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A55 Identify Flight Recorder Requirements for Unmanned Aircraft Systems (UAS) Integration into the National Airspace System (NAS)

November 14th, 2022

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16. Abstract

The purpose of this report is to determine the requirements for Flight Data Recorders (FDR) and Cockpit Voice Recorders (CVR) in the National Airspace System (NAS). For this purpose, a literature review was previously prepared in task 1 of the project, which is used in this task to evaluate current standards of FDRs and CVRs in manned aviation and to transfer them to UAS. It is investigated which requirements are transferable and which have to be adapted for UAS. Since UAS exist in a wide variety of forms, different groups of requirements have been defined. It was found that most of the requirements from manned aviation are adoptable. Only the FDR requirements for fully autonomous UAS could be problematic, since these autonomous systems record large amounts of data in a short time. This could push current systems to their limits in terms of storage capacity. In addition, the requirements for FDR for Urban Air Mobility (UAM) were analyzed, as well as the requirements for CVRs. In general, the report indicates that current standards can largely be adopted, and further research should be done on how large amounts of data can be stored and handled efficiently. In addition, it should be researched how often per second data must be recorded in order not to waste storage space but to be able to draw enough information from the data.

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ACL	Autonomous Control Levels
ADS-B	Automatic Dependent Surveillance-Broadcast
ANP	Actual Navigation Performance
AOA	Angle of Attack
ATC	Air Traffic Control
CFR	Code of Federal Regulations
CVR	Cockpit Voice Recorder
DL	Deep Learning
DME	Distance Measuring Equipment
EFIS	Electronic Flight Instrument System
ELOS	Equivalent Level of Safety
EPE	Estimated Position Error
EPU	Estimate of Position Uncertainty
ESC	Electronic Speed Controller
EUROCAE	European Organization for Civil Aviation Equipment
FAA	Federal Aviation Administration
FDR	Flight Data Recorder
GNSS	Global Navigation Satellite System
GPWS	Ground Proximity Warning System
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
LORAN	Long Range Navigation
LiDAR	Light Detection and Ranging
INS	Inertial Navigation System
LOA	Level of Autonomy
MLS	Microwave Landing System
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
PFV	Planetary Flights Vehicles
SWaP	Size, Weight, and Power
TAWS	Terrain Awareness Warning System
TCAS	Traffic Alert and Collision Avoidance System
UAM	Urban Air Mobility
UAS	Unmanned Aircraft Systems
UTM	Unmanned Traffic Management

EXECUTIVE SUMMARY

The purpose of this report is to recommend requirements for Flight Data Recorders (FDR) and Cockpit Voice Recorders (CVR) in the National Airspace System (NAS) for Unmanned Aircraft Systems (UAS). For this purpose, a literature review was previously prepared in task 1 of the project, which is used in this task to evaluate current standards of FDRs and CVRs in manned aviation and to transfer them to UAS. It is investigated which requirements are transferable and which have to be adapted for UAS. Since UAS exist in a wide variety of forms, different groups of requirements have been defined. It was found that most of the requirements from manned aviation are adoptable. The requirements for FDRs, which are needed for autonomous operations of UAS, should be tested in more detail under real conditions, since an interface between sufficient data for various analyses must be collected, but also attention must be paid to the current technical possibilities, since very large data sets are generated in a short time by these systems.

In addition, the requirements for FDR for Urban Air Mobility (UAM) were analyzed, as well as the requirements for CVRs. In general, the report indicates that current standards can largely be adopted, and further research should be done on how large amounts of different data can be stored and handled efficiently. In addition, the intervals at which the data should be recorded needs to be tested more closely under real conditions.

1 INTRODUCTION

1.1 Parameters

Within the scope of task 1, regulations for Flight Data Recorders (FDR) and Cockpit Voice Recorders (CVR) from several institutions for various types of aircraft were reviewed. These included regulations and requirements defined in the Code of Federal Regulations (CFR), the regulations of the European Organization for Civil Aviation Equipment (EUROCAE), and those of the International Civil Aviation Organization (ICAO).

Based on task 1, current standards are assessed and adjusted data recorder requirements for Unmanned Aircraft Systems (UAS) are proposed. Proposals are analyzed for safety benefits and whether these adequately address the data needed to assess accidents and incidents for UAS and prospective operational domains, such as Urban Air Mobility (UAM).

UAS can be very different and vary significantly based on weight, design, or area of application. Accordingly, several groups of requirements are defined in this report. The requirements for a particular UAS are thus composed of the requirements of the groups to which it belongs. These are the following:

- General Requirements:
  Requirements that every UAS must meet.
- Requirements based on Type:
  The two main groups of UAS are fixed-wing and rotary-wing.
- Requirements for UAM
- Requirements based on Autonomy*:*
  Depending on the degree of autonomy of a UAS, the requirements may differ. Accordingly, the extent to which the requirements have to be adapted based on the level of autonomy is discussed.

These categories can be transferred to the current requirements specified in the CFR for manned aviation. The CFRs that are particularly relevant for this research are 14 CFR Part 135, as well as Part 125 and Part 121. While Part 135 deals with FDR requirements for airplanes and helicopters, Part 121 deals with airplanes in general, and 125 deals with airplanes carrying 20 or more passengers. Accordingly, the categories defined above could be incorporated into the existing regulations. An additional appendix could be added to 14 CFR Part 135, defining the requirements for fixed-wing UAS and rotary-wing UAS. These annexes should contain the requirements mentioned in the section General Requirements and the respective sections of the corresponding type of UAS. An appendix could be added to 14 CFR Part 125 defining the requirements for UAMs for operations with more than 19 passengers. Since 14 CFR Part 121 defines the ‘operating requirements’, it is suggested to add the requirements for the FDR of autonomous UAS to this part.

