations. Displays that facilitate accurate threat assessment, prioritization, and resolution selection can significantly enhance safety margins in BVLOS operations. Key indicators of decision quality include the appropriateness of threat classifications, prioritization alignment with established guidelines, and the selection of resolution actions commensurate with the level of risk [74]. More nuanced measures, such as the efficiency of resolution maneuvers and the minimization of disruption to the overall mission plan, provide deeper insight into the quality of operator decisions.

Integrating decision quality metrics into the HITL test plan enables researchers to evaluate the impact of display configurations on higher-order cognitive functions. Extracting these metrics often requires a combination of manual scoring by subject matter experts and automated analysis of aircraft state data. Clear operational definitions and scoring rubrics are essential to ensure reliability and validity in decision quality assessment.

Error rate analysis complements response time and decision quality metrics by identifying potential pitfalls in display design and information presentation. Displays that effectively support error prevention, detection, and recovery can substantially mitigate risks in BVLOS operations. Error taxonomies developed for UAS operations provide a framework for categorizing and quantifying different error types, including display-related errors, procedural errors, and judgment errors [75].

The systematic analysis of error patterns across display configurations can reveal weaknesses in information presentation that contribute to operator mistakes. For example, a high frequency of data entry errors associated with a particular display element may indicate a need for improved interface design or data validation mechanisms. Examining the distribution of errors across different phases of flight and mission types can further inform display requirements by identifying high-risk areas that require additional support. Integrating error analysis into the HITL testing methodology enables researchers to identify and prioritize display improvements that enhance system safety and reliability.

In conclusion, the selection of human factors metrics for evaluating UAS displays should be driven by a comprehensive understanding of the cognitive demands and performance requirements of BVLOS operations. Response time, workload, situational awareness, decision quality, and error analysis provide complementary insights into the effectiveness of display configurations in supporting operator performance. Integrating subjective and objective measurement approaches can yield a more complete picture of human-machine interaction and inform the development of robust performance standards. By establishing a clear framework for human factors metric selection and prioritization, researchers can ensure that HITL simulation studies generate actionable insights that enhance the safety and efficiency of UAS operations.

Test Scenario Development

Developing effective test scenarios is crucial for assessing UAS display performance under operationally relevant conditions. Scenarios should be designed to replicate natural encounter geometries and realistic flight paths to the greatest extent possible [76]. This realism is essential for ensuring that the testing results are generalizable to real-world operations.

Scenario complexity should be carefully managed to avoid overwhelming participants while still providing sufficient challenge to evaluate display effectiveness. Factors such as the number of intruder aircraft, closure rates, and degrees of freedom in the encounter geometry can be manipulated to create scenarios of varying difficulty.

Balancing scenario realism with the need for experimental control is an important consideration in scenario design. While naturalistic encounters are desirable, the scenarios must also be structured to enable consistent data collection and analysis. Scripted encounters that follow predetermined trajectories can help maintain predictability and repeatability across trials.

The scenario development process should begin with a clear definition of the research objectives and the specific display features to be evaluated. Subject matter experts, such as experienced UAS pilots and human factors specialists, should be consulted to ensure that the scenarios are operationally relevant and appropriately challenging. Iterative refinement of the scenarios based on pilot testing and stakeholder feedback can help optimize their effectiveness [77].

Test Implementation Guidelines

Onboarding Procedure

Participant onboarding in HITL UAS display evaluations should follow a systematic and standardized process. This ensures consistent baseline competencies across all test pilots, which is critical for maintaining internal validity within the experimental design. A standardized onboarding approach is particularly important in within-subjects testing, where performance variations must be attributed to display configurations rather than inconsistent training exposures [55].

Initial Briefing and Documentation

The onboarding process should start with participants reviewing and signing an informed consent form. This form should clearly outline the experimental procedures, potential risks, and data handling protocols. After providing consent, participants should be asked to complete an anonymous demographic assessment. This assessment should collect information on relevant operational experience, including total flight hours, UAS operational experience, and specific experience with DAA systems. Documenting these background variables is essential, as previous HITL studies on UAS display configurations have shown that such factors significantly influence performance outcomes. Systematic documentation of these variables allows for appropriate statistical controls during analysis [53]. This ensures that observed performance differences are attributable to experimental conditions rather than participant variability.

Training Session

A structured 90-minute multimodal training session should form the foundation of the preparation process. This session alternates between informative instruction and hands-on practice, providing a balanced approach to learning. This method aligns with adult learning theory, which emphasizes the importance of combining theoretical knowledge with practical application for complex technical systems [78]. Additionally, research has shown that multimodal training enhances knowledge retention and skill transfer more effectively than unimodal methods, particularly in UAS operator training [79].

The training session should begin with slide show presentations that introduce participants to the experimental environment and its key components. These presentations should cover the following topics:

- *Alerting and Guidance Systems:* Participants should be briefed on the logic behind the alerting system, the parameters of the guidance algorithms, and the conventions used for display symbology. This includes an explanation of how alerts are generated, prioritized, and presented, as well as the meaning of various symbols and visual cues. These elements are critical for situational awareness and decision-making during UAS operations [80].
- *Simulator Interface and Features:* The presentation should provide an overview of the simulator interface, including the layout of key elements, the functionality of interactive features, and the levels of information that will be displayed. Participants should also be informed about which features and symbols will be available during the training and testing phases, as well as how these features may vary across different scenarios. This ensures participants are familiar with the tools at their disposal and can adapt to varying conditions [79].
- *Test Card Structure and Task Objectives:* Participants should be introduced to the structure of the test cards, which outline the specific tasks they will perform during the experiment. This includes a detailed explanation of task objectives, the operational context, and the

expected participant responses. For example, tasks may involve resolving conflicts, maintaining safe separation, or responding to alerts within a specified timeframe. Clearly defining these goals ensures participants understand the purpose of each task and how their performance will be evaluated.

- *Levels of Feature Availability:* Participants should be informed about the varying levels of features and symbology that will be displayed during the experiment. For instance, some scenarios may include full-featured displays with all available guidance and alerting tools, while others may simulate degraded conditions by limiting the information provided. This prepares participants to adapt their responses to different operational environments, a critical skill for UAS operators [81].

By covering these topics, the information provides participants with a clear understanding of the experimental environment, the tools they will use, and the tasks they are expected to perform. This foundational knowledge is essential for effective hands-on practice and successful task execution during the experiment.

Following each presentation segment, participants should engage in hands-on application exercises. These exercises are designed to reinforce specific competencies, such as interpreting alerts, executing initial response procedures, and resolving conflicts. Hands-on practice allows participants to apply the knowledge they have just acquired, bridging the gap between theoretical understanding and practical execution.

Scenario-based training (ScBT) is particularly effective in this context, as it immerses participants in realistic, task-specific environments. ScBT has been shown to accelerate the acquisition of expertise by simulating real-world conditions and requiring participants to exercise key knowledge, skills, and attitudes [51], [79]. For example, participants might practice responding to simulated airspace conflicts under varying levels of information availability, helping them develop adaptability and decision-making skills.

To ensure consistency and thoroughness, researchers should use a training evaluation checklist. This checklist should document participant progression through critical competency milestones, incorporating objective performance indicators for essential operational tasks. Standardized performance thresholds should be established to ensure all participants achieve a consistent baseline of operational capability before advancing to subsequent phases of training. This approach ensures that any observed performance differences during the experiment are attributable to the experimental conditions rather than variability in participant preparation. By alternating between informative instruction and applied practice, this structured multimodal training protocol ensures participants are well-prepared to operate within the experimental environment. Furthermore, the use of scenario-based training and standardized evaluation methods aligns with best practices for UAS training, as outlined in the literature [79], [81].

