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

Task 4

January 5, 2024

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16. Abstract

Task 4 discusses the research and results from Tasks 2 and 3 and updates the Task 2 report with relevant findings. In general, the FDR requirements were divided into two categories: data and parameter requirements, including type of data and refresh rate, and crash survivability, including the type of media used for data recording. Regarding parameters, a thorough examination of manned flight data monitoring standards was undertaken followed by augmentation with UAS-specific data. Task 2 findings also highlighted the importance of determining the optimal rate of data recording by the FDR, which depends on several factors. While a higher rate can provide more information and better analysis, it also increases the cost and power required. The document suggests that the best trade-off between data variety, recording rate, and cost may vary across different use cases. Task 4 also discusses the importance of crash survivability in the context of Unmanned Aircraft Systems (UAS), specifically small Unmanned Aircraft Systems (sUAS). It emphasizes the need for crash-survivable Flight Data Recorders (FDRs) due to the increasing use of UAS and the consequent rise in the probability of accidents. Crash-survivable FDRs are crucial as they maintain their integrity under challenging conditions and provide valuable information for accident investigation, analysis, and the development of enhanced safety measures. As an ancillary to this, Task 3 examined the crash survivability of SD cards commonly found in smaller UASs. There are several justifiable reasons for using an SD card in UAS, particularly small ones. Firstly, SD cards are lightweight and compact, which is a significant advantage in small UAS where every gram counts. They also require very little power, which is crucial for battery-operated UAS as it helps extend their flight time. The small size of SD cards allows them to be easily integrated into the limited space available in small UAS. Despite their compact size, SD cards can hold large amounts of data, making them suitable for extensive data collection missions. SD cards are also widely available, relatively inexpensive, and compatible with standard interfaces, making them a cost-effective and easily integrable solution for data storage in UAS applications. The document also outlines future research areas for improving crash survivability. These include expanding numerical simulations to study the influence of the Vehicle System (VS) location on loads and accelerations, designing a lightweight housing that can withstand critical conditions, and performing numerical analyses to optimize the material use and design of a prototype crash-protected FDR.

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ACL	Autonomous Control Levels
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
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
sUAS	small Unmanned Aircraft Systems
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
VS	Vehicle System

EXECUTIVE SUMMARY

Task 4 of the ASSURE A55 effort discusses the research and results from Tasks 2 and 3 and updates the Task 2 report with relevant findings. In general, the Flight Data Recorder (FDR) requirements were divided into two categories: data and parameter requirements, including type of data, refresh rate, and crash survivability, including the type of media used for data recording.

Regarding parameters, a thorough examination of manned flight data monitoring standards was undertaken followed by augmentation with UAS-specific data. Task 2 findings also highlighted the importance of determining the optimal rate of data recording by the FDR, which depends on several factors. While a higher rate can provide more information and better analysis, it also increases the cost and power required. The document suggests that the best trade-off between data variety, recording rate, and cost may vary across different use cases.

Task 4 also discusses the importance of crash survivability in the context of Unmanned Aircraft Systems (UAS), specifically small Unmanned Aircraft Systems (sUAS). It emphasizes the need for crash-survivable FDRs due to the increasing use of UAS and the consequent rise in the probability of accidents.

Crash-survivable FDRs are crucial as they maintain their integrity under challenging conditions and provide valuable information for accident investigation, analysis, and the development of enhanced safety measures. As an ancillary to this, Task 3 examined the crash survivability of SD cards commonly found in smaller UAS.

There are several justifiable reasons for using an SD card in UAS, particularly small ones. Firstly, SD cards are lightweight and compact, which is a significant advantage in small UAS where every gram counts. They also require very little power, which is crucial for battery-operated UAS as it helps extend their flight time. The small size of SD cards allows them to be easily integrated into the limited space available in small UAS. Despite their compact size, SD cards can hold large amounts of data, making them suitable for extensive data collection missions. SD cards are also widely available, relatively inexpensive, and compatible with standard interfaces, making them a cost-effective and easily integrable solution for data storage in UAS applications.

