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

Task 5 – Final report

April 12, 2024

v 1.1

NOTICE

LEGAL DISCLAIMER

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. A11L.UAS.101	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle A55 Identify Flight Recorder Requirements for Unmanned Aircraft Systems (UAS) Integration into the National Airspace System (NAS)		**5. Report Date** 12th April 2024 **6. Performing Organization Code**
7. Author(s) James Higgins		**8. Performing Organization Report No.**
9. Performing Organization Name and Address University of North Dakota Embry-Riddle Aeronautical University Wichita State University		**10. Work Unit No.** **11. Contract or Grant No.**
12. Sponsoring Agency Name and Address Federal Aviation Administration Washington, DC 20591		**13. Type of Report and Period Covered** **14. Sponsoring Agency Code** 5401
15. Supplementary Notes		

16. Abstract

The comprehensive analysis and evaluation undertaken in this report focuses on identifying and developing Flight Data Recorder (FDR) requirements for the integration of Unmanned Aircraft Systems (UAS) into the National Airspace System (NAS). This multifaceted project, structured into several key tasks, describes the complexities and nuances of adapting and innovating FDR technologies to meet the unique demands of unmanned aviation.

This report is segmented into summaries of each project deliverable (Sections 2, 3, 4, and 5), building upon one another to create a cohesive narrative and logical progression of research and findings. Each section provides a concise yet comprehensive overview, background, findings, conclusions, and recommendations derived from the respective task, offering readers a snapshot of the significant themes and contributions originating from each phase of the research. For an in-depth exploration of the methodologies, data analyses, and technical discussions that underpin each task, the report is supplemented with extensive appendices (A, B, C, and D), corresponding to the complete original deliverables of Tasks 1 through 4, respectively.

The research culminates in several key insights about the future development of FDR technology in UAS. Recognizing the historical trajectory of FDRs from manned to unmanned aviation sets a blueprint emphasizing transition from analog to solid-state technologies, focusing on data fidelity, storage capacity, and survivability. These principles are crucial as the UAS sector evolves to include diverse operational profiles and autonomous capabilities.

A major conclusion is the need for harmonization in the regulatory landscape to address the unique challenges of UAS operations. Establishing universal FDR standards that adapt to technological advancements and different UAS types is crucial. The integration of real-time telemetry and ensuring data integrity are particularly important, given the increasing reliance on autonomous decision-making systems in UAS.

The report emphasizes the importance of stakeholder engagement and collaborative development to enhance the effectiveness of FDR standards. It is suggested that involving industry stakeholders, regulatory bodies, and safety organizations will help ensure that the standards developed are practical, comprehensive, and reflective of the current and future needs of the UAS community.

Among the strategic recommendations, the report advocates for adopting specific FDR parameters detailed in Deliverable 4 and recognizing SD cards as feasible data storage solutions for smaller UAS. It also calls for further research into FDR survivability under extreme conditions and the development of dynamic mechanical tests to better simulate crash scenarios, enhancing the robustness of FDR designs.

Overall, the report lays out a roadmap for advancing FDR technology in UAS, guiding stakeholders through necessary research, policy initiatives, and collaborative efforts to ensure safe, efficient, and integrated UAS operations within the global airspace system.

17. Key Words Flight data recorder, Unmanned Aircraft	**18. Distribution Statement**		
19. Security Classification (of this report) Unclassified	**20. Security Classification (of this page)** Unclassified	**21. No. of Pages** 325	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

TABLE OF ACRONYMS

ATC	Air Traffic Control
CFR	Code of Federal Regulations
CVR	Cockpit Voice Recorder
EUROCAE	European Organization for Civil Aviation Equipment
FAA	Federal Aviation Administration
FDR	Flight Data Recorder
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
LiDAR	Light Detection and Ranging
LOA	Level of Autonomy
NAS	National Airspace System
SWaP	Size, Weight, and Power
TCAS	Traffic Alert and Collision Avoidance System
UAM	Urban Air Mobility
UAS	Unmanned Aircraft Systems
UTM	Unmanned Traffic Management

EXECUTIVE SUMMARY

The comprehensive analysis and evaluation undertaken in this report focuses on identifying and developing Flight Data Recorder (FDR) requirements for the integration of Unmanned Aircraft Systems (UAS) into the National Airspace System (NAS). This multifaceted project, structured into several key tasks, describes the complexities and nuances of adapting and innovating FDR technologies to meet the unique demands of unmanned aviation.

This report is segmented into summaries of each project deliverable (Sections 2, 3, 4, and 5), building upon one another to create a cohesive narrative and logical progression of research and findings. Each section provides a concise yet comprehensive overview, background, findings, conclusions, and recommendations derived from the respective task, offering readers a snapshot of the significant themes and contributions originating from each phase of the research. For an in-depth exploration of the methodologies, data analyses, and technical discussions that underpin each task, the report is supplemented with extensive appendices (A, B, C, and D), corresponding to the complete original deliverables of Tasks 1 through 4, respectively.

The research culminates in several key insights about the future development of FDR technology in UAS. Recognizing the historical trajectory of FDRs from manned to unmanned aviation sets a blueprint emphasizing transition from analog to solid-state technologies, focusing on data fidelity, storage capacity, and survivability. These principles are crucial as the UAS sector evolves to include diverse operational profiles and autonomous capabilities.

A major conclusion is the need for harmonization in the regulatory landscape to address the unique challenges of UAS operations. Establishing universal FDR standards that adapt to technological advancements and different UAS types is crucial. The integration of real-time telemetry and ensuring data integrity are particularly important, given the increasing reliance on autonomous decision-making systems in UAS.

The report emphasizes the importance of stakeholder engagement and collaborative development to enhance the effectiveness of FDR standards. It is suggested that involving industry stakeholders, regulatory bodies, and safety organizations will help ensure that the standards developed are practical, comprehensive, and reflective of the current and future needs of the UAS community.

Among the strategic recommendations, the report advocates for adopting specific FDR parameters detailed in Deliverable 4 and recognizing SD cards as feasible data storage solutions for smaller UAS. It also calls for further research into FDR survivability under extreme conditions and the development of dynamic mechanical tests to better simulate crash scenarios, enhancing the robustness of FDR designs.

Overall, the report lays out a roadmap for advancing FDR technology in UAS, guiding stakeholders through necessary research, policy initiatives, and collaborative efforts to ensure safe, efficient, and integrated UAS operations within the global airspace system.

1 INTRODUCTION

In the rapidly evolving landscape of aviation technology, the integration and optimization of Flight Data Recorders (FDRs) for Unmanned Aircraft Systems (UAS) stand at the forefront of enhancing operational safety, efficiency, and compliance with regulatory standards. This hopefully comprehensive report represents the culmination of extensive research, analysis, and evaluative efforts undertaken across multiple phases of the project, specifically encapsulated within Tasks 2, 3, 4, and 5. Each of these tasks has been designed and executed with the objective of establishing a path towards robust, adaptable, and technologically advanced FDR solutions tailored to the unique requirements and operational concepts of UAS.