Full Practice Session

After completing the initial training block, participants should engage in a comprehensive practice session designed to integrate all elements of the simulation environment. This session provides an opportunity for participants to apply their training in a realistic and controlled setting, ensuring they are fully prepared for the experimental trials. The practice session should include the following components:

- *Background Traffic Scenarios:* Participants should navigate simulated airspace populated with background traffic to replicate real-world operational complexity. These scenarios should vary in density and complexity to expose participants to a range of conditions they may encounter during the experimental trials. ScBT has been shown to enhance situational awareness and decision-making by immersing participants in realistic environments [79].
- *Background Traffic Scenarios:* Participants should navigate simulated airspace populated with background traffic to replicate real-world operational complexity. These scenarios should vary in density and complexity to expose participants to a range of conditions they may encounter during the experimental trials. ScBT has been shown to enhance situational awareness and decision-making by immersing participants in realistic environments [79].
- *Task-Specific Exercises:* The session should include exercises that require participants to demonstrate proficiency in key operational tasks, such as interpreting alerts, executing conflict resolution maneuvers, and maintaining safe separation. These tasks should align with the key knowledge, skills, and attitudes identified as critical for UAS operations.
- *Daily Practice Sessions:* A practice session should be conducted at the start of each new testing day, regardless of whether the same UI or a different UI is being tested. This daily practice session serves to refresh participants' familiarity with the test environment and tasks, mitigating the effects of skill decay and ensuring a consistent baseline of performance across all testing days [82]. For days involving a change in UI, the practice session should focus on re-orienting participants to the new interface, highlighting its unique features and differences from previously tested UIs.
- *Training for Multiple UIs:* Participants should only test one UI per day to avoid cognitive overload and ensure they have sufficient time to adapt to the interface. When researchers need participants to test more than one UI on the same day, a separate full practice session should be conducted to familiarize the participants with the new display. This ensures participants are familiar with the unique features of each interface and can perform tasks effectively. The order of UI testing should be counterbalanced across participants to prevent order effects, where UIs tested later in the week may benefit from participants' increased experience [79].

The practice session should last a minimum of 20 minutes but may be extended as needed to ensure participants demonstrate competence in all aspects of the test environment. Researchers should observe and assess participants' performance throughout the session, providing guidance and clarification as necessary. A standardized performance checklist should be used to evaluate readiness, incorporating objective criteria for assessing proficiency in key tasks such as alert interpretation, response accuracy, and task prioritization. Participants must meet predefined performance thresholds before transitioning to the experimental phase. This ensures consistency across participants and enhances the reliability of the experimental data [81].

Re-Training Requirements

If participants return for multiple days or instances of testing, re-training may be necessary to ensure they maintain proficiency and consistency across sessions. Re-training should focus on refreshing participants' knowledge of the experimental environment, tools, and tasks. A brief review session, lasting approximately 15–20 minutes, should be conducted to include:

A summary of the key concepts covered during the initial training.

A review of the simulator interface and task objectives.

A practice session to re-familiarize participants with the test environment.

Re-training is particularly important to mitigate the effects of skill decay, which can occur when there is a gap between training and task performance [82]. Additionally, re-training ensures that participants approach each testing session with a consistent baseline of knowledge and skills, reducing variability in performance due to differences in familiarity or experience.

Transition to Experimental Trials

Once participants have successfully completed the full practice session and demonstrated proficiency, they can transition to the experimental trials. This transition marks the beginning of the data collection phase, where participants' performance will be evaluated under controlled experimental conditions.

The structured training and practice approach ensures that all participants enter the experimental phase with a consistent level of understanding and capability. This consistency is critical for maintaining the internal validity of the study, particularly in within-subjects designs where performance differences must be attributed to experimental manipulations rather than variability in participant preparation [55].

By addressing the unique challenges of training for multiple UIs, including counterbalancing strategies, daily practice sessions, and re-orientation requirements, researchers can ensure that the training process adequately prepares participants for all UIs being tested. This approach maintains the validity and reliability of the experimental data while minimizing the risk of confusion or bias.

9 Conclusion

This research provides a detailed analysis of the current state of UAS operator displays and establishes a foundation for defining the minimum display requirements necessary for safe and efficient BVLOS operations. As BVLOS missions grow in complexity and scale, the absence of clearly defined display requirements presents challenges to operational safety, situational awareness, and regulatory compliance. This study addresses these challenges by identifying common features across existing GCS platforms, proposing evidence-based display requirements, and outlining a roadmap for HITL testing to validate these requirements.

The findings of this report emphasize the critical role of GCS displays in BVLOS operations, where operators depend entirely on the information presented to maintain situational awareness and make safety-critical decisions. The analysis of current GCS platforms revealed significant variability in design, functionality, and usability. While some systems incorporate advanced features such as multi-sensor data fusion, predictive trajectory indicators, and adaptive alerting systems, others rely on basic telemetry and position indicators. This inconsistency underscores the need for well-defined display requirements to ensure consistent operator performance and safety outcomes.

The proposed display requirements focus on key operational areas, including traffic and alert displays, contingency management, weather information, and airspace constraints. For traffic and alert displays, features such as timely alerting, comprehensive data presentation, maneuver guidance, and recovery capabilities are recommended to help operators maintain safe separation and respond effectively to potential conflicts. Contingency management displays should prioritize system reliability, sensor fusion, and real-time processing to enable operators to handle emergencies, such as system failures or communication loss, with confidence. Weather information displays must integrate real-time meteorological data and provide clear visualizations of atmospheric conditions to support safe flight planning and execution. Additionally, airspace and ground constraint displays should incorporate advanced mapping tools, regulatory compliance features, and automated deconfliction capabilities to enhance situational awareness and reduce operator workload.

Human factors play a pivotal role in GCS display design. Effective displays must prioritize critical information, reduce cognitive workload, and enhance situational awareness through intuitive visualizations, modular architectures, and adaptive interfaces. The integration of standardized overlays, predictive analytics, and multi-sensor data fusion is essential for supporting operator decision-making in complex and dynamic environments. The proposed HITL testing roadmap offers a structured methodology for evaluating display configurations under controlled conditions, enabling systematic assessment of operator performance, workload, and situational awareness. Simulation-based platforms provide a cost-effective and safe means of validating display requirements and ensuring compliance with performance standards.

While this research provides a robust framework for defining and evaluating UAS display requirements, certain limitations must be acknowledged. The variability in existing GCS platforms and the rapid pace of technological advancements present challenges to achieving consistent implementation across the industry. Additionally, while this study addresses multi-UAS operations to some extent, further exploration is suggested to define display requirements for complex fleet management scenarios, where operators must monitor and control multiple aircraft simultaneously.

Future efforts could focus on executing the HITL testing roadmap developed in this project to validate the proposed display requirements. This process could involve gathering input from standards organizations such as ASTM International and RTCA, as well as regulatory guidelines from the FAA, to create a comprehensive framework. These requirements would benefit from a formal user interface and user experience iterative development process, followed by rigorous HITL testing using the methodology outlined in this report.