Within these groups, the parameters, the recording range, the sampling interval, and the reason for recording the corresponding parameter are analyzed. Some metrics, such as accuracy and resolution, would need to be tested extensively in real-world settings in order to be able to give sufficient recommendations. Accordingly, these have not been added to the following parameter lists. It can be assumed that for UAS the default values should be the same as defined in the CFR for manned aircraft. In addition to the requirements for FDRs, requirements for CVRs are also discussed in the document.

1.2 Crash Survivability

The crash survivability of Flight Data Recorders (FDRs) holds significant importance in the field of aviation. These recorders must withstand extreme conditions to ensure the preservation and recovery of the aircraft flight data during and after an accident. These extreme conditions include mechanical forces, intense heat, vibrations, and other hazardous circumstances that are characteristic of crash events. By maintaining their integrity under such challenging conditions, crash-survivable FDRs play a pivotal role in providing valuable information for accident investigation, analysis, and the development of enhanced safety measures.

The exponential growth of Unmanned Aircraft Systems (UAS) operations has amplified the need for crash-survivable FDRs specific to this domain. The increased probability of UAS accidents necessitates the recovery of data from these events. However, current standards do not explicitly define the critical conditions applicable to UAS accidents, resulting in a gap between existing regulations and the unique requirements of UAS FDRs. Therefore, the development of comprehensive standards that encompass the crash survivability demands specific to UAS becomes essential. By addressing these gaps, the aviation industry can ensure the effective preservation and retrieval of data, enabling thorough accident investigations and facilitating continuous improvements in UAS safety standards.

1.3 Updates

This section was updated with an introductory paragraph regarding crash survivability.

2 GENERAL FDR REQUIREMENTS FOR UAS

The general requirements refer to requirements that apply to all types of UAS and operational domain. Therefore, they provide the foundation for further requirements:

The parameters listed below are based on the documents earlier reviewed in the task 1 literature review. These documents are: ED-112A (ED-112A - MOPS for Crash Protected Airborne Recorder Systems, September 2013), 14 CFR Appendix E to Part 125 - Airplane Flight Recorder Specifications (14 CFR Appendix E to Part 125 - Airplane Flight Recorder Specifications), 14 CFR Appendix D to Part 125 - Airplane Flight Recorder Specification (14 CFR Appendix D to Part 125 - Airplane Flight Recorder Specification), and 14 CFR Appendix B to Part 121 - Airplane Flight Recorder Specification (14 CFR Appendix B to Part 121 - Airplane Flight Recorder Specification).

Parameters To Be Measured:

1. Date
2. Time
3. Time of each radio transmission to or from air traffic control (If applicable)

4. Temperature of the fuselage
5. Airspeed
6. Vertical acceleration
7. Heading
8. Altitude
9. Roll input (and aileron position after input)
10. Roll trim
11. Pitch input (and elevator position after input)
12. Pitch trim
13. Yaw input (and rudder position after each input)
14. Yaw trim
15. Electronic Speed Controller (ESC) status
16. Engine(s) Thrust (rpm)
17. Reverse thrust status
18. Variable pitch propeller position or status (if applicable)
19. Battery status
20. Fuel Level Status (If Applicable)
21. Autopilot engagement status (if applicable)
22. Global Positioning System (GPS) status
23. Distance Measuring Equipment (DME) - Distance between aircraft and ground station through signal propagation delay
24. Marker Beacon Status (if applicable)
25. Electronic Flight Instrument System (EFIS) display format (if applicable)
26. Instrument Landing System (ILS)/ Glide Path (If Applicable)
27. Navigation Systems e.g., GNSS, INS, MLS, ANP, EPE, EPU, LORAN, Glideslope (If applicable)
28. Link type/Telemetry status
29. Satellite connectivity status or level
30. Latitude and Longitude
31. Failsafe initiation (if applicable)

All auxiliary actuators such as:

- Payload mounting or release mechanism status (if applicable)
- Retractable gears position (if applicable), etc.

All (warning) sensors e.g.

- Traffic Alert and Collision Avoidance System (TCAS)
- Ground Proximity Warning System (GPWS) /Terrain Awareness Warning System (TAWS)
- Low power level warning
- GPS loss
- Transmission loss warning (with transmitter or Ground station).

Table 1. General requirements.

	PARAMETERS	RANGES	REASONS/JUSTIFICATION	MAXIMUM RECORDING INTERVAL IN HERTZ(Hz)	
1.	Date*[1]	365(+1) days	Date of each flight	0.0167	
2.	Time*[2]	24 Hrs.	Determines when certain events occur and aids establishing cross-references between themselves	1	
3.	Temperature of the fuselage	±100°C	This helps to determine the fuselage's temperature is SAFE for all onboard components.	0.5	
4.	Airspeed	5knots or minimum to maximum for aircraft+	Determines if the airspeed of the aircraft on every event is within aircraft's specified operational range.	1	
5.	Normal acceleration (Vertical)	−3g to + 6g	Measures the vertical acceleration of the aircraft.	8	
6.	Heading *[3]	0 – 360 degrees	Determines the orientation of the aircraft at every point in time.	4	
7.	Altitude	−1000 ft to max certificated altitude of aircraft. + 5000 ft	Measures how high or low the aircraft is or the approaching height at every point in time.	1	
8.	Roll attitude (and aileron position after input)	±180 degrees	Measures and ensures all bank angles and/or maneuvers are within a safe operational range on every event.	4	
9.	Roll trim	Full range	Measures the added compensation to the initial roll attitude.	1	
10.	Pitch attitude (and elevator position after input)	±90 degrees	Measures and ensures all pitch angles are within a safe	4	