To facilitate a coherent and accessible narrative, this report is systematically organized into distinct sections that correspond to the respective tasks, hopefully ensuring a seamless flow of information and insights. The structure is intentionally crafted to cater to a diverse audience, encompassing industry stakeholders, regulatory bodies, academia, and other entities engaged in the UAS domain.

1.1 Final Report Format

Each section of the report adheres to a uniform format, comprising the following components:

1.1.1 Overview

Initiating each task section, the overview provides a concise yet comprehensive summary of the task's core objectives, scope, and pivotal findings. This segment is engineered to offer readers a snapshot of the essential themes and contributions emanating from each phase of the research, setting the appropriate stage for the detailed exposition that follows.

1.1.2 Background

Delving deeper, the background segment offers a rich tapestry of contextual information, tracing the historical evolution of FDR technology from its inception in manned aviation to its current and potential applications within the realm of UAS. The foundational rationale for integrating FDRs into UAS operations, highlighting the parallels, divergences, and lessons drawn from the broader aviation industry is explored in this section. It sets the stage for a nuanced understanding of the challenges and opportunities inherent in adapting FDR technology to the unique characteristics of unmanned flight.

1.1.3 Findings

At the center of each task section is the findings—a detailed account of the results yielded from rigorous investigative and analytical processes undertaken during each task. This includes an exploration of technical specifications, operational challenges, regulatory implications, and the potential for improvement within the FDR domain as it pertains to UAS. The findings section is replete with data-driven insights, observations, and thematic assessments that underscore the complexities and nuances of developing and implementing FDRs in UAS.

1.1.4 Conclusions

Synthesizing the insights garnered from each task, the conclusions segment distills the findings into central themes and takeaways. It reflects on the broader implications of the research, explaining the critical role of FDR technology in advancing UAS safety, regulatory adherence, and operational efficacy. The conclusions drawn hopefully serve as a strategic compass, guiding future endeavors in the FDR and UAS landscape.

1.1.5 Recommendations

Building upon the foundational conclusions, this segment formulates a series of forward-looking recommendations designed to propel the development and integration of FDRs within the UAS sector. These recommendations are framed to address the multifaceted challenges identified, offering actionable guidance for industry stakeholders, regulatory authorities, and the research community. The recommendations aim to foster innovation, standardization, and best practices in FDR technology, ensuring its alignment with the evolving needs and potentials of UAS operations.

1.1.6 Comprehensive Appendices

For those desiring a deep dive into the granular details, methodologies, data analyses, and technical discussions underpinning the tasks, the report is supplemented with an extensive set of appendices. Appendices A, B, C, and D correspond to the complete original deliverables of Tasks 2, 3, 4, and 5, respectively. These appendices serve as a repository of in-depth information, providing detailed insights that form the backbone of the conclusions and recommendations connected within the main body of the report.

1.2 Major Themes

Several themes have emerged during this research. These themes will be further explored in each subsequent section, but they are presented here as a means of introduction.

1.2.1 Enhancing FDR Functionality for UAS Adaptability

The dynamic nature of UAS operations, characterized by diverse platforms, varying levels of autonomy, and a wide range of applications, underscores the need for FDR systems that are not only adaptable but also resilient to the unique challenges presented by unmanned aviation. The report examines these challenges, exploring innovative solutions and technologies that can be leveraged to enhance FDR functionality and adaptability. This includes the examination of data storage mediums, such as the feasibility of utilizing SD cards for smaller UAS, and the exploration of advanced data encoding and decoding methods to ensure data integrity and reliability.

1.2.2 Regulatory Frameworks and Technological Advancements

A significant portion of the report is dedicated to addressing the intersection between regulatory frameworks and technological advancements in FDR development for UAS. The conclusions drawn from the analysis highlight the imperative for regulatory bodies and industry stakeholders to work in tandem, fostering an environment contributing to innovation while ensuring compliance with established safety standards. The recommendations put forth advocate for the harmonization of regulatory practices at both national and international levels, facilitating seamless integration of UAS into the global airspace system.

1.2.3 *Future Directions in FDR Research and Development*

Looking ahead, the report outlines a series of future research directions aimed at advancing FDR technology for UAS. This encompasses a broad range of areas, from enhancing the survivability of FDRs in adverse conditions to developing dynamic mechanical tests that more accurately replicate crash scenarios involving UAS. The recommendations also emphasize the importance of expanding numerical simulations and finite element models to improve FDR design and placement within UAS, ensuring maximum flexibility and effectiveness in data recording and preservation.

1.2.4 *Collaboration and Stakeholder Engagement*

A recurring theme throughout the report is the critical role of collaboration and stakeholder engagement in driving forward the development of FDR technologies for UAS. The collaborative efforts between regulatory authorities, industry leaders, academic institutions, and research organizations are essential in combining expertise, resources, and perspectives. This collective approach not only accelerates improvements but also ensures that the developed FDR standards and technologies are comprehensive, practical, and reflective of the diverse needs of the UAS community.

This final report represents the concerted efforts aimed at enhancing the FDR framework for UAS, contributing to a safer, more efficient, and compliant operational environment for unmanned aviation. Through a structured presentation of overviews, backgrounds, findings, conclusions, and recommendations, complemented by the rich reservoir of information contained in the appendices, this document aspires to be a reference for advancing FDR development in the UAS domain.

The endeavor to develop and refine FDR technologies for UAS is both a response to the expanding growth of UAS applications across various sectors and a proactive measure to integrate these systems into the aviation ecosystem with enhanced safety and efficiency. As UAS operations become increasingly complex and widespread, the necessity for robust FDR capabilities becomes ever more critical. This report, through its analysis and comprehensive recommendations, aims to start a process towards achieving this goal.

2 TASK 1 DELIVERABLE

2.1 Overview

The integration of UAS into the National Airspace System (NAS) represents a central advancement in aviation technology, promising to redefine the landscape of aerial operations. The ASSURE A55 Literature Review, which is the Task 1 deliverable for the overall project, investigates the critical aspect of this integration: the identification and standardization of Flight Recorder Requirements for UAS.

The backdrop of this widespread review is set against the rich history and proven efficacy of FDRs and Cockpit Voice Recorders (CVRs) in manned aviation. These devices have been instrumental in enhancing flight safety by providing invaluable data for accident investigation and preventive safety measures. However, the transition of such technologies to the realm of unmanned aviation presents unique challenges and considerations, given the intrinsic differences between manned and unmanned aircraft operations.