This approach has the potential to lead to the creation of a reference GCS display application that serves as an industry benchmark. Rather than mandating standardization, such a reference implementation—validated through extensive HITL testing—could provide industry with a pre-validated DAA solution, reducing development costs and time to market. For operators, this could result in consistent interfaces across platforms, reduced training requirements, and enhanced safety through validated conflict resolution capabilities. Regulatory bodies would gain evidence-based certification standards and validated human factors considerations to support the establishment of performance-based requirements.

The development of a reference implementation could follow the model of other successful open-source platforms, which have achieved widespread industry adoption in applications requiring complex airspace management and multi-UAS fleet operations. This approach would encourage innovation while ensuring that fundamental safety and human factors principles are consistently applied across different platforms and implementations.

In conclusion, this research establishes a strong foundation for improving the safety and efficiency of BVLOS UAS operations. By addressing gaps in display design, regulatory alignment, and human factors considerations, it provides actionable insights for enhancing GCS interfaces and supporting the broader adoption of UAS technology in public safety, commercial, and governmental applications. The findings pave the way for innovations that will enable UAS operators to navigate increasingly complex airspace environments with confidence and precision, facilitating the safe and seamless integration of UAS into the National Airspace System.

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Appendix A – Simulated Operations for Aerial Research

Key Takeaways

- SOAR is an open-source simulation platform designed for human-in-the-loop testing of detect-and-avoid displays and ground control station interfaces.
- The platform evolved through multiple development stages, transitioning from Qt to Unreal Engine and incorporating AirSim to achieve greater capabilities.
- SOAR integrates high-fidelity models, advanced algorithms, and modular components to evaluate UAS operations in realistic scenarios.
- The architecture separates the simulation environment from display interfaces, allowing for easier integration with existing ground control stations and DAA applications.
- The RFRL-DAA App serves as a proof-of-concept application for DAA functionality but is not field-ready and can be further developed with additional funding or collaboration.

Introduction

The Simulated Operations for Aerial Research (SOAR) platform was developed as part of this project to address the critical need for a robust, flexible, and cost-effective testing environment for evaluating detect-and-avoid (DAA) displays and ground control station (GCS) interfaces. As Beyond Visual Line-of-Sight (BVLOS) operations expand in scope and complexity, ensuring the safety and efficiency of Unmanned Aircraft Systems (UAS) operations requires rigorous testing of display configurations and human-machine interactions. SOAR provides a simulation-based framework that replicates real-world scenarios under controlled conditions, enabling researchers to systematically assess the performance of DAA displays and GCS interfaces while mitigating the risks and costs associated with live flight testing.

Developed by the Raspet Flight Research Laboratory (RFRL), SOAR is an open-source platform designed to support human-in-the-loop (HITL) testing of user interfaces. The platform integrates advanced simulation technologies, high-fidelity physics models, and modular components to create a realistic testing environment that matches complex operational contexts. SOAR can accommodate various vehicle types, such as quadcopters, hexacopters, and both standard and VTOL fixed-wing vehicles, across different airspace configurations and operational scenarios. This flexibility allows researchers to evaluate display effectiveness under conditions that closely approximate real-world operations while maintaining experimental control.

The platform enables systematic assessment of different display configurations, particularly focusing on information levels and presentation formats that significantly impact pilot response metrics. Research by Fern et al. has demonstrated that advanced information displays can result in faster pilot response times compared to basic displays when responding to traffic alerts, highlighting the importance of display design considerations in DAA systems [1], [2]. SOAR also incorporates standardized metrics for evaluating pilot-DAA interaction, such as an eight-stage response timeline that captures detection, determination, and execution functions.

SOAR can serve as a valuable tool for regulatory bodies and industry stakeholders, providing a standardized platform for assessing compliance with minimum DAA display requirements. This approach aligns with ASTM industry standards for DAA system performance requirements. With further development of the RFRL-DAA App, data can be extracted from the simulation to inform future industry standards and best practices, supporting the safe integration of BVLOS UAS into the national airspace system. By leveraging simulation environments like SOAR, research can ensure that DAA displays meet necessary safety and performance criteria, reducing the risk of mid-air collisions and enhancing overall UAS operational safety in shared airspace.

This appendix details the development, architecture, and capabilities of the SOAR platform, highlighting its role in advancing the safety and operational effectiveness of BVLOS UAS missions. From its initial conception as a modification of existing GCS software to its current implementation as a modular, multi-component system, SOAR has evolved to address the complex challenges of simulating UAS operations and testing DAA displays. By providing a standardized testing environment that replicates real-world conditions while mitigating safety risks and cost constraints, SOAR contributes to the advancement of UAS technology and operational capabilities.

Use Cases

SOAR provides a versatile and cost-effective simulation environment for evaluating DAA displays and GCS interfaces. The flexibility and modularity make it applicable across a wide range of research, training, and operational contexts. Below are some of the primary use cases for SOAR:

Regulatory Compliance Testing
SOAR enables developers to test DAA displays and GCS interfaces against established standards, such as ASTM F3442/F3442M, in a controlled environment. By simulating real-world scenarios, the platform provides a cost-effective way to validate compliance with regulatory requirements, ensuring that systems meet safety and performance benchmarks for BVLOS operations.

Pilot Training and Proficiency
The platform can be configured as a training tool for remote pilots, allowing them to practice responding to various traffic encounter scenarios. By simulating realistic operational environments, SOAR can help improve pilots' ability to interpret DAA information, make timely decisions, and maintain situational awareness without the risks associated with live flight training.

BVLOS Operations Planning
SOAR supports organizations planning BVLOS missions by simulating specific operational areas, traffic patterns, and contingency scenarios. This capability allows operators to develop and refine robust operational procedures, ensuring mission success while maintaining compliance with airspace regulations.

Emergency Response Simulation
The platform can replicate emergency response scenarios, such as disaster relief operations involving multiple UAS. By simulating time-critical missions, SOAR helps develop coordination

protocols and optimize DAA display configurations for high-stress environments, improving safety and efficiency in emergency operations.

System Integration Testing

Before deploying new hardware or software components in a DAA system, SOAR can provide a virtual environment to test integration compatibility and performance. This ensures that new components function seamlessly within existing systems, reducing the risk of operational failures during live missions.

Research and Development

SOAR can serve as a valuable tool for academic institutions and research organizations conducting studies on human factors in DAA systems. Researchers can use the platform to develop and test new display concepts, evaluate pilot performance metrics, and refine interface designs before implementation in real-world applications.

Background and Initial Approach

The development of SOAR began with a fundamental challenge: creating a simulation environment that could realistically replicate the complexities of UAS operations while providing a flexible platform for testing various display configurations. The team's approach focused on leveraging existing technologies to build a customizable simulation environment. As the project progressed, the team faced several technical limitations that prompted strategic changes, ultimately resulting in the current architecture that integrates multiple specialized components to form a comprehensive simulation platform. This section traces the development journey of SOAR, from its conceptual origins through its current implementation, highlighting the technical decisions and architectural evolution that shaped its capabilities.

Qt Meta-Object Language Framework

In early 2022, the development team conducted a thorough evaluation of available frameworks for designing user interfaces suitable for BVLOS UAS operations. The team initially selected Qt Meta-Object Language (Qt) due to its widespread use in graphical interface development. Qt provides a comprehensive set of tools for developing sophisticated user interfaces. Its cross-platform compatibility, extensive APIs, network management capabilities, and graphical design make it an attractive starting point for development efforts [3].