The document also outlines future research areas for improving crash survivability. These include expanding numerical simulations to study the influence of the Vehicle System (VS) location on loads and accelerations, designing a lightweight housing that can withstand critical conditions, and performing numerical analyses to optimize the material use and design of a prototype crash-protected FDR.

1 INTRODUCTION

1.1 Overview

Flight data requirements within aviation encompass a comprehensive range of criteria, crucial for ensuring the safety and efficiency of flight operations. These requirements are twofold, focusing not only on the data parameters that need to be recorded but also on the crash survivability of the recording devices, particularly the media within these devices.

Data parameters form the backbone of flight data requirements. These parameters include a wide array of flight-specific information such as altitude, airspeed, heading, engine performance, flight control inputs, and communication transcripts. The precise recording of these parameters is vital for multiple purposes. Firstly, they provide real-time data for flight monitoring, aiding pilots and operators in making informed decisions during the flight. Secondly, this data is invaluable for post-flight analysis, especially accident investigation. The number and nature of these parameters are continually evolving with advancements in aviation technology, thereby enhancing the scope and accuracy of flight data analysis.

The mere recording of flight data parameters is not sufficient. The survivability of the recording devices, especially the media that stores this data, is equally critical. In the event of an aviation incident, such as a crash, the retrieval of intact and readable flight data is paramount for investigation purposes. This necessitates the recording media to be exceptionally resilient. The design and construction FDRs are already governed by stringent regulations and standards outlined in Task 1 and further expanded in Task 2 (Appendix A). These standards ensure that the recorders can withstand extreme conditions such as high impact forces, deep-sea pressure, fire, and immersion in water.

The crash survivability features of these recording devices include robust, fire-resistant casings, and the use of solid-state memory, which is more durable than traditional magnetic tape or moving parts. The ability of these devices to survive severe crash scenarios and protect the integrity of the data they hold is a testament to the rigorous engineering and testing they undergo.

1.2 Parameters

Within the scope of Task 1, regulations for 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.

Based on Task 1, current standards are assessed and adjusted data recorder requirements for 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 Part 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 UAM 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 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.

1.3 Crash Survivability

The crash survivability of 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 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.

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., Global Navigation Satellite Systems (GNSS), Inertial Navigation Systems (INS), Microwave Landing Systems (MLS), Actual Navigation Performance (ANP), Estimated Position Error (EPE), Estimate of Position Uncertainty (EPU), Long Range Navigation (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)
- Detect and Avoid Sensors
- 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.

No	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	Determines if the airspeed of the aircraft on every event is		

		maximum for aircraft+	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 operational range on every event.	4	
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)/ Glide Path (If Applicable)	Full Range	Determines all landing aids along with their accuracies.	1	
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	1	+

			satellite(s), which can influence the performance of an aircraft.		
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 Retractable gears position (if applicable), etc. *[11]	Full Range/ Discrete	Measures all other integrated systems that are not crucial to aircraft flights but might affect aircraft performance, if faulty.	1	+
44.	**All (warning) sensors e.g.** • TCAS (Traffic Alert and Collision Avoidance System) • GPWS/TAWS – (Ground Proximity Warning System/Terrain	Discrete or as installed	Indicates fault or possible fault in an aircraft.	1	

	Awareness Warning System) • Low power level warning • GPS loss • All engine malfunctions • Low hydraulic pressure Transmission loss warning (with transmitter or Ground station).				

NOTE

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

*[1-11], This 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 as follows:

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

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

*[3], Most UAS are relatively smaller than manned aircraft, hence can change heading much quicker than manned aircraft, so 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 an aircraft's performance, it would be great to know the status of this per second.