The document begins by tracing the evolution of FDRs and CVRs in manned aviation, highlighting their role in accident investigation and safety management systems. It then transitions to the nascent application of these technologies in UAS, underlining the necessity for distinct requirements due to the operational and structural differences between manned and unmanned aircraft. The review examines the current regulatory landscape, encompassing both federal and international regulations governing the use of recording devices in aviation. It underscores the efforts by organizations such as the International Civil Aviation Organization (ICAO) and the European Organization for Civil Aviation Equipment (EUROCAE) in establishing recording standards, and how these might serve as a foundational basis for UAS flight recorder requirements.

Central to the discussion is the innovative potential of leveraging real-time telemetry data, transmitted from UAS to Ground Control Stations (GCS), as a modern analog to traditional FDRs. This approach not only addresses the unique operational dynamics of UAS but also introduces new concepts in data retrieval and analysis post-flight. The review explores various structural testing methodologies, both destructive and non-destructive, to assess the survivability of recording devices in the event of an accident, emphasizing the need for tailored standards that account for the distinguishing operational environments of UAS.

The literature review concludes with a compelling argument for the critical role of FDRs and CVRs in enhancing the safety and efficacy of UAS operations within the NAS. It suggests that the establishment of well-defined requirements for unmanned flight recorders is not only imperative for advancing UAS integration into the airspace but also for maintaining the high safety standards characteristic of aviation.

In synthesizing a broad array of literature, regulatory standards, and technical specifications, the ASSURE A55 Literature Review lays a foundation for the development of UAS flight recorder requirements. It attempts to encapsulate the collective expertise and foresight of the aviation community, steering the discourse towards novel solutions that promise to secure the future of unmanned aviation within the framework of global airspace integration.

2.2 Background

The emergence of UAS has catalyzed a transformative phase in aviation, extending its reach into unique commercial, recreational, military, and scientific domains. This paradigm shift demands a thorough reevaluation and adaptation of the prevalent aviation standards, especially those concerning flight safety mechanisms and data recording devices like FDRs and CVRs. This background section explores the historical trajectory of these recording devices within manned aviation, the rapid proliferation of UAS, the complex regulatory framework governing their operation, and the urgent need to create recorder standards specifically crafted for UAS integration into the NAS.

2.2.1 Evolutionary Trajectory of Flight Data and Voice Recorders

The inception of recording flight data traces back to the formative years of manned aviation, marking a foundation in aviation safety. The 1950s witnessed the deployment of the first-generation flight recorders, employing analog systems to capture rudimentary flight parameters and cockpit conversations. Subsequent technological advancements signaled the evolution of these devices, culminating in rapid advancement. This era ushered in solid-state memory recorders, characterized by their capacity to store extensive flight parameters and audio data, ensuring higher reliability and robustness in most conditions.

The pivotal role of FDRs and CVRs in aviation safety is indisputable, as they have consistently provided invaluable data contributing to numerous safety enhancements and regulatory formulations. The progressive refinement of these devices epitomizes the aviation industry's relentless quest to improve the ability to recreate pre-incident events, significantly mitigating the recurrence of accidents.

2.2.2 The Ascendance of Unmanned Aircraft Systems

Recent decades have seen a meteoric rise in UAS development and deployment, fueled by rapid technological progress and expanding applications. UAS, devoid of onboard human pilots, are either autonomously governed by onboard computational systems or remotely piloted from a Ground Control Station (GCS). The extensive diversity in UAS types, capabilities, and applications introduces a unique set of challenges and opportunities for the aviation sector, particularly with safety protocols and airspace integration considerations.

2.2.3 Regulatory Framework and UAS-Specific Standardization Imperatives

The seamless integration of UAS into the NAS is entangled within a complex matrix of regulations and standards laid down by various national and international entities. Domestically, the Federal Aviation Administration (FAA) is at the forefront of shaping the UAS regulatory landscape, drawing upon existing manned aviation standards while addressing the distinctive facets of unmanned operations. On the global front, the ICAO and EUROCAE stand as vital bodies in shaping UAS policies and guidelines.

In navigating through the regulatory environment, several standards and rules have been crucial in shaping the discourse on UAS recorder requirements. Notably, the Federal Code's stipulations for manned aircraft FDRs and CVRs and the technical standards, such as EUROCAE's ED-112A, serve as foundational elements. Additionally, regulations like 14 Code of Federal Regulations (CFR) Parts 23, 25, 27, and 29, along with ICAO Annexes 6, 10, 11, and 12, and EUROCAE documents such as ED-55/ED-112A and ED-155, have been instrumental in guiding the development of recorder standards. However, the unique operational dynamics, control mechanisms, and the potential for autonomous functioning of UAS necessitate a systematic reevaluation of data recording paradigms, storage methodologies, and recorder survivability standards.

2.2.4 Envisioning the Future: Crafting UAS Recorder Standards

The formulation of comprehensive, adaptable flight recorder standards for UAS is crucial for their harmonious incorporation into the NAS. Such standards must be deeply rooted in the rich historical context of FDRs and CVRs in manned aviation yet must be innovatively tailored to meet the operational demands of unmanned flight. A collaborative synergy among regulatory authorities, industry stakeholders, and the academic realm is indispensable in this venture, harnessing collective expertise to forge best practices and guidelines that bolster the safety, reliability, and operational efficiency of UAS within the shared airspace.

In essence, the narrative of UAS integration into the NAS is connected with the legacy of flight data recording in manned aviation, demanding a visionary approach to surmount the challenges unique to unmanned flight. The crafting of UAS-specific recorder standards surpasses mere technical and regulatory hurdles, marking a pivotal stride towards the full actualization of UAS potential within the global aviation safety architecture.

2.3 Findings

The exploration into the requirements for FDRs and CVRs within UAS has yielded significant insights. This section defines the key findings derived from a comprehensive review of existing literature, regulatory standards, and the operational characteristics of UAS. These findings underscore the complexities and challenges inherent in integrating UAS into the NAS, while also highlighting potential pathways and considerations for establishing effective recorder standards specific to unmanned aviation.

2.3.1 Operational Diversity of UAS

A primary finding is the vast operational diversity of UAS, which encompasses a wide range of sizes, capabilities, and applications. This diversity poses a significant challenge in formulating universal recorder standards. Small hobbyist drones, commercial delivery UAS, and large-scale military drones, for instance, each have distinct operational parameters and safety considerations. The findings suggest that a tiered or category-based approach to recorder standards might be more practical, taking into account factors such as the UAS's operational altitude, range, weight, and intended use.

2.3.2 Data Transmission and Storage Technologies

The capability of many UAS to transmit real-time telemetry data to a GCS represents both an opportunity and a challenge for recorder standardization. The findings indicate that while real-time data transmission offers a potential alternative to traditional onboard recorders, it also introduces concerns regarding data integrity, security, and availability. Issues such as signal interruption, encryption, and data loss in the event of a catastrophic failure need to be addressed to ensure that transmitted data can reliably serve the same investigatory and safety purposes as data stored onboard.