			operational range on every event.		
11.	Pitch trim	Full range	Measures the added compensation to the initial pitch attitude.	1	
12.	Yaw input (and rudder position after each input)		Measures and ensures all yaw input and angles are within a safe operational range on every event.	4	
13.	Yaw trim	Full range	Measures the added compensation to the initial yaw attitude.	1	
14.	Electronic Speed Controller (ESC) status *[4]	Discrete or Full Range	Ensures there's no obstruction to the flow of power in the propulsion system	1	+
15.	Engine(s) Thrust (rpm) and throttle stick position	Full range forward	Measures the thrust of each engine at every point in time	1	
16.	Brakes (if applicable)	Full range		1	
17.	Hydraulic Pressure (if applicable)	Full range	Measure hydraulic pressure of the unmanned aircraft.	2	
18.	Engine Bleed Valve (if applicable)	Discrete		4	
19.	AC/DC Electrical Bus Status (if applicable)	Discrete		4	
20.	Reverse thrust status (If applicable)	Full Range or as installed	Determines the reverse thrust applied to each engine at every point in time	1	
21.	Variable pitch propeller position or status (if applicable) *[5]	Discrete or full range	Measures the variation(s) in propeller pitch which can significantly affect an aircraft's performance	1	+
22.	Battery status *[6]	0 – 100% and/or 0 or min to max voltage	Measures and ensures power is within safe operational level at every point in time	1	+

23.	Fuel Status Level*[7]	Full Range	Ensures it is within the operational level at every point in time.	0.03	
24.	Autopilot engagement status (if applicable)	Suitable combination of discrete	Determines at what point in time the aircraft is operated autonomously.	1	
25.	Longitudinal Acceleration	±1g		8	
26.	Lateral Acceleration	±1g		8	
27.	Outside Air Temperature	±100°C	This helps to know the surrounding temperature (outside the fuselage) as it can affect the aircraft’s performance.	0.5	
28.	GPS Status	Discrete or as installed	Determine the location of the aircraft and its accuracy level at every point in time.	1	
29.	Radio Altitude	-20ft to +2500ft	Measures the altitude difference between the aircraft and any immediate terrain/obstacle below it.	1	
30.	Manual radio transmission keying (If applicable)	Discrete		1	
31.	DME (Distance Measuring Equipment) *[8]	As installed	Measures the distance between the aircraft and the ground station.	0.25	
32.	Marker Beacon Status (if applicable)	Discrete or as installed	Determine the landing orientation as seen by the aircraft, faulty ones can give the wrong orientation.	1	
33.	EFIS (Electronic Flight Instrument System) display format (if applicable)	Discrete	For cross-references of aircraft status	1	
34.	ILS (Instrument Landing System)/	Full Range	Determines all landing aids along with their accuracies.	1	

	Glide Path (If Applicable)				
35.	Navigation Systems e.g., GNSS, INS, MLS, ANP, EPE, EPU, LORAN, Glideslope (If applicable)	As installed	To determine the accuracies and consistencies of all navigation systems used.	1	
36.	Link type/Telemetry status *[8]	Discreet or Full Range	Determines whether connection status of the aircraft to the ground control station is active or lost.	1	
37.	Satellite connectivity status or level *[9]	Full Range	Determines aircraft's connection strength to satellite(s), which can influence the performance of an aircraft.	1	+
38.	Latitude and Longitude *[11]	As installed	Determines the location of the aircraft at every point in time	0.25	
39.	Wind Speed and Direction	As installed	Navigation data	0.25 (eCFR Title 14)	
40.	Drift Angle	As installed	Navigation data	0.25 (eCFR Title 14)	
41.	GPS correction (if applicable)	As installed	Navigation data	1	
42.	Failsafe initiation (if applicable) *[10]	Discrete	Indicate which/when/why failsafe was initiated	1	+
43.	**All auxiliary actuators such as:** • Payload mounting or release mechanism status	Full Range/ Discrete	Measures all other integrated systems that are not crucial to aircraft flights but might affect aircraft performance, if faulty.	1	

	Retractable gears position (if applicable), etc. *[11]				+
	All (warning) sensors e.g. • TCAS (Traffic Alert and Collision Avoidance System) • GPWS/TAWS – (Ground Proximity Warning System/Terrain Awareness Warning System) • Low power level warning • GPS loss • All engine malfunctions • Low hydraulic pressure Transmission loss warning (with transmitter or Ground station).	Discrete or as installed	Indicates fault or possible fault in an aircraft.	1	+

NOTE

“+” – represents parameters that weren’t part of the original manned aircraft parameters but are crucial for UAS.

*[1-11] represents parameters whose recording intervals are recommended to be changed from those of the manned aircraft provided in the documents earlier mentioned. The justifications for the proposed changes are stated below:

*[1], Date is recommended to be recorded every minute, give accuracy when sorting data.

*[2], was changed because it is necessary for recording to be detailed to 1 second, knowing how data changes every second compared to 4seconds interval of the manned aircraft parameters.

*[3], Most UAS are relatively smaller than manned aircraft, hence can change heading much quicker than manned aircraft, hence it is recommended to record more data per second for better accuracy.

*[4], Electronic Speed Controller is a crucial part of propulsion, and any fault should be detected as soon as possible. Hence, its status should be known every second.

*[5], since varying propeller pitch can instantly affect aircraft's performance, it would be great to know the status of this per second.

*[6], Most UAS are heavily dependent on batteries and hence the status of the battery should be known every passing second.

*[7], Most UAS can only carry limited amount of fuel as compared to manned aircraft, so the fuel status should be known at the least once in every 30 seconds.

*[8], *[9], UAS connection to ground control station and satellites is highly recommended to be known every second, as late awareness can lead to undesired results.