The initial strategy focused on modifying QGroundControl (QGC), an established open-source ground control station built using Qt. QGC already includes advanced mapping functionality, mission planning tools, and MAVLink protocol compatibility—all essential components for UAS control interfaces. The development plan aimed to modify the user interface (UI) to display varying levels of information and expand QGC's capabilities to incorporate DAA functionality while preserving its core features. Figure 1 illustrates the main interface of QGroundControl, showcasing basic flight controls and mapping features. This served as the initial inspiration for building custom UIs from an existing open-source platform.

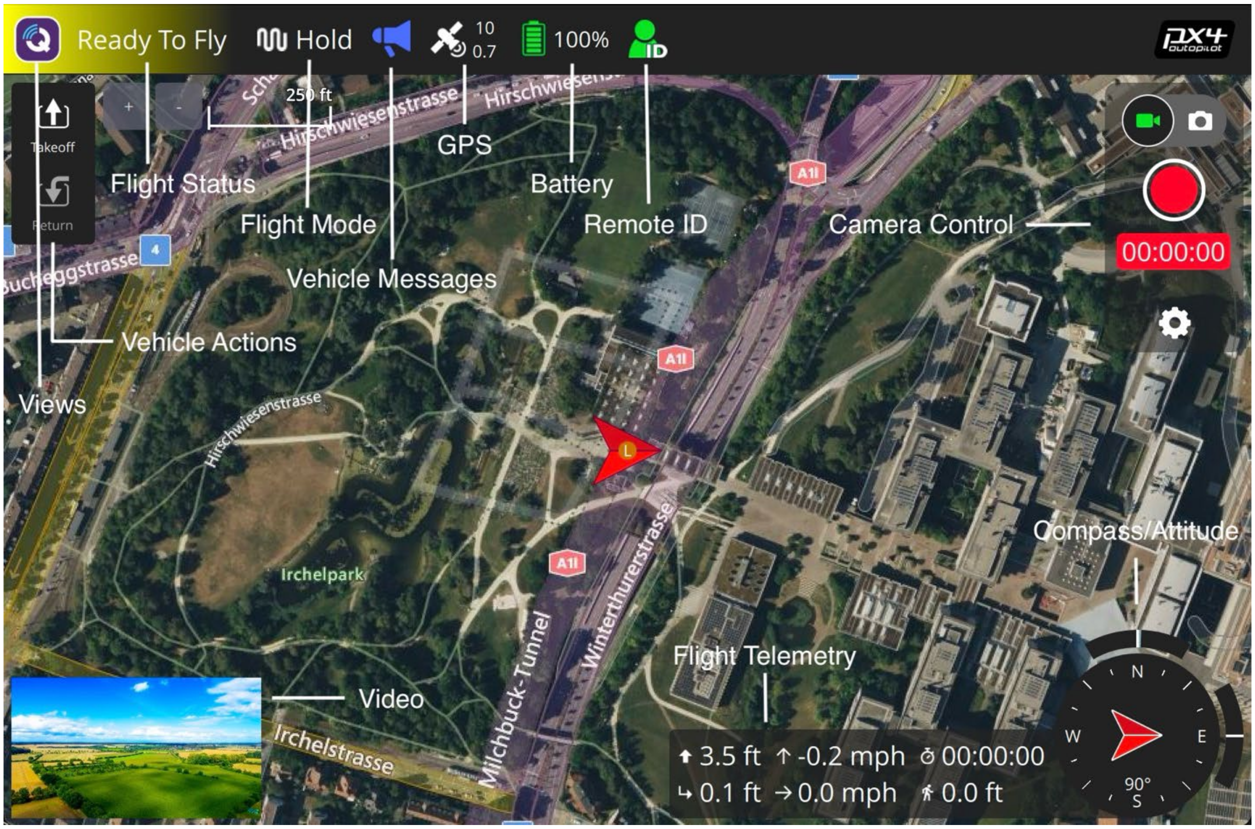

Figure 1. QGroundControl [4].

As development progressed, significant limitations in this approach became clear. QGC's intricate source code structure presented substantial challenges for integrating new UI components and custom widgets. More importantly, modifying QGC to the extent required for incorporating payload sensor data and creating the desired geographically accurate 3D environment exceeded the project's scope, though it was technically feasible with adequate resources. The team recognized that modifying QGC, even at just the UI level, would require more extensive code refactoring than initially expected. Furthermore, QGC's limited support for software-in-the-loop simulations restricted the ability to create the immersive testing environment that was originally envisioned [4]. While modifying QGC presented challenges, it would be feasible with the right amount of time and resources. The development team shifted focus to prioritize adding more features, such as enhancing the realism of the simulation environment by adding payload sensor data support.

Transition to Unreal Engine: Expanding Capabilities

The challenges encountered with Qt/QGC led the development team to consider a fundamentally different approach to creating the simulation environment. Rather than continuing to focus on modifying existing GCS software, the team decided to leverage game engine technology to create a more flexible and visually rich simulation platform.

After evaluating several options, Epic Games' Unreal Engine (UE) was selected as the new development platform. UE offers advanced capabilities in 3D graphics, physics simulation, and custom map development that far exceed what was possible with Qt/QGC. Unreal Engine is widely used across industries to generate immersive 3D content and realistic simulations. UE's accessible source code enables developers to add custom 3D models and simulate real-world scenarios with remarkable fidelity [5].

The integration of the Cesium plugin within Unreal Engine was particularly valuable for the SOAR platform. This plugin enables the incorporation of real-world geographic data, including OpenStreetMap and satellite imagery, into the simulation environment. This capability was crucial for creating both top-down satellite views and immersive 3D environments that accurately represented real-world locations. The Cesium plugin allowed operators to simultaneously view satellite imagery from above and a first-person view (FPV) perspective from the aircraft's position. Figure 2 presents the top-down view of the DAA display developed in Unreal Engine 5.3.2. This interface integrates satellite imagery with critical flight information overlays.

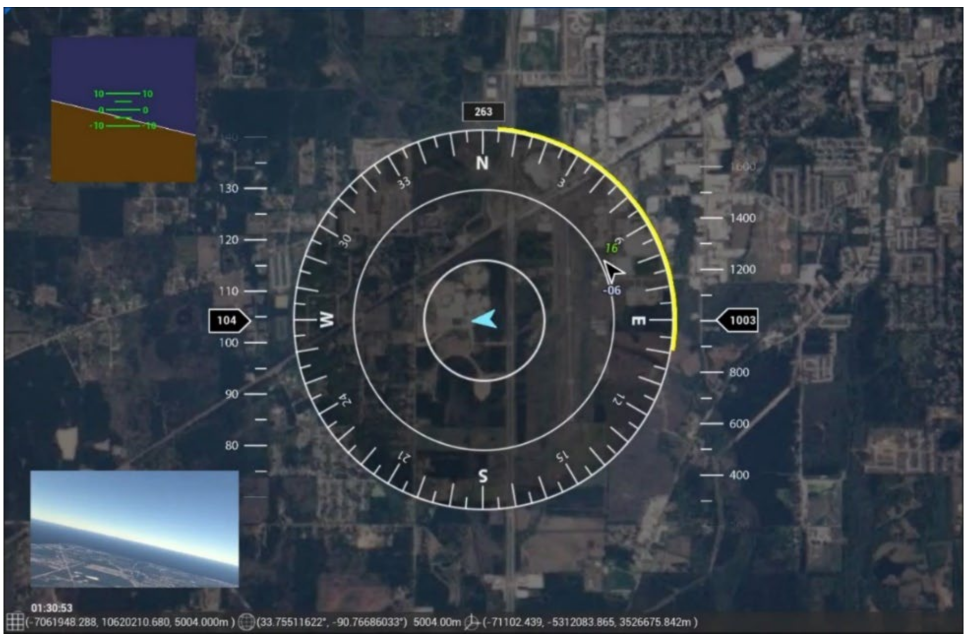

Figure 2: Top-down view of custom UI developed in UE 5.3.2

The transition to Unreal Engine has enabled the development of a user interface that incorporates multiple view perspectives and essential flight information displays. The team implemented both a top-down 2D view and a first-person view (FPV), providing operators with complementary perspectives for enhanced situational awareness. The display features a compass rose with directional markings (N, E, S, W), concentric circles representing different safety thresholds around the ownship (shown as a blue chevron in the center), and numerical indicators for altitude, heading, and airspeed. The yellow arc visible on the eastern portion of the compass indicates a potential conflict zone that the pilot should avoid. In the lower-left corner, the FPV sensor feed from the aircraft offers additional situational awareness. In the top-left corner, a primary flight display (PFD) presents the pilot with critical flight information such as pitch, roll, and yaw.