2.3.3 Autonomy and Decision-making Data

The increasing autonomy of UAS operations, particularly with advancements in artificial intelligence and autonomous navigation systems, necessitates the recording of not just physical flight data but also decision-making processes and algorithmic responses. The findings reveal a gap in current recorder standards, which are predominantly focused on physical parameters. There is a need for recorder systems that can capture the logic and decision-making processes of autonomous UAS, providing insights into the actions taken by the onboard systems in response to dynamic operational environments.

2.3.4 Survivability and Accessibility of Recorders

The survivability of recording devices in UAS crash scenarios is a critical concern, especially given the potential for UAS to operate over remote or inaccessible areas. The findings highlight the need for strong survivability standards that account for various crash scenarios unique to UAS operations. Additionally, the accessibility of data for investigative purposes post-incident is identified as a key requirement, necessitating considerations for data retrieval mechanisms that can function even in challenging recovery situations.

2.3.5 Regulatory and International Harmonization

A significant finding is the current lack of harmonization in UAS recorder standards both within national boundaries and internationally. The review of existing regulations and standards reveals a fragmented landscape, with various bodies and nations adopting differing approaches to UAS integration and recorder requirements. The findings underscore the importance of collaborative efforts towards regulatory harmonization, facilitating unified and safe UAS operations across different jurisdictions and enhancing the global safety framework for unmanned aviation.

2.3.6 Best Practices from Manned Aviation

The review of FDR and CVR standards in manned aviation has provided valuable insights that can inform the development of UAS recorder standards. Best practices regarding data parameters, recorder survivability, and data accessibility offer a solid foundation upon which UAS-specific considerations can be built. The findings suggest that while direct transposition of manned aviation standards to UAS is not optimal, the principles and objectives underlying these standards remain relevant and can guide the creation of effective UAS recorder requirements.

2.3.7 Technological Innovations and Future Directions

The investigation into current technological advancements has uncovered emerging trends and advances that could shape the future of UAS recorder standards. Developments in solid-state memory, data encryption, and remote data retrieval technologies present opportunities for enhancing the functionality, reliability, and efficiency of UAS recording systems. The findings point to the need for standards that are adaptable and forward-looking, capable of concurrently evolving in tandem with technological progress in unmanned aviation.

2.3.8 Stakeholder Perspectives

Engagement with various stakeholders, including regulators, industry representatives, safety experts, and academic researchers, has highlighted a consensus on the critical role of FDRs and CVRs in advancing UAS safety and integration into the NAS. However, divergent views on specific requirements and implementation strategies underscore the complexity of the issue. The findings emphasize the value of inclusive and collaborative approaches to standard development, ensuring that the diverse needs and perspectives of all stakeholders are adequately addressed.

2.3.9 Safety and Efficiency Implications

Another important finding is the potential for well-designed UAS recorder standards to significantly enhance both the safety and efficiency of UAS operations. By providing a reliable means of investigating incidents and analyzing operational data, recorder systems can facilitate continuous safety improvements and inform the development of best practices for unmanned aviation. Moreover, standardized recorder requirements can modernize regulatory compliance and operational procedures for UAS operators, contributing to more efficient and predictable integration into the NAS.

The findings from this comprehensive review clarify the multifaceted challenges and considerations involved in establishing FDR and CVR standards for UAS. The diversity of UAS operations, the nuances of data transmission and autonomy, the requirements of recorder survivability and accessibility, and the need for regulatory harmonization constitute key themes that must be navigated in the pursuit of safe and effective UAS integration into the airspace. These findings lay a foundational basis for the subsequent sections on conclusions and recommendations, where strategic directions and actionable insights for advancing UAS recorder standards will be further discussed.

2.4 Conclusions

The extensive review of literature, regulatory standards, and the operational nuances of UAS within the NAS culminates in a set of the following conclusions. These findings not only underscore the complexities inherent in integrating UAS into shared airspace but also highlight the transformative potential of well-conceived flight recorder standards in enhancing aviation safety and efficiency. The conclusions drawn from this comprehensive analysis are intricate, touching upon the evolutionary trajectory of flight recording in aviation, the regulatory landscape, technological advancements, and the path forward for UAS recorder standardization.

The historical progression of FDRs and CVRs within manned aviation provides a foundational blueprint for UAS recorder standards. The transition from analog to solid-state recording technologies underscores a course of increasing data fidelity, storage capacity, and survivability—principles that are equally pertinent to UAS operations. The longstanding utility of FDRs and CVRs in accident investigation, safety analysis, and regulatory compliance within manned aviation attests to the critical role that such recording devices could play in the increasing domain of unmanned flight.

The regulatory examination reveals a complicated framework that currently governs UAS operations, marked by a patchwork of national and international standards. The analysis underscores an urgent need for harmonization and the development of UAS-specific recorder standards that address the unique operational profiles, autonomy levels, and technological capabilities of unmanned systems. Such standards should not only align with existing regulations but also anticipate future advancements and operational paradigms in UAS technology.

The rapid technological evolution of UAS and recording technologies presents both opportunities and challenges in standardization efforts. The capability of UAS to transmit real-time telemetry data introduces advanced approaches to flight data recording and retrieval. However, this also necessitates stringent standards for data integrity, encryption, and transmission reliability to ensure that remotely stored data can serve investigative and safety purposes as effectively as onboard recorders. The advancement in autonomous navigation and decision-making algorithms further necessitates the inclusion of algorithmic decision logs in recorder standards, ensuring transparency and accountability in autonomous UAS operations.

One of the most salient conclusions pertains to the integration of autonomy and Artificial Intelligence (AI) within UAS operations. As UAS continue to advance towards higher levels of autonomy, recorder standards must evolve to capture not just physical parameters but also the complex decision-making processes undertaken by onboard AI systems. This includes algorithmic decision pathways, sensor fusion logs, and adaptive responses to dynamic operational environments, ensuring a comprehensive understanding of autonomous actions in post-incident analyses.

The review highlights the principal importance of recorder survivability and data accessibility in the event of UAS accidents, especially in remote or inaccessible crash sites. Future recorder standards must encompass strong survivability specifications, including impact resistance, fire resistance, and water immersion survivability, akin to those developed for manned aviation but fashioned to the unique crash profiles of UAS. Additionally, the standards should address the future-proofing of recording technologies, accommodating advancements in data storage, encryption, and retrieval methodologies to ensure continued relevance and effectiveness in the face of rapid technological evolution.

A critical conclusion from this review is the indispensable role of stakeholder engagement in the standardization process. The diversity of applications, operational concepts, and technological frameworks within the UAS domain necessitates a collaborative approach to standard development. This includes active participation from regulatory bodies, industry stakeholders, academic researchers, and safety organizations, ensuring that the developed standards are comprehensive, practical, and reflective of the diverse needs and perspectives within the UAS community.