*[10], Most UAS are integrated with failsafe and the initiation of this at any point in time should be known, hence recommended to be recorded every second.

*[11], Auxiliary actuators status for payloads, should be known every second as initiating this can sometimes affect aircraft performance (e.g., aircraft weight, cg, etc., in drone delivery).

3 FDR REQUIREMENTS BASED ON TYPE

There are several types of UAS. The two primary ones are fixed-wing and rotary-wing UAS. Depending on the type, the requirements for the flight data recorder differ.

3.1 Fixed-Wing UAS

Parameters To Be Measured

1. Flaperons (if applicable)
2. Flaperons trim
3. Elevons (if applicable)
4. Elevon trim
5. Flaps position
6. Slats position
7. Spoilers
8. Speed Brake position (if applicable)
9. Ground speed (if applicable)
10. Angle of Attack (AOA) (if applicable)
11. L/D (if applicable)

Table 2. Fixed wing requirements.

	PARAMETERS	**RANGES**	**REASONS/JUSTIFICATION**	**MAXIMUM RECORDING INTERVAL IN HERTZ(Hz)**	
1.	Flaperons (if applicable) *[12]	±180 degrees	Determines the degree of flaperon commands given to the aircraft at every point in time.	4	+
2.	Flaperons trim *[13]	Full range	Measures the added compensation to the initial flaperon attitude.	1	+
3.	Elevons (if applicable) *[14]	±180 degrees	Determines the pitch and/or roll angle at every point in time.	4	+
4.	Elevon trim *[15]	Full range	Measures the added compensation to the initial elevon attitude.	1	+

5.	Flaps position	Full Range or discrete positions	Determines the degrees of flap applied at every point in time.	0.5	
6.	Slats position	Full Range or discrete positions	Determines the slat input given to the aircraft.	1	
7.	Spoilers	Full Range or discrete positions	Determines the spoiler input given to the aircraft.	2	
8.	Yaw Damper (if applicable)	Discrete	Compensates for undesired oscillation of rolling and yawing motion	2	
9.	Speed Brake position (if applicable)	Discrete or Full Range		2	
10.	Ground speed (if applicable)	Full Range	Speed of the aircraft on the ground until take-off or complete stop on land	1	
11.	Angle of Attack (AOA) (if applicable)	As Installed	Angle of attack of the aircraft at every point in time	2	

NOTE

"+" – represents parameters that weren't part of the original manned aircraft parameters but are crucial for UAS.

*[12-15] represents parameters whose recording intervals are recommended to be changed from those of the manned aircraft provided in the documents earlier mentioned. Because these are combination of at least two (2) traditional control surfaces and recommended to have similar recording interval as individual control surfaces in Table 1.

3.2 Rotary-Wing UAS

Parameters To Be Measured

1. Flying mode status- Free flight (attitude), GPS lock, Speed mode (sport) etc. (if applicable)
2. Motor/Rotor Brake engagement.
3. Collective pitch (if applicable)
4. Longitudinal cyclic pitch (if applicable)
5. Lateral cyclic pitch (if applicable)

6. Controllable Stabilator (if applicable)
7. Gearbox oil pressure (if applicable)
8. Gearbox oil temperature (if applicable)

Table 3. Rotary wing requirements

	PARAMETERS	**RANGES**	**REASONS/JUSTIFICATION**	**MAXIMUM RECORDING INTERVAL IN HERTZ(Hz)**	
1.	Flight mode status- Free flight (attitude), GPS lock, Speed mode (sport) etc. (if applicable) *[16]	Full Range or discrete positions	Indicates the mode the UAS is in. Some modes cause the UAS's speed, warning sensors, stability, etc., to change significantly.	1	+
2.	Motor/Rotor Brake engagement.	Discrete or Full Range	Indicates the abrupt shutdown of all motors while the aircraft is in flight. This is commonly initiated in an emergency or to carry out a particular maneuver.	1	+
3.	Collective pitch (if applicable)	Full Range	For control movement of the aircraft	8	
4.	Longitudinal cyclic pitch (if applicable)	Full Range	For control movement of the aircraft	8	
5.	Lateral cyclic pitch (if applicable)	Full Range	For control movement of the aircraft	8	
6.	Controllable Stabilator (if applicable)	Full Range	For control movement of the aircraft	8	
7.	Gearbox oil pressure (if applicable)	As installed		1	
8.	Gearbox oil temperature (if applicable)	As installed		0.5	

NOTE

"+" – represents parameters that weren't part of the original manned aircraft parameters but are crucial for UAS.

*[16] is a parameter whose recording intervals is recommended to be changed from that of the manned aircraft provided in the documents earlier mentioned. Because switching flight modes instantly affect UAS performance, some modes deactivate some sensors automatically (e.g., speed modes most often than not deactivates obstacle avoidance sensor/warnings). It is therefore recommended to record this status every second of flight.

4 FDR REQUIREMENTS FOR UAM

UAM plans to use highly automated aircraft that fly at lower altitudes within urban and suburban regions to operate and carry people and cargo in a safe and effective manner. For this reason, additional parameters must be recorded that may be relevant for passengers and cargo. The following parameters are also mentioned in 14 CFR Appendix E to Part 125 for manned aircraft with 20 or more passengers. They are the only parameters that effectively indicate the condition of the passengers and are therefore the only ones that go beyond the previously defined requirements and are relevant to be added.

Parameters To Be Measured

1. Cabin pressure altitude
2. Loss of cabin pressure

Table 4 shows the UAM requirements, where red values are unchanged from the manned aircraft parameters and the green values have been modified from manned aircraft parameters.

Table 4. UAM requirements.