While Unreal Engine significantly expanded the platform's capabilities, the development team encountered limitations with the physics models available for uncrewed vehicles. The platform was initially restricted to a single fixed-wing aircraft model (JSBSim's 787-8), which limited the types of UAS operations that could be simulated.

The team found themselves with a visually impressive and flexible environment but constrained by the available physics models. To create a truly comprehensive simulation platform, support for a wider range of vehicle types, including multi-rotors and various fixed-wing configurations, was needed.

This limitation led to the next significant evolution in the SOAR platform's development: the integration of AirSim.

Integration of AirSim: Enhanced Physics and Multi-Vehicle Support

To address the limitations of Unreal Engine's built-in physics models, the development team integrated AirSim. AirSim, originally developed by Microsoft, is an open-source simulation platform for autonomous vehicles that runs on Unreal Engine. When Microsoft dropped support for AirSim, Colosseum picked up the project and continued the development. The new fork worked to extend and refine AirSim capabilities, particularly in supporting the new version of UE—Unreal Engine 5. AirSim now supports different physics engines for various vehicle types and goes further by incorporating realistic sensor models like LiDAR, depth-sensing cameras, and GPS, which are essential for autonomous operations. Colosseum bridges gaps by efficiently handling multi-vehicle simulations and offering enhanced aerodynamic modeling that overcomes the inherent limitations of JSBSim. As a result, AirSim (and Colosseum) can simulate a broader range of unmanned vehicle types—from fixed-wing aircraft to multi-rotors—within immersive and high-fidelity environments.

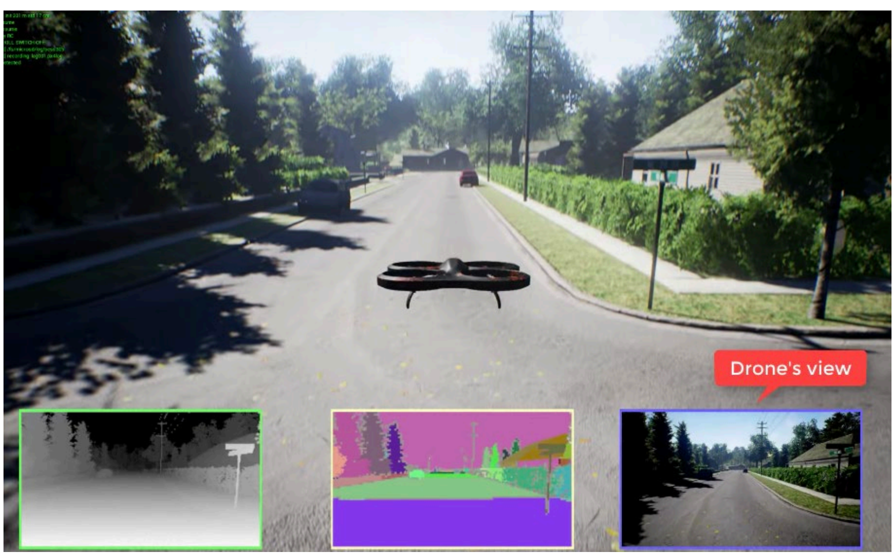

Figure 3: AirSim Environment in Unreal Engine 5

The integration of AirSim with Unreal Engine created a powerful combination that addressed many of the limitations encountered in earlier development stages. AirSim's compatibility with Unreal

Engine meant that all the visual and environmental features developed previously could be maintained while adding more sophisticated physics simulations.

Key capabilities enabled by the AirSim integration included:

- Support for multirotor aircraft simulations
- Enhanced sensor modeling for cameras, IMUs, and other onboard systems
- APIs for programmatic control across multiple programming languages
- Cross-platform compatibility across Windows, Linux, and macOS
- Computer vision mode for machine learning applications
- Simulation of various weather effects for testing under different environmental conditions

Despite these significant advantages, the development team faced new challenges as the computational complexity of running the simulation environment increased. UI-heavy games in Unreal Engine emphasize the limitations of creating complex UIs directly within game engines. Creating and modifying user interface elements directly within Unreal Engine became more tedious, especially when implementing advanced DAA displays with multiple information layers. As the SOAR platform's functionality grew, the team recognized that building complex user interfaces directly within Unreal Engine was neither efficient nor practical. This needed a workaround with a front-end framework to be able to communicate with other software used in the SOAR environment. This realization led to the current architecture of SOAR, which separates the simulation environment from the display interfaces.

SOAR Architecture

Key Takeaways:

- SOAR runs on high-performance computing hardware with specific requirements for the simulation environment
- The architecture combines Unreal Engine, QGroundControl, and PX4 for a comprehensive simulation platform
- Communication between components uses established protocols for data transmission
- Development in Unreal Engine includes specialized functions for location tracking and video streaming

System Overview and Communication Infrastructure

The SOAR platform was developed over a distributed architecture comprising multiple computers, each responsible for specific aspects of the simulation. The system has up to two computers running the base AirSim environment, managing the UAV physics and pilot interactions. The third computer acts as the control computer, serving as the central hub for data integration, experiment management, and data logging. The fourth machine (optional) contains an instance of Microsoft Flight Simulator, X-Plane 12, and FlightGear, which can transmit live positional data to the DAA display through the control computer. The communication infrastructure is shown in Figure 4 below, which details the hardware configuration and illustrates the bidirectional data flows between system components that form the foundation of the SOAR platform.