Finally, the conclusions underscore the profound implications of well-designed UAS recorder standards for the safety and efficiency of unmanned aviation. By facilitating detailed incident investigations, promoting regulatory compliance, and fostering continuous safety improvements, effective recorder standards have the potential to significantly enhance the operational safety of UAS. Standardized recording requirements can streamline operational procedures for UAS operators, contributing to more efficient and predictable integration into the NAS, thereby advancing the broader goals of aviation safety and efficiency.

Table 1 depicts a structured summary of the conclusions drawn from the extensive review on UAS integration into the NAS and the need for specific flight recorder standards. This table encapsulates the multifaceted conclusions derived from the review, highlighting the intricate balance between leveraging historical insights, addressing regulatory and technological challenges, and ensuring the active involvement of the UAS community in shaping the future of unmanned aviation safety standards.

Table 1. Conclusion Summary.

Aspect	Key Conclusions
Evolution from Manned Aviation	Historical progression of FDRs and CVRs offers foundational insights. Principles of data fidelity, storage, and survivability are applicable to UAS.
Regulatory Framework	A need for harmonized, UAS-specific standards that accommodate unique operational profiles. Future standards should be adaptable to technological advancements and operational paradigms.
Technological Advancements	Real-time data transmission introduces new paradigms for flight data recording. Standards must ensure data integrity, encryption, and transmission reliability.
Autonomy and AI	Recorder standards must evolve to capture algorithmic decision-making processes. Inclusion of algorithmic logs and adaptive responses is crucial for transparency in autonomous operations.
Survivability and Accessibility	Emphasis on robust survivability specs tailored to UAS crash profiles. Future-proofing of technologies to maintain relevance amid rapid advancements.
Stakeholder Engagement	Collaborative standard development is essential, reflecting diverse needs and perspectives within the UAS community. Active participation from all stakeholders ensures comprehensive and practical standards.
Safety and Efficiency	Effective recorder standards can significantly enhance operational safety and regulatory compliance. Standardized requirements can streamline operations, facilitating efficient UAS integration into the NAS.

The conclusions derived from this review paint a complex yet optimistic picture of the future of UAS integration into the NAS. They highlight the critical need for adaptive, forward-looking recorder standards that address the unique challenges and opportunities presented by unmanned aviation. As the UAS landscape continues to evolve, these conclusions provide a roadmap for the development of recorder standards that balance safety, regulatory compliance, technological advancement, and operational practicality, paving the way for the safe and efficient integration of UAS into the global airspace infrastructure.

2.5 Recommendations

Based on the comprehensive review and analysis encompassing the evolution of flight data recording, the advent and propagation of UAS, the regulatory landscape, and the significant findings and conclusions drawn, a series of detailed recommendations are proposed. These recommendations aim to address the many challenges and opportunities identified, paving the way for the safe, efficient, and harmonious integration of UAS into the NAS. The recommendations are structured around key thematic areas to provide clarity and focus to the proposed actions.

1. **Development of Tiered UAS Recorder Standards**

Develop a categorization system for UAS based on operational parameters such as size, weight, altitude, range, and type of operation (commercial, recreational, scientific, military). This will facilitate the creation of specific recorder standards that reflect the diverse operational profiles of UAS.

Implement tiered recorder standards that correspond to the UAS categorization, ensuring that requirements are proportionate to the complexity and risk profile of the operation. For example, small, low-risk UAS may have simplified data requirements compared to larger, higher-risk systems.

2. **Regulatory Harmonization and International Collaboration**

Consider the establishment of a dedicated working group comprising representatives from the FAA, ICAO, EUROCAE, and other relevant bodies to work towards regulatory harmonization.

Organize international forums and working groups to facilitate dialogue, exchange best practices, and foster collaboration on UAS recorder standards. This will help ensure global consistency and interoperability in UAS operations.

3. **Enhancing Data Integrity and Security**

Develop and mandate robust encryption standards for UAS data transmission to protect sensitive information and ensure data integrity from the point of capture to analysis.

Recommend the implementation of data redundancy measures, such as dual recording or backup transmission systems, to safeguard against data loss in the event of system failure.

4. **Addressing Autonomy and Artificial Intelligence**

Mandate the logging of AI decision-making processes, including sensor data inputs, algorithmic decision pathways, and control command outputs. This will ensure transparency and accountability in autonomous UAS operations.

Develop ethical guidelines and standards for AI systems used in UAS, focusing on safety, non-discrimination, privacy, and human oversight.

5. **Survivability and Accessibility Enhancements**

Encourage the use of advanced materials and design practices to enhance the survivability of recording devices in extreme conditions, including high-impact crashes and underwater submersion.

Promote the development and adoption of technologies that enable remote data retrieval from recording devices, ensuring accessibility even in the event of inaccessible crash sites.

6. **Stakeholder Engagement and Public-Private Partnerships**

Form a consortium of industry stakeholders, including UAS manufacturers, operators, technology providers, and academic institutions, to provide input on recorder standard development.

Foster public-private partnerships to leverage private sector innovation in recording technologies, data analytics, and encryption methods, aligning them with public safety objectives.

7. Safety and Efficiency Optimization

Integrate UAS recorder data into comprehensive Safety Management Systems, enabling proactive risk management and safety optimization based on empirical data.

Utilize recorder data to analyze and optimize UAS operational efficiency, including flight path optimization, battery usage, and payload management, contributing to more sustainable and cost-effective operations.

8. Research and Development Support

Advocate for increased government and industry funding dedicated to research and development in UAS recording technologies. This funding should support innovations in data storage, encryption, transmission, and analysis, focusing on enhancing data integrity and survivability.

Encourage collaborations between universities and the UAS industry to leverage academic research capabilities in advancing recorder technologies. These collaborations can explore novel materials, AI algorithms for data analysis, and advanced encryption methods.

9. Training and Education

Develop comprehensive training programs for UAS operators, focusing on the importance of recorder systems, data management practices, and the role of data in safety and operational efficiency.

Integrate UAS recorder technology and data analysis into aviation and aerospace engineering curricula to prepare the next generation of professionals with the skills needed to leverage recorder data for safety and efficiency improvements.

10. Standardization of Data Formats and Protocols

Establish common data formats and communication protocols for UAS recorder data to facilitate interoperability, data sharing, and analysis across different platforms and systems.

Launch an open standards initiative to develop and promote the adoption of universal data formats and protocols, involving stakeholders from across the UAS ecosystem.

11. Incident Investigation and Analysis

Create a centralized, anonymized database of UAS incident and operational data, derived from recorder systems, to support safety research, trend analysis, and the development of risk mitigation strategies.

Develop and disseminate advanced data analysis tools to regulatory bodies and industry stakeholders, enabling them to extract actionable insights from recorder data for safety improvement and regulatory compliance.

12. Public Awareness and Engagement

Conduct public information campaigns to raise awareness about the role of UAS recorder systems in enhancing flight safety and operational transparency, addressing public concerns related to privacy and surveillance.

Engage with community groups and local authorities to discuss the benefits and implications of UAS operations and recorder systems, fostering a collaborative approach to UAS integration into shared airspace.