	PARAMETERS	**RANGES**	**REASONS/JUSTIFICATION**	**MAXIMUM RECORDING INTERVAL IN HERTZ(Hz)**
1.	Cabin pressure altitude	As installed (0 – 50,000ft recommended)	Ensures the safe and normal breathing of onboard passengers	1
2.	Loss of Cabin pressure (warning)	Discrete	Indicates when Cabin pressure is compromised.	1

5 FDR REQUIREMENTS BASED ON AUTONOMY

In the past, a lot of research has already been conducted for autonomous Planetary Flight Vehicles (PFV) and other autonomous missions. To achieve the desired level of autonomy, in order to be considered a PFV, the researchers precisely focus on design autonomy metrics for aerial missions, thus proposing Autonomous Control Levels (ACL). Likewise, it can be observed that autonomous UAS must have an Equivalent Level Of Safety (ELOS) as a PFV and manned system. The autonomous aerial system should consider the following for achieving the fundamental desired safety: system safety and reliability (which considers airworthiness, obstacle avoidance as well as validation and verification), fault tolerance system architecture (which considers robustness, situational awareness, and automated operation), and contingency management (which considers fault detection and prognostics, follows the emergency procedures and other miscellaneous factors including software certification, ELOS certification, and air traffic management) (Young, Yetter, & Guynn, 15 Jun 2012).

Firstly, **Error! Reference source not found.** (Young, Yetter, & Guynn, 15 Jun 2012) provides an overview of the different levels of autonomy. Secondly, real-time civil applications of UAS in the ongoing circumstances are investigated. Finally, a few FDR parameters are suggested, based on the level of autonomy given in the table.

The Air Vehicles Directorate at the Air Force Research Laboratory first proposed the ACL concept to develop autonomous air vehicles and autonomous agents for UAS control systems (Clough, 2002) (Unmanned Aerial Vehicles Road Map 2000-2025, 2001). The goal was to replace the human in the aircraft for any mission. Therefore, the aerial vehicle has to be given autonomy, in order to complete the mission successfully. It was discussed, how a UAS should act and perform different tasks, or how it could have performed the tasks more effectively in order to complete the mission's objectives.

From those efforts, the ACL chart was created via intense discussions, conducting research with various research laboratories funded by government departments, institutions, and other industries.

Nowadays, various versions of the ACL chart are proposed in different literature and an improved version can be found in the report published by the Defense Technical Information Center (Unmanned Aerial Vehicles Road Map 2000-2025, 2001), which is now used as a standard. Afterwards, the National Aeronautics and Space Administration (NASA) team concluded that these ACL charts are too complex and too extensive to handle which made them adopt a simplified set of metrics for the Levels Of Autonomy (LOA). Regarding the LOA the concept of “hands-on-time” is introduced. This illustrates the percentage of a pilot’s time that would be needed to operate a UAS safely in an ongoing mission. The hands-on-time is thereby limited to a pilot/operator and does not integrate other personnel during the mission. It is therefore important to know the level of autonomy in order to define the FDR requirements accordingly.

Table 5. Levels of autonomy.

LOA	LEVEL	DESCRIPTION (FEATURES)	SAMPLE CHARACTERISTICS

0	Remote Controlled	Remotely piloted aircraft with a human in the loop, making all the decisions. The operator is in constant control. (100% hands-on-time.)	> R/C airplane
1	Simple Automation	Remotely piloted with some automation techniques to reduce pilot workload. Human monitoring to start/stop tasks. (80% hands-on-time.)	> Basic autopilot
2	Remotely Operated	Human operator allows UAS onboard systems to do the piloting. As part of the outer control loop, the human decides where to go, when, and what to do once there. Remotely supervised, with health monitoring and limited diagnostics. The operator allows UAS to execute preprogrammed tasks, only taking over if the UAS is unable or fails to properly execute them. (50% hands-on-time.)	>Integrated Vehicle Health Management (IVHM) > Onboard Contingency Management capabilities > Waypoint navigation
3	Highly-Automated or Semi-Autonomous	UAS automatically performs complex tasks. The system understands its environment (situational awareness) and makes routine decisions and mission refinements to dynamically adjust to flight and mission variables. Limited human supervision, managed by exception. Adaptive to failures and evolving flight conditions. (20% hands-on-time.)	> Loss-link mission continuation > Automatic take-off/land > Adaptive control techniques > Reactive “search and find” terrain recognition
4	Fully Autonomous	UAS receives high-level mission objectives (e.g., location, time) and translates them into tasks that are executed without further human intervention. UAS has the ability and authority to make all decisions. Extensive situational awareness (internal and external), prognostics, and onboard flight re-planning capability. Single vehicle operations. (Less than 5% hands-on-time.)	> Automated in-flight replanning > Mission sensor-directed operations
5	Collaborative Operations	Brings in aspects of multiple UASs working autonomously together as a collective intelligent system. Group coordination. Individual vehicles/systems in a collaborative group will have at least	> Cooperative and collaborative flight

		semi-autonomous LOA (3) to keep the operator workload of the collaborative operation at a manageable level. (Sum of total hands-on-time of all air vehicles would not exceed a single operator hands-on-time of 100%.)	> Mother- and daughter-ship collaborative operations > Team leader concept for cooperative systems > Robotic swarms

A survey conducted by the NASA Vehicle System Program (VSP) team suggests different types of civil UAS missions, shown in Table 6. Generally, a great number of applications have been proposed for autonomous system technologies. Here, it can be observed that there are some terrestrial and planetary applications, which use autonomous system technologies with certain characteristics, challenges, and difficulties. Consequently, the LOA can be fit into the outlined autonomous system technologies applications scenario to verify the system's capabilities handling the FDR autonomous requirements accordingly. Hence, whenever a UAS is on a mission to fulfill a task, it will measure the parameters provided in the General FDR requirements section and shall save all the data for further processing, e.g., in the event of a malfunctioning or hazardous situation.