*[6], Most UAS are heavily dependent on batteries, 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)	See Note Below
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

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

*[12-15], These represent parameters whose recording intervals are recommended to be changed from those of the manned aircraft provided in the documents earlier mentioned. These are a 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

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

*[16], This is a parameter whose recording interval is recommended to be changed from that of the manned aircraft provided in the documents previously mentioned. Because switching flight modes instantly affects 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 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 focused 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 to complete the mission successfully. It 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 and 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 LOA 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 > 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 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%.)	> Cooperative and collaborative flight > Mother- and daughter-ship collaborative operations > Team leader concept for cooperative systems > Robotic swarms

A survey conducted by the NASA Vehicle System Program 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 record 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 K ft) long range (>1000 Km) cruise within operation area after increasing altitude to >60kft and tracking the storm for 4 to 10 days	Powerful structure and capabilities of handling aero characteristics that may fly in modest turbulence		Aero-Handling Control Surface Failure, Science payload Management, sensor or payload driven in-flight replanning such as onboarding	Aircraft loss due to strong winds, severe weather
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	Long enduring, with lower speed loiter capability coupled with large payload.		Science payload management	Service Disruption

	ft) duration loiter greater than 30 days				
Long-range Scientific Missions & Surveillance Mission	Transient Observation or widely 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<60			Sensor/Science driven navigation and goal-based decision making	Not able to obtain and transfer critical observation to certain decision-makers in a timely manner

	k ft), Navigation by preplanned GPS Points and sensor. Science driven 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 Ground 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	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

	provide information regarding coordinates to groundcrews and manned aircraft for firefighting (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				

Impacts of Data Quantity on Recorded Data

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, 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). Other 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 to avoid collisions. Some UAS could use systems from manned aviation, such as TCAS or 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 measurements	Tbd
Lidar (if applicable)	To be able to test after crashes or other incidents if there was a bad measurements	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 National Airspace System (NAS) which means, that UAS pilots will have to communicate with Air Traffic Control (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 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 this research is to recommend the minimum FDR and 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, 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 and more memory space and is therefore 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 and 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.
- 56-58 and 79-81: Same as 52-59 of excluded parameters in A.
- 61 and 72: Same as 61 and 69 of excluded parameters in A.

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 and 69 of excluded parameters in A.
- 38-45: Same as 38-45 of excluded parameters in A.
- 48: Same reason as 76 of excluded parameters in A.

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 CRASH SURVIVABILITY

10.1 Task 3 Findings

The crash survivability requirements for FDRs have undergone continuous adaptation since the introduction of the first crash-protected unit. The current standards are the result of extensive research and feedback from accident investigations. Although the fast-growing number of UAS operations have increased the number of incidents involving these types of aircraft, the lack of data for these events has led to an existing gap between the standards for traditional and lightweight flight recording systems. While documents like EUROCAE ED-155 have addressed some of these gaps for lightweight FDRs, it remains uncertain if these requirements are applicable to sUAS.

In the present task, the most common devices to store flight data in sUAS were reviewed. It was observed that most of the current sUAS brands use micro SD cards as the preferred technology to store the data. NIAR has evaluated the mechanical performance of two different types of micro SD cards for static compression, penetration resistance, and low-intensity fire loading conditions. Additionally, NIAR has studied crash-scenarios involving sUAS by utilizing advanced numerical models developed during previous ASSURE programs. The cutting-edge numerical methodologies to analyze similar devices were reviewed and applied in several preliminary simulations of electronic board drop tests. It was found that simplifying the chips in the numerical models by using the smeared properties is a powerful methodology to predict the transient response of the electronic boards without incurring a high computational cost. Additional methodologies to define the appropriate damping and post-processing settings were developed and verified through the LVI validation exercise of a DJI Phantom III PCB.

NIAR modified three sUAS finite element models (Quadcopter 2.7lb., Fixed-wing 2.55lb., and Fixed-wing 55lb.) by including a representative model of a sUAS FDR (Virtual Sensor). These models have been included in several crash analyses involving the sUAS and a variety of targets, such as aircraft structures, pedestrians, vehicles, buildings, and ground surfaces. The targets were selected to consider most of the possible crash-scenarios for the type of sUAS considered in this work. Considering the type of metrics defined in the mechanical standards for crash survivable FDRs, the loads in every direction, the resultant acceleration, and the impulse transferred to the VS were extracted from the analyses.