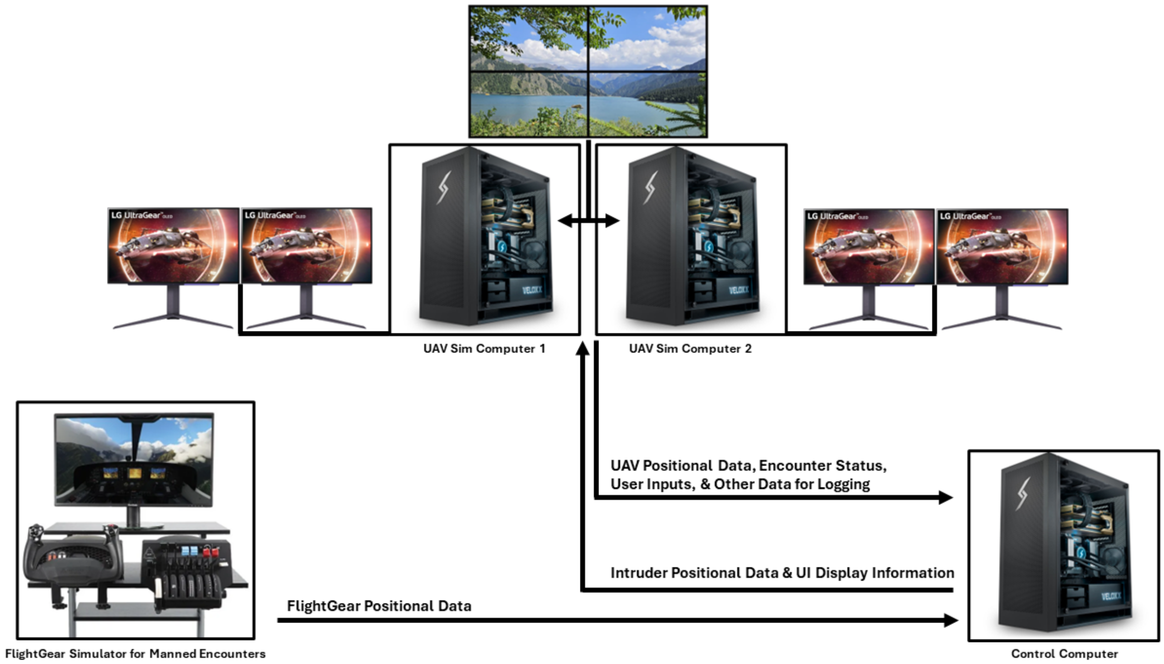

Figure 4. SOAR Hardware Setup and Communication Pipeline

This figure shows how data flows between the UAV simulation computers, the control computer, and the display systems. X-Plane 12 provides positional data to the control computer, which processes this information along with UAV positional data, encounter status, user inputs, and other logging data. This architecture emphasizes the platform's scalability and flexibility for future enhancements.

Running the simulation involves launching AirSim and the DAA application on one computer and using the control computer to forward encounter data to the DAA for simulated operations. It should be noted that while Figure 4 references FlightGear, to date, only X-Plane 12 has been integrated into the SOAR environment, although extending this to the other simulators should be feasible. Custom shell scripts provided by the developers simplify starting the individual components of the SOAR simulator.

Software Integration Architecture

The current SOAR environment combines several specialized software components to create a comprehensive simulation platform. Unreal Engine provides a visual rendering environment with advanced 3D graphics capabilities. AirSim delivers high-fidelity physics simulations for various aircraft types within the UE environment. QGroundControl functions as the interface for mission planning and UAS control. PX4 serves as the autopilot flight stack that enables autonomous vehicle behavior.

These components are interconnected through standardized communication protocols. The MAVLink Protocol facilitates communication between the simulated aircraft and QGC. TCP/IP Sockets enable data exchange between the simulation environment and external applications. UDP Streaming supports video transmission from the simulation to display interfaces (QGC).

This integrated software architecture creates a modular system where individual components can be updated or replaced as technology evolves, ensuring the platform remains adaptable for future research needs. The integration of AirSim with Unreal Engine was significant, as it expanded the platform's capabilities to include support for multiple vehicle types, advanced sensor modeling, and programmable control interfaces.

The simulator architecture integrates multiple components, including AirSim, QGC, PX4, Gazebo, and RFRL DAA App, to facilitate UAV telemetry and sensor data processing. The DAA App receives UAV telemetry either directly from Unreal Engine when using AirSim or via a Python MAVLink pipeline when utilizing Gazebo for primitive graphics. This pipeline enables QGC to transmit telemetry data to the DAA App for processing. Additionally, a GStreamer pipeline is employed to stream FPV sensor data to QGC, ensuring real-time visualization and situational awareness within the simulation environment. This architecture provides a comprehensive and flexible framework for UAV testing and development.

Hardware

Raspet Flight Research Laboratory invested in four computers to develop and evaluate the SOAR simulator. The hardware configuration exceeds typical simulation system specifications to ensure smooth operation during complex multi-aircraft scenarios with high-resolution visual rendering. Three computers use Ubuntu 20.04 as their primary operating system, and one computer uses Windows 11. Each computer is equipped with:

- **Processor:** AMD Ryzen Threadripper 7970X (32-Core CPU)
- **Motherboard:** ASUS Pro WS TRX50-SAGE
- **System Memory:** 128GB DDR5 5600MHz (ECC) (32GB x 4 Modules RAM)
- **Graphics Card(s):** 1x GeForce RTX 4090 24GB (GPU)
- **Storage:** 2x SSD 4TB Kingston Fury Renegade (SSD)

These specifications exceed the recommended hardware requirements for the SOAR simulator, which are based on Unreal Engine 5's recommendations:

- Quad-core Intel or AMD processor
- Nvidia GeForce 2080 GPU
- 32 GB of RAM

The hardware ensures that system performance is not a limiting factor during human-in-the-loop testing, where real-time responsiveness is essential for valid experimental outcomes. The high-performance GPUs are particularly important for rendering the detailed visual environment while maintaining frame rates above 60 fps, which is necessary for realistic simulation of flight dynamics and traffic encounters.

To accommodate research groups with limited hardware resources, the SOAR platform includes support for Gazebo Classic as an alternative physics engine, requiring only a graphics card with 1 GB of memory. The Gazebo integration provides a lower-fidelity but functionally equivalent simulation environment that preserves the core testing capabilities while reducing hardware requirements. This flexibility extends the potential user base for the SOAR platform across different research environments with varying resource constraints.

Physical Testing Environment

RFRL provides a dedicated space for SOAR human-in-the-loop testing, with workstations for both pilots and test engineers. The physical layout can be seen below in Figure 5.