Table 6. Examples for autonomous UAS missions.

Civilian Mission	**Flight/Mission Profile**	**Critical Capabilities**	**Technical Hurdles**	**Autonomous System Technology Challenge**	**Hazard Awareness**
Telecom Relay Services	Launching from Local Airport to Station-Keeping Altitude (>60k ft) Long duration lingers (> 30 days)	Capacity of Payload and flight stationing bearing	Electrical Power, Propulsion's reliability	Need to be highly autonomous during flight endurance, payload management autonomous, health monitoring and prognostics of overall flight	Services Interference/Disruption
Violent Storm Tracker	Transit/launch from a few regional centers; mid altitude (40K<Alt<60	Powerful structure and capabilities of handling aero characteristic		Aero-Handling Control Surface Failure, Science	Aircraft loss due to strong winds, severe weather

	K ft) long range (>1000 Km) cruise within operation area after increasing altitude to >60kft and tracking the storm for 4 to 10 days	s that may fly in modest turbulence		payload Management, sensor or payload driven in-flight replanning such as onboarding	
Border and Coastal Patrol	Initialization from a regional center cruise at 40L<Alt<60K < ft) (>1000KM) Long-range duration of 4 to 10 days	Perfect flight platform including high resolution sensing/imaging ability that can cover large survey areas		Science payload management, re-planning considering real-time awareness, secure, high-bandwidth data networking or relaying	Not able to obtain and transfer critical observation to certain decision-makers in a timely manner
Station-Keeping for Scientific Purposes	Monitor the Volcanoes, Ozone holes, polar Toxic Ocean Blooms, etc. Deployment from National Science Centers, Station keeping altitude (>60k ft) duration loiter greater than 30 days	Long enduring, with lower speed loiter capability coupled with large payload.		Science payload management	Service Disruption
Long-range Scientific Missions &	Transient Observation or widely			Sensor/Science driven navigation	Not able to obtain and transfer

Surveillance Mission	distributed event such as survey of damages and coordination of larger scales natural disasters, hurricanes and earthquakes, Migration pattern of animal or insects, measurement of spatiotemporal changes in air or ocean currents, Assessing compliance of international regulations over international laws, such as whale harvesting prohibition. long range (>1000 km) 4 to 10 days moderate mission (40K<Alt<60k ft), Navigation by preplanned GPS Points and sensor. Science driven			and goal-based decision making	critical observation to certain decision-makers in a timely manner

	decision making				
Distributed/Sensor Network Aerial Constellation	Repeat Pass Interferometry (RPI), Military and Civilian Detection (association with manned aircraft), deployment of drones, UAS connected coordinating together for a common goal	Near-real-time or better information fusion/data from various aircraft and other assets	Repeated precision over-flight of critical way points	Challenge is vehicle to vehicle and vehicle to Gound control, vehicle to other intelligent system coordination	Collison Avoidance, Operational Difficulties managing multiple UASs
Forest Fire/ Wild life Surveyor	After satellite monitoring for affected areas the launch of UAS is performed from national regional centers which does the real time monitoring of propagation of fire including provide information regarding coordinates to groundcrews and manned aircraft for firefighting	Real-time planning and real time re tasking	Should be cost-effective with on demand reliability and availability	High speed data & information sharing, networking and intelligent mission management	Not making appropriate decisions in a timely manner due to inability to opt and share the critical intelligence to given decision makers

	(Highspeed (>100knots)) Altitude (40K<Alt<60 K ft) Capability for long-range >1000 km with short duration of 1 day				
Aerial Explorers	Planetary Surveys, Surface Collaborative association with probes and robotic devices, Capabilities of Vertical Take Off and Landing (VTOL), Non-GPS navigation requirement				

Parameters To Be Measured

An important factor on which the FDR requirements depend is what algorithms are used to ensure autonomy. Current approaches are often based on computer vision and deep learning (Dergachov, Bahinskii, & Piavka, 2020) (Li, et al., 2021), which results in two problems: 1) Sensor data, especially cameras and Light Detection and Ranging (LiDAR), can require a lot of computing power and a large storage medium. Current estimates suggest that autonomous vehicles can generate up to 3 Gbit/s at low autonomous levels and up to 40 Gbit/s at high autonomous levels (Heinrich, 2017). Although not all of these data may be required for an evaluation of an incident, these values give a rough idea of the amount of data these systems work with. 2) Decisions made by Deep Learning (DL) approaches which are often used in autonomous systems are not transparent and, therefore, difficult to explain, which can be a problem when analyzing the cause of a crash. Current storage media quickly becomes too small for the amount of data generated. This means that although it would be good to record these sensors, it is hardly feasible with current possibilities. This leads to the problem that while one can determine if the position of the flaps, velocity, etc., are an anomaly and may be a cause of a problem, it is not possible to tell if that problem was a technical failure of the hardware or caused by an incorrect prediction of the deep learning models. This means to determine whether the cause of a problem was an incorrect prediction or a hardware failure, the exact configurations of the software and its version used should be stored, as well as all the data that were available as inputs at any given time. Without this information, it is impossible to determine the cause of a problem. However, even if all inputs are recorded, it is often difficult to understand the reasons for a bad decision. Especially when these are based on DL methods like artificial neural networks. It can be determined that a decision of an autonomous system was bad, but often it cannot be explained why. For this reason, explainable artificial intelligence (XAI), that can give insights in the decision making of DL systems, is still an important research topic that needs further investigation and has been addressed in many recent papers (Došilović, Brčić, & Hlupić, 2018). Another information that could optionally be recorded to help interpret the decisions of a DL system would be the intent of the system. Thus, certain additional information could be recorded, e.g. when an obstacle has been detected and an avoidance maneuver is initiated, or due to unexpected events the flight path has to be adjusted, etc.