By addressing these areas through targeted recommendations, the goal is to create a conducive environment for the safe, efficient, and integrated operation of UAS within the NAS. The emphasis on research, education, standardization, incident analysis, policy support, and public engagement is crucial in building a robust framework that supports the growth of the UAS industry while ensuring the highest standards of safety and operational excellence. These recommendations provide a roadmap for stakeholders across the UAS ecosystem to collaborate effectively in realizing the full potential of UAS technologies in a manner that is safe, efficient, and beneficial to society at large.

3 TASK 2 DELIVERABLE

Within this section, the research and results addressed under Task 2, Assess and Develop Proposed Data Recorder Requirements. The full technical report for Task 2 has been included in Appendix B of this report.

The Task 2 summary includes:

- An **overview** of the task including the problem being addressed, its scope, and the team's approach. (Section 3.1)
- Relevant **background** information regarding manned FDR and CVR standards and unmanned system autonomy levels. (Section 3.2)
- The team's **findings** addressing general FDR requirements, additional FDR requirements based on aircraft type, and automation level, and CVR requirements. (Section 3.3)
- Conclusions from Task 2 are presented with a final list of key recommendations (Section 3.4)

The team's results suggest that the majority of current FDR and CVR standards in manned aviation can be adopted with some necessary modifications, additions, and exclusions. These new requirements could be integrated as appendices to existing parts of Title 14 CFR, or as new regulations/standards.

3.1 Task Overview

The objective of Task 2 is to recommend data requirements for FDR and CVR hardware to enable UAS integration into the NAS. From Task 1, a survey of current regulations, standards, and guidance materials provides a foundation for the Task 2 study. Data parameters identified from these sources were each reviewed to determine the category of the requirement, its applicability to UAS (applicable, applicable with revision, or non-applicable), and evaluated to determine what data collection requirements exist for each attribute. Requirements were grouped as follows:

- General Requirements,
- Requirements for Fixed-wing UAS,
- Requirements for Rotary-wing UAS,
- Requirements Based on Level of Autonomy, and
- Requirements for Urban Air Mobility (UAM) aircraft.

For each of the recommended parameters, the analysis determines the range off the measured value, a justification for its inclusion, and the maximum recording interval in hertz (Hz).

3.1.1 Scope

This research task shall leverage the comprehensive review of regulations governing FDRs and CVRs across organizations and aircraft categories conducted in Task 1 (see Appendix A). The review encompassed regulations and guidance materials from Title 14 CFR, EUROCAE, and those stipulated by ICAO.

Current standards were meticulously evaluated to propose tailored adjustments to manned FDR and CVR requirements to define such requirements for UAS. These proposed modifications underwent rigorous scrutiny to ascertain their safety implications and assess whether they adequately addressed the data needed to investigate accidents and incidents across various UAS categories and anticipated operational domains, such as UAM.

3.1.2 Approach

The approach taken recognizes the diverse nature of UAS which vary based on factors such as weight, design, and intended application. The report delineates several groups of requirements tailored to the specific characteristics of UAS. These groups include:

- General Requirements,
- Requirements for Fixed-wing UAS,
- Requirements for Rotary-wing UAS,
- Requirements Based on Level of Autonomy, and
- Requirements for UAM aircraft.

The team conducted an analysis of the existing manned standards. Requirements from these standards were placed within one of the groups listed above and further analyzed to determine the range, recording interval, and a reason for its inclusion. Changes made from a manned requirement to an unmanned requirement such as a change in recording interval are reported with each required parameter.

3.2 Background

3.3 FDRs are devices that store flight information made by an aircraft or airborne platform while in flight which can later be recalled and reviewed. In the case of an aircraft accident, FDRs are essential to help investigators determine the underlying causes. There are other important uses for flight data stored on FDRs and audio recording on CVR, including use for proactive and predictive hazard identification. Different institutions define different standards for flight and voice recorders. As such, standards of the United States, ICAO and EUROCAE were summarized and evaluated for manned aircraft FDR, which assist to provide recommendations for UAS FDR data parameter requirements. Findings

This section distills the findings of the Task 2 research for general FDR requirements, FDR requirements by aircraft type, autonomy-related FDR requirements, and CVR requirements.

Table 2 summarizes the regulations, rules, and standards with further details in **Error! Reference source not found.** of Appendix B.

Outside of the general requirements, requirements can exist based upon the level of autonomy. In Appendix B, **Error! Reference source not found.** describes six levels of autonomy for UAS:

- (0) Remote Controlled,
- (1) Simple Automation,
- (2) Remotely Operated,
- (3) Highly Automated/Semi-autonomous,
- (4) Fully Autonomous, and
- (5) Collaborative Operations.

3.4 Findings

This section distills the findings of the Task 2 research for general FDR requirements, FDR requirements by aircraft type, autonomy-related FDR requirements, and CVR requirements.

Table 2. Regulatory documents analyzed for manned aircraft FDRs/CVRs.

Government Documents	ICAO Annexes	EUROCAE MOPS	Industry
14 CFR § 23, 25, 27, 29, 91, 121, 125, 129, 135, 830 49 USC § 1154, 20137, and 44901	Annex 6, Annex 10, Annex 11, and Annex 12	ED-55/ED 112A Minimum operational Performance specification for crash Protected Airborne ED-155 Minimum operational performance Specification for Lightweight Flight Recording Systems	ASTM American society for Testing and Materials, ASTM F3228-17 Standard Specification for Flight Data and Voice Recording in Small Aircraft, RTCA Radio Technical Commission for Aeronautics, Future Flight Data Collection Committee Final Report

3.4.1 General UAS FDR Requirements

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 reviewed in the Task 1 Literature Review (see Section **Error! Reference source not found.** or **Error! Reference source not found.**). For additional details on the parameters including ranges, reasons/justification, and maximum recording interval, we would encourage readers to refer to the Appendix B, **Error! Reference source not found.**. The team recommends to following attributes be collected for all UAS:

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) [If applicable]
10. Roll trim [If applicable]
11. Pitch input (and elevator position after input) [If applicable]
12. Pitch trim [If applicable]
13. Yaw input (and rudder position after each input) [If applicable]
14. Yaw trim
15. Electronic Speed Controller status
16. Engine(s) 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- Distance between aircraft and ground station through signal propagation delay
24. Marker Beacon Status (if applicable)
25. Electronic Flight Instrument System display format (if applicable)
26. Instrument Landing System/ Glide Path (If Applicable)
27. Navigation Systems e.g., Global Navigation Satellite System, Inertial Navigation System, Microwave Landing System, Actual Navigation Performance, Estimated Position Error, Estimate of Position Uncertainty, Long Range Navigation, 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:

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

All (warning) sensors e.g.