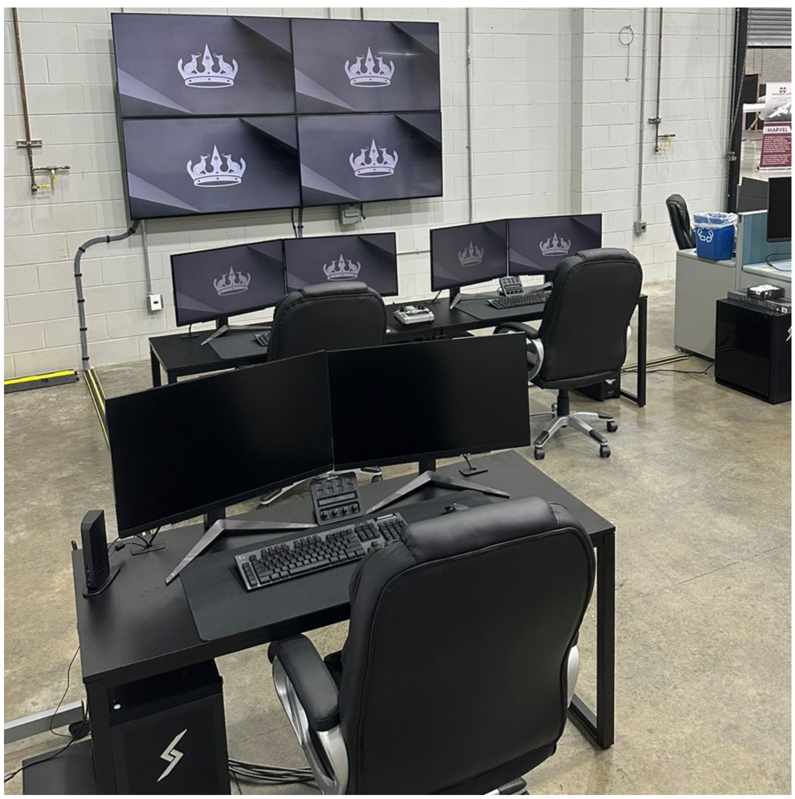

Figure 5. SOAR Workstations

Figure 5 showcases the physical layout of the SOAR simulation workstation, designed to support human-in-the-loop testing. Each station features a dual-monitor setup with dedicated input devices. The two workstations side-by-side in the front serve as the operators' workstations. While currently only configured for single-pilot operation, the hardware infrastructure supports eventual expansion to allow testing scenarios where multiple operators oversee many vehicles (m:N). The 2×2 grid of displays mounted on the wall provides more real estate for monitoring other variables and data streams for realistic situational awareness. Each operator can individually toggle which displays they want to mirror during testing sessions. The workstation behind the operator workstations serves as the control computer, which determines what information the Pilot-in-Command sees and what encounters will be simulated. This station also functions as the data collection and logging computer, capturing performance metrics during testing sessions. The workstation at the rear serves multiple functions: experiment control and scenario management, data collection and performance logging, system monitoring and technical support, and observer position for experimental protocols. The strategic separation between pilot and control stations prevents test subjects from viewing scenario control interfaces or performance metrics during experimental sessions, maintaining experimental integrity while allowing the test conductor at the control station to still have oversight.

This setup implements a platform to support complex simulations and human-in-the-loop testing, providing operators with a realistic and immersive environment for advanced UAS research. The layout accommodates multiple research personnel, enabling the efficient execution of experimental protocols with proper separation between test subjects and researchers.

Operator Interface Design

The SOAR platform incorporates multiple user interface configurations that can be evaluated for effectiveness in different operational scenarios. These interfaces present varying levels of information and use different visualization techniques to communicate traffic alerts and navigational data to remote pilots. Figure 6 below shows an example of the integrated pilot interface that operators could interact with during testing sessions.

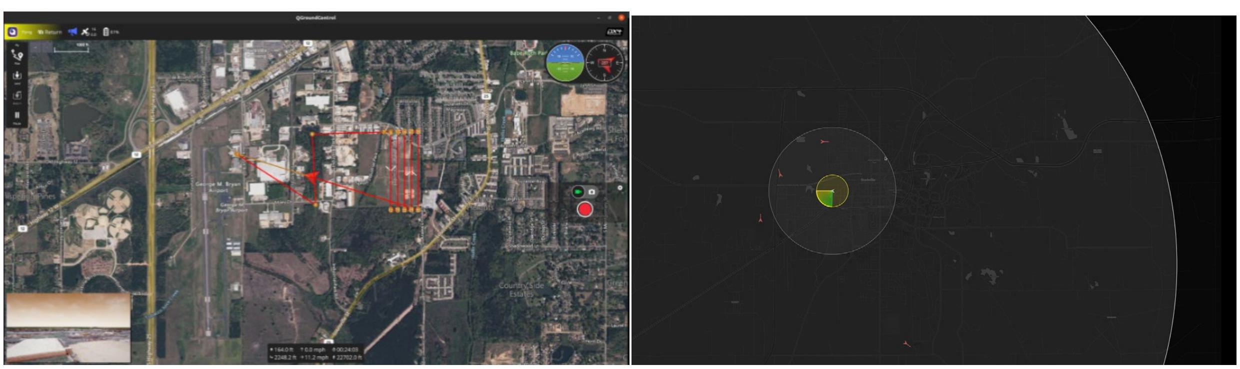

Figure 6. Example Operator UI

Figure 6 demonstrates one implementation of the SOAR operator interface, featuring a dual-monitor display configuration that provides perspectives on the operational environment.

RFRL-DAA App: A Proof-of-Concept Implementation

To demonstrate the capabilities of the SOAR platform, the development team created the RFRL-DAA App, a proof-of-concept application showcasing how DAA displays can integrate with the simulation environment. This application leverages the SOAR platform for aircraft physics and implements a custom user interface developed in Flutter. While the RFRL-DAA App is not field-ready and does not implement all the features identified in this research, it provides a valuable foundation for future development and testing.

The RFRL-DAA App offers several benefits as a standalone application. By separating the DAA display from the simulation environment, the app improves performance and reliability, reduces resource usage, and ensures cross-platform compatibility. This modular approach allows for faster development, easier maintenance, and better version control. Additionally, the use of Flutter provides greater flexibility in UI design, enabling the creation of intuitive and adaptable displays tailored to specific operational needs.

The application implements a socket-based network communication protocol, allowing it to receive location data from AirSim. This approach ensures compatibility with other DAA applications capable of socket-based communication, enabling seamless integration with various simulation environments. The app supports multiple UI configurations, each designed to test different levels of information presentation and visualization techniques. These configurations allow researchers to evaluate how varying display designs impact operator performance, situational awareness, and decision-making.

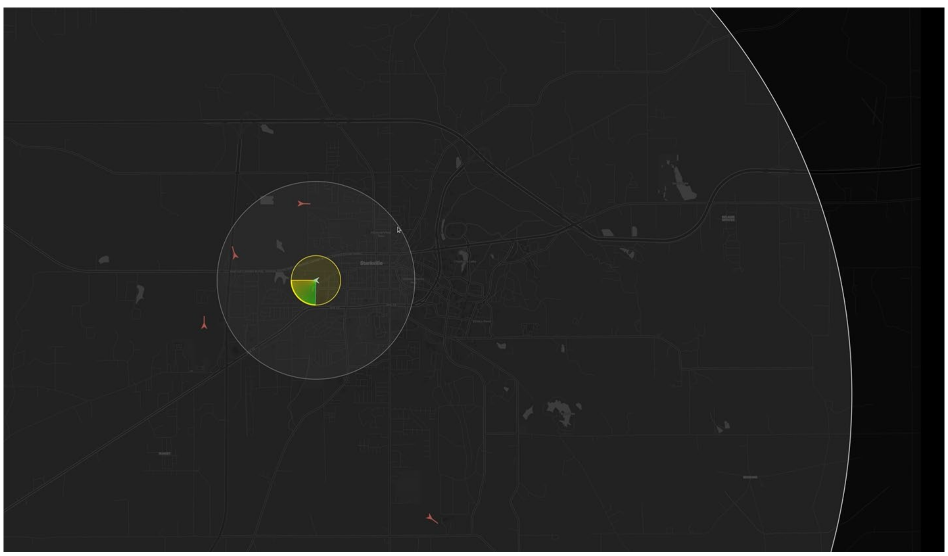

Figure 7: Standalone RFRL DAA App.

Key features of the RFRL-DAA App include:

- **Multiple UI Configurations**: Four distinct user interfaces with varying levels of information and presentation formats allow for testing different display concepts. These configurations range from minimalistic designs to more complex visualizations with advanced features like conflict zones and maneuver guidance.
- **DAA Algorithm Implementation**: The app incorporates algorithms that calculate collision and recovery bands based on the relative positions and trajectories of the ownship and

intruder aircraft. These bands are visually represented on the display to guide operators in maintaining safe separation.

- **Threat Level Visualization**: The app uses color-coded indicators to represent different threat levels, providing operators with clear visual cues for potential conflicts and recommended avoidance maneuvers.
- **Flexible Data Input**: The app can process intruder data from both static CSV files and real-time TCP connections, enabling flexibility in testing scenarios and data sources.