To solve this dilemma, the researchers recommend the following requirements for the different levels of autonomy: For level 0 to 2, there is a human in the loop most of the time. In an emergency, a pilot should always be able to intervene before a crash occurs. Therefore, it can be ruled out with high certainty that a UAS crashes due to a wrong prediction in these levels of autonomy as the UAS is closely monitored despite. In these scenarios, the previously defined requirements should be sufficient. For level 3 to 5, on the other hand, there is ideally no pilot in the loop most of the time. This means that in this scenario, it is more likely a problem can occur due to an incorrect prediction by an algorithm, since these problems will probably not be noticed quickly and, therefore, an intervention by a pilot may not be in time or take place at all. Accordingly, it is important to record all inputs available to the DL system as well as the exact configuration of these systems. As mentioned before, there may be problems with data storage especially on smaller UAS due to lack of storage capacity in a necessary compact form. The data could be stored either with a very small resolution or would have to be deleted every few seconds so that only the last few seconds before a problem occurred are available. In the future, however, these workarounds should be avoided if technology permits. In UAS of larger formats, however, this should not be a problem at the present time.

To achieve higher levels of autonomy, different subsystems of the UAS are automated. These include procedures such as Detect and Avoid, whereby the UAS automatically detects other aircraft and obstacles in order to avoid collisions. Some UAS could use systems from manned aviation, such as TCAS (traffic collision and avoidance systems) or ADS-B (automatic dependent surveillance-broadcast). However, additional sensors which manned aircraft does not necessarily have might be required. Table 7 lists some examples of sensors that can be used for this task. Especially for higher levels of autonomation some or all these sensors will be required and are fundamental for the decision making of the overall system. Accordingly, they are important in the evaluation of crashes and should be recorded especially when the hands-on time of the pilot is low.

Table 7. Additional sensors for autonomous UAS.

PARAMETERS	REASONS/JUSTIFICATION	RECORDING INTERVAL
Exact configuration of all algorithms and machine learning models used	To be able to test the system in case of incorrect predictions.	on change
Camera (if applicable)	To be able to test after crashes or other incidents if there was a bad prediction.	Tbd
Lidar (if applicable)	To be able to test after crashes or other incidents if there was a bad prediction.	Tbd
Ultrasonic (if applicable)	To be able to test after crashes or other incidents if there was a bad prediction.	Tbd
All other sensor values used as inputs for the algorithms. which do not overlap with the previously defined requirements.	To be able to test after crashes or other incidents if there was a bad prediction.	Tbd

6 CVRS FOR UAS

The requirements from the documents analyzed in the literature review showed that CVRs from manned aircraft usually include all voice communication from the flight crew members, the communication transmitted from or received in the airplane by radio, and datalink communication (14 CFR § 23.1457 - Cockpit voice recorders.). Currently there are no existing voice communication requirements for UAS or UAM. In future scenarios UAS might be fully integrated into the NAS which means, that UAS pilots will have to communicate with ATC or in a UAM scenario there will be communication with passengers or a flight crew on board that should be recorded. The current requirements for manned aircraft must therefore be adapted under the consideration that the pilot of a UAS is in a ground station and not in the aircraft if a pilot is needed at all and the UAS is not fully autonomous. This means that the requirements must be adjusted depending on the scenario. Thus, in the following section CVR requirements are defined for non-autonomous UAS and for autonomous UAS.

6.1 CVR Requirements for Non-Autonomous UAS/UAM

If the pilot communicates with Air Traffic Control (ATC) It is important to record the communication. In scenarios where there is a flight crew on board, e.g., in a UAM scenario, the complete communication of the flight crew is recommended to be recorded. This includes communication with the passengers via loudspeaker, as well as communication between the flight crew and the pilot. If there is a data link, the data transmitted from and received by the aircraft should be recorded. If there is no crew on board, it is not necessary to store the recordings on a CVR recorder on board the UAS. The data can be stored directly in the ground station to ensure that no data is lost or destroyed in the event of a crash. However, if a crew is on board, existing requirements (14 CFR § 23.1457 - Cockpit voice recorders.) can be adopted.

6.2 CVR Requirements for Autonomous UAS/UAM

When considering CVR for autonomous UAS, it becomes more complicated to adapt existing requirements. This is mainly due to the lack of communication between the pilot and ATC. The Federal Aviation Administration (FAA) and NASA are currently researching Unmanned Traffic Management (UTM) systems that will allow UAS to be integrated into the NAS (Unmanned Aircraft System Traffic Management (UTM)). Accordingly, the data exchanged, and the communication between the UTM and the UAS must be recorded accordingly. Since it is possible that the communication could be interrupted and information sent by the UAS or the UTM could not be received, it is important to record the communication from both sides. This means that even if there is no crew on the UAS, a CVR is necessary to find out if any data has been corrupted or lost during the transfer. Microphones that record ambient noise are recommended in the case of UAMs in which a flight crew or passengers are on board, to record their communication. Optionally, additional microphones could be aligned in such a way that it is also possible to detect whether, for example, an engine has failed. Additionally, vibrations could be recorded with those additional microphones, which could be help to draw conclusions about the state of the aircraft during evaluation after a crash. This would be particularly useful for larger UAS and UAM.

7 EXCLUDED PARAMETERS

Since the goal of the research is to recommend the minimum FDR & CVR requirements for various UAS operational domains, certain parameters were therefore excluded or summed up into a single parameter.