1. Traffic Alert and Collision Avoidance System (TCAS)
2. Ground Proximity Warning System/Terrain Awareness Warning System
3. Low power level warning

4. GPS loss
5. Transmission loss warning (with transmitter or Ground station)

3.4.2 Additional FDR Requirements by UAS 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. For details on the below mentioned types, refer to Appendix B.

3.4.2.1 Fixed-Wing UAS

For fixed-wing UAS, additional FDR data attributes measure the state of the aircraft's control surfaces and flight characteristics. In Appendix B, **Error! Reference source not found.** specifies the data collection requirements for the following attributes:

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

Rotary-Wing UAS

For rotary-craft UAS, the attributes recorded must address the flight mode of the UAS and the state of its major flight elements. In Appendix B, **Error! Reference source not found.** specifies the data collection requirements for the following attributes:

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)

3.4.3 Additional FDR Requirements by Autonomy Level

In the Task 2 report (Appendix B, Section **Error! Reference source not found.**), the research team summarized the six levels of autonomy and considered multiple sample UAS missions (telecom relay services, storm sensing/tracking, border and coastal patrol, station-keeping for scientific missions, long-range scientific or surveillance, distributed sensor network aerial constellation, forest fire/wildfire search and rescue, and aerial exploration.

For automation levels 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. At this level of autonomy, the likelihood of a UAS accident due to automated operations remains low such that no autonomy-specific data requirements are necessary.

For level 3 to 5, on the other hand, there is ideally no pilot in the loop for most of its operation. With a higher demand of automation to take over the pilot's functions, the likelihood of an automation error increases while the abilities of a remote pilot to intervene lowers. Accordingly, it is important to record all inputs available to a machine learning/artificial intelligence system and its outputs to distinguish the root cause being a result of faulty hardware (i.e., sensors) or automation error.

To achieve higher levels of autonomy, different subsystems of the UAS are automated, which results in additional FDR requirements as attributes coming from the vehicle state and its sensors can enable better diagnostics of faults/failures in automated operations. These address procedures such as DAA, 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.

Without a pilot onboard providing situational awareness, additional sensors which manned aircraft do not necessarily have might be required.

Table 3 lists some examples of sensors that can be used for this task. 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 to the evaluation of crashes and should be recorded especially when the hands-on time of the pilot is low.

Table 3. Potential Sources/Parameters for UAS Automation-related FDR Needs.

Vehicle State/Sensors	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
Light Detection and Ranging (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

3.4.4 Additional FDR requirements for UAM operations

The UAM initiative aims to leverage highly automated aircraft operating at lower altitudes within urban and suburban areas to facilitate the transportation of passengers and cargo in a safe and efficient manner. In pursuit of this objective, it is imperative to document additional parameters pertinent to the well-being of passengers and cargo. The parameters delineated in 14 CFR Appendix E to Part 125, designated for manned aircraft accommodating 20 or more passengers, have been identified as crucial indicators of passenger condition. These parameters thus warrant inclusion for their significant relevance in ensuring comprehensive safety protocols. The additional parameters (see Appendix B, Section **Error! Reference source not found.** for more details) to be measured are:

i. Cabin pressure altitude
ii. Loss of cabin pressure

3.4.5 UAS CVR Requirements

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 Air Traffic Control (ATC), or in a UAM scenario, there will be communication with passengers or a flight crew onboard 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. In the following subsection, CVR requirements are defined for non-autonomous UAS and for autonomous UAS.

3.4.5.1 CVR Requirement for Non-Autonomous UAS/UAM (Pilot-onboard or Pilot-in-the-loop)

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, all flight crew communication 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 pilot or crew on board, it is not necessary to have CVR onboard the UAS. The voice and data link data can be stored directly at 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.

3.4.5.2 CVR Requirement for Autonomous UAS/UAM (No Pilot onboard or in the loop)

When considering CVR for autonomous UAS, it becomes more complicated to adapt existing requirements. This is largely due to the lack of communication between the pilot and ATC. The FAA and the National Aeronautics and Space Administration are currently researching Unmanned Traffic Management (UTM) systems that will allow UAS to be integrated into the NAS (Federal Aviation Administration, 2024). 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. A similar requirement would exist between UAM and Providers of Service to UAM (PSUs). If there is no crew in 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.

3.4.6 Excluded Parameters

Since the goal of the 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.

Parameters 25, 27, 34-35, 38-45, 47, 52-59, 61 & 69, 76, and 80-82 from ED-122A (September 2013) were excluded due to one or more of the following reasons: they may be unnecessary for UAS to measure, results in large amount of redundant data and may pose unnecessary cost to manufacturer, etc.

The specific justification for each excluded parameter can be seen in the Task 2 Report (see Appendix B, Section **Error! Reference source not found.**), 14 CFR § 125, Appendix E parameters 46-54, 56-58, 61, 71-77, 79-81, and 88-91 were excluded for the similar reasons as the ED-122A exclusions.

Helicopter parameters 15, 19, 35, 38-45, 48 and 52-53 from ED-112A (September 2013) were excluded due to similar reasons.

3.4.7 Interval Frequency

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 the same 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 recording rates are only rough estimates 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.

3.5 Conclusions

The general requirements 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 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 are used by commercial and recreational UAS manufactures, but presently lack a standard set of parameters based on UAS type. The team concludes that most of most general and UAS type specific requirements are implementable. Only the requirements for FDRs for highly autonomous UAS (e.g., autonomy level 5) are problematic because a large amount of data must be recorded to be capable of diagnosing accidents caused by an automated function. In such cases, the specific algorithms used play a role in deciding what parameters are needed. This poses future challenges, as research should be done on how high the sampling rate needs to be to get meaningful information from the data such as LIDAR or camera rates, resolutions, etc. In such cases, the FDR recording capability and computing requirements vary based upon the types of inputs and parameters of the model.

3.5.1 Ease of Requirement Implementation

The proposed requirements are mostly part of existing FDR requirements for standard manned aircraft. The requirements should be practical for larger UAS with comparable size and weight as regular aircraft.

Since UAS can be much smaller than standard manned aircraft, the Size, Weight, and Power (SWAP) limitations of the vehicle can impact characteristics of its FDR. The volume of data and the robustness requirements of the FDR can impact size, weight, and power. Tests in real environments can be performed to be able to say with certainty which parameters are most valuable for a crash evaluation, how often samples must 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.

3.5.2 Open Challenges

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 FDR. This rate depends on several factors, as discussed before. A higher rate can provide more information and enable 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.

Since functions of autonomous systems as well as autonomous UAS are often using Deep Learning algorithms, it is important to make the behavior of these models comprehensible. Although the records of FDR can provide information about the inputs that occurred during a s misbehavior, the decision of the model cannot necessarily be retraced. To make these autonomous systems safer in the long term, further research should be conducted to assess 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 quite different files per manufacturer. It would make sense to investigate in the future whether it would be helpful to define a standard.