Based on the results from the 41 impact scenarios and the mechanical tests performed during the present effort, the following conclusions were extracted:

- The analyzed micro SD specimens remained readable after static crush testing in the load range between 70-2,785lb. (311.38-12,388.3N) and after a penetrating load with a 3/8” spherical indentor up to 30lb. (133.45N). The lower load range for the penetration resistance tests shows the structural limitations of these devices under dynamic loading conditions. On the numerical side, the maximum loads observed for the F2.55, Q2.7, and F55 sUAS were 500.2N (112.45lb.), 910.43N (204.67lb.), and 559.6N (125.8lb.), respectively. These predicted loads occur during a shorter period of time (0.5-3ms) than the analyzed penetration loads. The duration of these loads hinders the use of traditional mechanical tests such as the ones utilized in this work. Additionally, the affected area in the simulations differ from case to case and it cannot be associated to a specific indentor geometry. However, these values can be used as a reference for comparison with the failure loads obtained in the penetration resistance tests and the loads specified in the standards. The most similar condition described in the FDR mechanical standards is the penetration resistance. The latest versions of TSO-C123 **Error! Reference source not found.** and TSO-C124 **Error! Reference source not found.** specify an impact with a 500lb. (2224.11N) weight dropped from a height of 10 feet. The ED-155 does not require penetration resistance for fixed recorders; for deployable recorders, it requires the equivalent of an impact that simulates a landing velocity of 25m/s (80ft/s) onto a hard surface. The maximum load observed at the VS exceeds the minimum failure load of 35lb. obtained in the penetration resistance tests for 21 out of 41 analyses. This indicates that the flight data could be lost in more than 50% of the impact scenarios analyzed in this work. However, it is uncertain whether the penetration resistance loads outlined in TSO-C123 [4], TSO-C124 [5] and ED-155 accurately reflect those observed during a sUAS crash scenario. Therefore, consideration of new criteria specific to these aircraft may be necessary. In that case, the loads obtained during this work should serve as a guideline for the development of qualification tests.

- The maximum average accelerations observed for the F2.55, Q2.7, and F55 sUAS for a time window of 0.5ms were 4,850g, 9,800g, and 17,500g, respectively. It was observed that the recording devices used in sUAS are not required to comply with any mechanical standard. However, two of the most common commercially available brands (SanDisk and ATP) test these devices for a shock acceleration profile with a magnitude of 1,500g and a duration of 0.5ms. It is important to remark that only in 8 out of the 41 analyzed crash scenarios the maximum average acceleration level did not exceed this 1,500g level. The technical documentation of these devices does not specify if a failure occurs for shock magnitudes higher than this value. However, the acceleration values obtained from the simulations suggest that a crash-protection is essential to achieve a high probability of survival for the shock magnitudes expected in the analyzed crash conditions.
- Note that in this work, the FDR models replicated the mechanical behavior of the current sUAS recording devices. These devices are not crash-protected. Therefore, the loads and accelerations obtained from the numerical analyses should be considered critical when designing a lightweight crash-protection for sUAS FDRs.
- The highest loads were observed for the Q2.7lb. sUAS, which is a quadcopter architecture. The polycarbonate carcass failed in most of the simulations, leading to an unprotected FDR, which was then subjected to secondary impacts causing high loads and accelerations. The highest accelerations were observed for the F55lb. sUAS, which is a fully composite fixed-wing architecture. The composite skin and frames absorbed most of the impact energy by failing, which resulted in high-magnitude vibrations. The lowest loads and accelerations were observed for the F2.55 lb., a foam-based fixed-wing architecture. The foam body absorbed most of the impact energy in all the cases and redirected the high-mass components stopping them from aligning with the impact trajectory. Additionally,

for this sUAS, the VS was protected by the camera. This shows that the sUAS architecture and its construction materials affect the loads and accelerations observed at the FDR.

- The maximum temperature at which the micro SD cards were tested was 200°C. The specimens remained readable for all the tests.