A). Parameters 25, 27, 34-35, 38-45, 47, 52-59, 61 & 69, 76, and 80-82 from (ED-112A - MOPS for Crash Protected Airborne Recorder Systems, September 2013) were excluded from the UAS parameters to be measured due to the following reasons:

- 25-27: Navigation and status data- which has already been accounted for in the parameters in Table 1, adding this will result in large amount of redundant data which may not be necessary and can be costly for manufacturers to integrate.
- 38-45: These are cockpit selected altitude, airspeed, heading etc., which are already recorded per time above and this would result in large amount of redundant data, more memory space and hence recommended to be excluded for UAS.
- 47: Falls under engine status (hence large amount of redundant data).
- 52-59: Propulsion and warning status- Already recorded in the Tables above.
- 61 & 69: Ice detection and deicing system are not necessary and can be costly for manufacturers to research and implement both for sUAS and medium-sized UAS. Hence inside and outside temperature would suffice as stated in FDR for UAS parameters above.
- 76: Event Marker - Used by pilots in the cockpit to mark events and are not necessary for UAS as all events are recorded. Hence the reason for FDR for UAS.

B). In the document, (14 CFR Appendix E to Part 125 - Airplane Flight Recorder Specifications) parameters 46-54, 56-58, 61, 71-77, 79-81, and 88-91 were excluded for the following reasons:

- 46-54: Same as 38-45 of excluded parameters in A above.
- 56-58 & 79-81: same as 52-59 of excluded parameters in A above.
- 61&72: same as 61&69 of excluded parameters in A above.

C). Helicopter parameters 15, 19, 35, 38-45, 48 and 52-53 from (ED-112A - MOPS for Crash Protected Airborne Recorder Systems, September 2013) were excluded due to the following reasons:

- 15: Accounted for in flying modes in Table 3.
- 19: Replace with auxiliary actuators for payload mounting.
- 35: Same as 61&69 of excluded parameters in A above.
- 38-45: Same as 38-45 of excluded parameters in A above.
- 48: Same reason as 76 of excluded parameters in A above.

8 SAMPLING INTERVALS

Although, most manned aircraft have greater maximum airspeed as compared to UAS, parameters related to speed, acceleration, pitch attitude etc., of UAS are recommended to have maximum recording intervals as those of manned aircraft. This will provide more data to be measured and consequently greater precision and accuracy during crash analysis.

These values are only a rough estimate and are based on the values of existing requirements. Whether and how far this can be optimized would have to be tested in detailed real-world scenarios.

9 EASE OF IMPLEMENTATION OF THE PROPOSED REQUIREMENTS

The proposed requirements are mostly part of existing FDR requirements for standard manned aircraft. The requirements should be practicable for UAS with comparable size and weight as regular aircraft. However, since UAS can be much smaller than standard manned aircraft, it should be considered that size, weight, and power (SWaP) limitations may occur. These smaller UAS, which are currently often used for recreational purposes and are freely available on the market, already meet most of the requirements. These UAS are often limited by a small battery which means that an important factor is the efficiency while recording the data. Furthermore, depending on the specified size, and the necessary requirements for the robustness of the flight recorder, it could happen that it becomes too heavy or large for smaller UAS. So more detailed tests in a real environment would have to be performed to be able to say with certainty which parameters are most valuable for a crash evaluation, how often samples have to be recorded per second to achieve sufficient resolution, and how heavy a dedicated FDR can be. Further testing should establish a threshold to define at what size of UAS the requirements should apply, and a dedicated FDR must be installed on the UAS.

10 OPEN CHALLENGES

Several research questions emerged from this task that require further investigation in order to draw firm conclusions. One important aspect is the rate at which data is to be recorded by the FDR. This rate depends on several factors, as discussed before. A higher rate can provide more information and even better analysis, but it increases the cost and power required. If more sensors are recorded, more power is also required, especially recording camera images can increase this drastically. Accordingly, the best trade-off between a greater variety of data, recording rate, and cost may be different in different use cases. Unfortunately, this could not be analyzed in more detail within this project's scope, so future research on finding the best trade-off with real prototypes would be interesting.

Since functions of autonomous systems as well as autonomous UAS are often using DL algorithms, it is important to make the behavior of these models is comprehensible. Although the records of the FDR can provide information about the inputs that occurred during a possible misbehavior, the decision of the model cannot necessarily be retraced. In order to make these autonomous systems safer in the long term, it is, therefore, necessary to further investigate the transparency and explainability of these systems.

Another challenge is reading and interpreting the recorded data. There is currently no fixed standard for a file format in which the data must be recorded, which can lead to very different files per manufacturer. Accordingly, it would make sense to investigate in the future whether it would be helpful to define a standard.

11 CONCLUSION

It was found that the general requirements that every UAS should fulfill can be adopted from manned aviation with slight modifications. The requirements for fixed-wing and rotary-wing UAS can also be taken over to a large extent from the existing requirements for airplanes and helicopters. For UAMs, recording parameters where anomalies in the sensor values would have an impact on the crew or passengers is recommended. For example, this includes the air pressure in the cabin. Most of the requirements recommended in this report are currently required and implemented in manned aviation and they are already used by manufacturers of commercial and recreational UAS to a large extend. Accordingly, the conclusion is drawn that the suggested requirements are implementable. It was found that only the requirements for FDRs for highly autonomous UAS with an autonomy level of 5 are problematic, since large amounts of data have to be recorded depending on the algorithms used. The reason for this is, that the decisions made by DL algorithms are difficult to explain. Without knowing the exact inputs, no conclusion can be made as to whether there was an incorrect prediction or the hardware was faulty. This poses future challenges, as research should be done on how high the sampling rate needs to be in order to get meaningful information from the data, as sensors like LiDAR or cameras can produce very large amounts of data in a short time.

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