The RFRL-DAA App demonstrates how the SOAR platform can support the development and testing of specialized applications for UAS operations. While this implementation focuses on DAA functionality, the same approach could be applied to other types of displays and interfaces. By providing a flexible and modular testing environment, the RFRL-DAA App contributes to the iterative development of UAS display requirements, supporting the broader goal of enhancing safety and operational effectiveness in BVLOS missions.

This DAA display supports custom intruder data read from CSV files, and it also supports any flight path that is in a valid format. In addition to static flight path data, the DAA app can accept real-time flight data from flight simulations, e.g., X-Plane, Microsoft Flight Simulator, etc.

Figure 8: Graduate research assistant operating X-Plane during takeoff (left) and cruise (right)

Four example UIs have been designed with varying levels of information and different presentation methods. Toggleable functions between these UIs are available through the control computer and keyboard function “Alt + (UI number 0-3).”

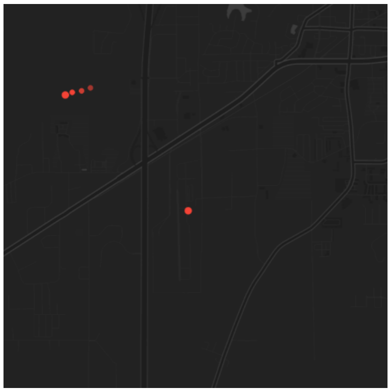

Figure 9-a. Simple UI

Figure 9-b. DAA UI

Figure 9. Different UIs developed in the project

Figure 9-a shows UI #1, which simply represents all entities as red dots. Figure 9-b shows UI #4, where the ownship position and heading are displayed with a green chevron. Intruders are shown in red chevrons with a visualization of the well-clear boundary and self-separation threshold. If an intruder enters the self-separation threshold, a notification will appear, allowing the operator to zoom in and center the screen on the ownship. Two heading lines—current and recommended—offer suggested avoidance maneuvers.

The block diagram in Figure 10 represents the suggested avoidance logic of the DAA algorithm developed under USRA Task 4. The red band represents the collision band, and the green band is the recovery band. The collision and the recovery bands are generated if the intruder traverses the designated volume of the ownship aircraft. Assuming that the designated volume of the ownship aircraft is a cylinder and the intruder's path is a straight line at the observed moment, two cross points appear on the cylinder's outer wall. The points divide the 360-degree heading angle into two bands. The collision band is one of the divided bands in which the angle between two points is less than or equal to 180° based on the ownship aircraft. The recovery band is the complementary set of the collision band. The algorithm outputs these points as start and end angles with respect to the circle around the ownship. These points draw threat bands on the UI, shown in Figure 11. Recommended heading angle is the mean of these start and end angles.

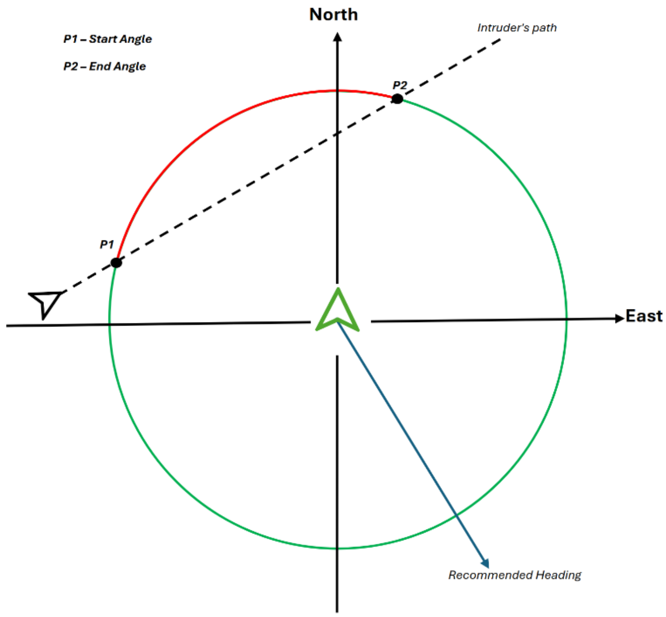

Figure 10. Block diagram of DAA algorithm

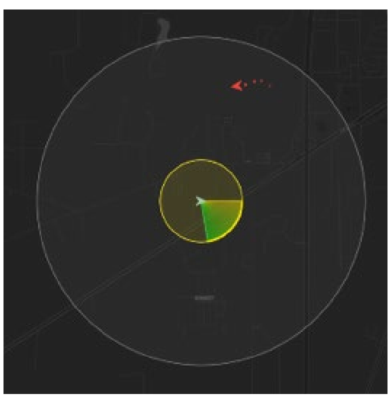

Figure 11-a. Threat level 1

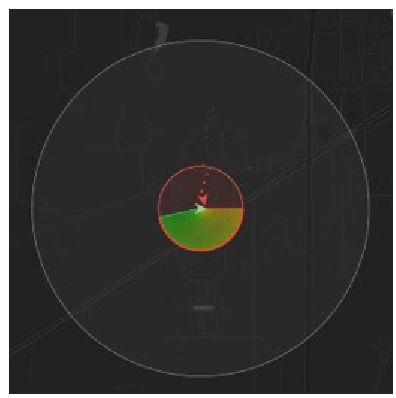

Figure 11-b. Threat level 2

Figure 11. Different screens with different threat levels

The images depict different threat levels in the DAA UI. Figure 11-a illustrates Threat Level 1, where the ownship is marked with a green chevron, and a yellow warning boundary around the well-clear volume. Figure 11-b represents Threat Level 2, showing a loss of well-clear where the ownship is surrounded by a red well-clear boundary, signaling a higher threat level. The images visually differentiate between varying levels of potential danger in the system.

The development of the RFRL-DAA App demonstrates how the SOAR platform can support the creation and testing of specialized applications for UAS operations. While this implementation focuses specifically on DAA functionality, the same approach could be applied to develop and test other types of displays and interfaces.

The SOAR platform has the potential to support the development of standardized DAA display applications that could become industry standards for UAS operations. By providing a flexible, open-source platform for testing and evaluation, it contributes to the safe integration of UAS into the national airspace system, particularly for BVLOS operations.

Conclusion

The development of the SOAR platform illustrates the iterative, problem-solving approach required to create a comprehensive simulation environment for UAS operations. From its initial conception as a modification of existing GCS software to its current implementation as a modular, multi-component system, SOAR has evolved to address the complex challenges of simulating UAS operations and testing DAA displays.

The platform's transition from Qt/QGC to Unreal Engine, and the subsequent integration of AirSim, demonstrates the importance of selecting appropriate technologies to achieve specific goals. Each transition was driven by the need to overcome technical limitations and enhance the platform's functionality, resulting in a simulation environment that combines visual fidelity, accurate physics, and interface flexibility.

The current architecture of SOAR, with its separation of simulation and display components, provides a flexible framework for testing various display configurations and interface designs. This approach enables researchers, developers, and operators to evaluate different DAA display concepts under controlled conditions, contributing to the development of safer and more effective UAS operations.

As UAS operations continue to expand, particularly in BVLOS scenarios, platforms like SOAR will play an increasingly important role in ensuring that DAA displays and GCS interfaces meet the necessary performance requirements for safe integration into the national airspace system. By providing a standardized testing environment that replicates real-world conditions while mitigating safety risks and cost constraints, SOAR contributes to the advancement of UAS technology and operational capabilities.

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