11 OPEN CHALLENGES

11.1 Future Parameter Research

Several research questions emerged from this task that require further investigation 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 as 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. To make these autonomous systems safer in the long term, it is, therefore, necessary to further investigate the transparency 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.

11.2 Future Crash Survivability Research

The following topics could be addressed in future studies for sUAS FDRs:

1. Expand the numerical simulation matrix to study the VS location's influence on the loads and accelerations.
2. Design a lightweight housing able to withstand the critical conditions obtained during the present work. Note that depending on the sUAS type and operation, the housing should offer protection for other hazardous conditions not analyzed during this work, such as water/fluid immersion, low and high temperature, and hydrostatic pressure.
3. Perform numerical analyses, including a detailed finite element model of a prototype crash-protected FDR into the crash simulations developed under this task. Optimize the material use and the design based on the simulation results. It is recommended that the crash-protected FDR is valid for any sUAS architecture.
4. Develop dynamic mechanical tests similar to the ones developed in **Error! Reference source not found.** to understand the effect of the shock duration and magnitude and

support the numerical analyses to find the conditions that best represent an actual crash scenario involving a sUAS.

5. Use the results of the dynamic experimental test to build more robust FEMs of an FDR for a sUAS. Additionally, use the experimental results to calibrate the post-processing filters for loading conditions representative of a crash scenario.
6. Consider a broader temperature range along with soak times for the low-intensity fire tests.

12 CONCLUSION

12.1 Parameters 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 extent. 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.

12.2 Crash Survivability Conclusion

In Task 1 (Appendix B), the authors conducted a literature review from the initial phase of the project, and included an evaluation the existing standards of FDRs and CVRs in manned aviation and their potential adaptation to UAS. The document acknowledges the varied nature of UAS, leading to the categorization of different sets of requirements. It is noted that while many standards from manned aviation are applicable to UAS, the specific needs of FDRs for autonomous UAS operations warrant additional detailed testing in real-world conditions due to the large volumes of data these systems generate quickly.

The analysis also covers the FDR requirements for UAM and CVRs, concluding that while current standards are broadly suitable, further research is necessary for the efficient handling and storage of large and diverse data sets. The document also highlights the criticality of determining the appropriate intervals for data recording.

The findings suggest that the proposed FDR specifications for UAS, similar to those for standard manned aircraft, are viable for UAS of comparable size and weight. However, it points out that smaller UAS, typically used for recreational purposes, might encounter SWaP challenges. Although these smaller UAS generally meet most of the criteria, further empirical testing is recommended to determine the most crucial parameters for crash analysis, the ideal frequency of data recording, and the maximum allowable weight for an FDR.

12.3 Use of SD Cards for sUAS

Using an SD card to record data from UAS, particularly small ones, offers several compelling advantages, especially considering SWaP constraints.

Firstly, SD cards are incredibly lightweight and compact. In small UAS, where every gram counts, the minimal weight of an SD card is a significant advantage. This lightweight nature doesn't compromise its storage capacity, which is crucial for data-intensive applications like high-resolution photography or video recording. Small UAS can thus carry out their missions without being burdened by heavy storage devices.

Additionally, SD cards require very little power, an essential factor for battery-operated UAS. The low power consumption of SD cards helps extend the flight time of UAS, allowing for longer missions or more data collection. This is particularly beneficial for small UAS, which may have limited battery capacity due to their size.

The size of SD cards also plays a critical role. Their small form factor allows them to be easily integrated into the limited space available in small UAS. This compact size does not mean a compromise in storage capacity; modern SD cards can hold large amounts of data, making them suitable for extensive data collection missions.

Furthermore, SD cards are widely available and relatively inexpensive, making them a cost-effective solution for data storage in UAS applications. Their universal design and compatibility with standard interfaces mean they can be easily integrated into most UAS without the need for specialized hardware.

As demonstrated in Task 3, the work conducted by NIAR makes a compelling case for the use of SD cards where standalone FDRs are neither possible or feasible.

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