3.6 Recommendations

From the team's research and analysis, the following recommendations can be made to industry stakeholders:

1. The set of parameters provided herein are adopted from the general aviation requirements. To verify the feasibility of those parameters for the UAS, further experiments are recommended including tests in real-world settings. requires an experimental work approach or in real-world settings. It is recommended that further research should be conducted to check and assess the recorded samples and their quality.
2. The methods used in encoding and decoding for recording those parameters can be verified to check the differences between actual physical values and recorded values. This can also help to extract the data easily for further data analysis.
3. For the autonomous UAS missions, it is recommended to know the Level of Autonomy (LOA) to define the exact set of FDR parameters requirements.
4. Standard file format for recording should be established to analyze all data recorded irrespective of the manufacturer.
5. Ground control station large enough to accommodate 2 or more people, should be treated as cockpit for current manned aircraft, hence, existing requirements (14 CFR § 23.1457 – Cockpit Voice Recorders) should be adopted.
6. For handheld ground control stations, all communications amongst flight crew (Pilot-in-command, persons manipulating controls, and visual observers) should be recorded.

4 TASK 3 DELIVERABLE

This section summarizes the research effort conducted toward understanding the current state of the art for small UAS FDR devices. NIAR developed mathematical models to virtually assess the survivability of the most common UAS FDRs for a wide variety of crash scenarios. Additionally, physical tests were conducted to assess the survivability of these devices for static compression, penetration resistance, and low-intensity fire conditions. A summary of the findings and conclusions from the assessment is also included.

4.1 Overview

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. By establishing some parallelisms between manned aircraft and small UAS FDRs and analyzing the current requirements and limitations of UAS FDRs, this work aims to support the ongoing efforts to address these existing gaps. The main objectives of this task are:

- Research what type of FDRs are used in small and medium-sized UAS.
- Evaluate the current crash survivability standards for this type of FDR.
- Evaluate the mechanical performance of the FDR for static crush, penetration resistance, and low-intensity fire conditions.
- Explore numerical methods to develop predictive tools for assessing the applicability of crash survivability standards to FDRs for UAS.
- Application of the numerical methods in different crash scenarios to predict a range of loads and accelerations that will contribute to future decision-making on FDR standards for small UAS.

4.2 Background

The crash survivability properties of an FDR play a crucial role in protecting the flight data during and after an accident. The extreme conditions (mechanical forces, intense heat, vibrations, and others) during such events impose demanding requirements to preserve the device's integrity. The data recorded in these devices is a key element during an accident reconstruction. Therefore, it is crucial to develop safety standards that aim to increase the survivability of these units.

Safety standards for FDRs have been continuously evolving since 1940, when the predecessor of the FAA, the Civil Aeronautics Board, mandated the safeguarding of flight data beyond crash impact [1]. Early regulations required the FDR to withstand a shock pulse of 1,000g and to be located at the rear of the aircraft to minimize the impact velocity. The FAA, the EUROCAE, and the National Transportation Safety Board further refined the survivability requirements of FDRs by incorporating low-intensity and high-intensity fire conditions into their standards. These cumulative efforts have supported the development and improvement of early Technical Standard Orders (TSOs), leading to the latest versions of TSO-C123 [2] and TSO-C124 [3]. Other standards have been introduced to specify the minimum requirements for smaller aircraft that carry a lightweight flight recording system. Appendix C enumerates the survivability requirements described in both TSO-C123 and TSO-C124, as well as the EUROCAE ED-155 [4] for lightweight data recorders.

None of the existing standards specify the survivability requirements for UAS FDRs. However, by identifying the flight data recording technology being integrated into the most common small UAS, it is possible to compare the survivability standards of this technology and traditional FDRs.

4.3 Findings

4.3.1 Findings from the current state of the art for sUAS FDRs

A forecast study performed to find the most common UAS in the market revealed that most of these aircraft carry a micro-SD card to record the flight data. Table 4 gathers the most representative UAS in the market with the maximum take-off weight and the type of FDR being used. Note that ATP and Sandisk were identified as the most common micro-SD cards used for flight data recording in UAS.

Table 4. Most common UAS in the market and their flight data recording technology.

Manufacturer	Model	Weight [g]	FDR Technology
DJI	Mavic 3	895	Micro SD
DJI	Inspire 2	3,440	Micro SD
DJI	Phantom 4	1,375	Micro SD
Wingtra	One Gen II	3,700	Micro SD
Yuneec	Typhoon H+	1,645	Micro SD
Yuneec	H520 RTK	1,645	Micro SD
Ruko	F11GIM2	584	Micro SD
Ruko	Bwine F7	549	Micro SD
Autel Robotics	EVO II	1,127	Micro SD
Autel Robotics	Pro V3	1,191	Micro SD
Parrot	ANAFI Ai	898	Micro SD
HUBSAN	Ace Pro	600	Micro SD
HUBSAN	Mini	249	Micro SD
HUBSAN	ZINO Pro+	792	Micro SD
Intel	Falcon 8+	1,200	Micro SD

Other crash-protected lightweight FDRs were identified during the forecast study. However, due to their size limitations compared to the most common small UAS, these were only documented and not considered for this study. Examples of these lightweight FDRs are the SferiRec LCR 100 [5] and the FDR01 [6]. More details for these FDRs are provided in Section 2.1 of Appendix C.

Since the majority of the sUAS use a micro-SD card to record the flight data, the survivability standards of these devices were compared to the requirements for traditional and lightweight FDRs. Note that the survivability standards for micro-SD cards were taken from the JEDEC JESD22-B104 [7] and MIL-STD (882-2-2002.5) [8] for mechanical shock conditions and EN 60529 [9] and IEC 605:1989 [10] for Ingress Protection (IP). Table 6 compares the survivability standards for traditional, lightweight FDRs and micro-SD cards.

Table 5. Crash-survivability standards for traditional, lightweight, and micro-SD FDRs.

Test	Traditional FDRs (ED-112)	Lightweight FDRs (ED-155)	Micro SD "FDRs"
Impact shock	• 3,400g for 6.5ms (fixed) • 152ft/s impact with a hard surface (deployable)	•1,000g for 5±1ms (fixed) • 80ft/s impact with a hard surface (deployable)	ATP: 1,500g for 0.5ms SanDisk: 1,500g for 0.5ms
Penetration resistance	• 500lb. dropped from 10ft. with a 1/4in. diameter contact point (fixed) • 55lb. dropped from 6in. with a 0.25x0.98in. (max.) sized impactor (deployable)	N/A	N/A
Static crush	•5,000lb. for 5min (fixed) • 2,000lb. for 5min (deployable)	• 1,020lb. for 5min (fixed)	N/A
Hydrostatic pressure	• 20,000ft. pressure for 30 days (fixed and deployable)	N/A	ATP: 3.28ft. (1m) for 72 hours SanDisk: 3.28ft. (1m) for 72 hours
High-intensity fire	• 158 kW/m^2 for 60min (fixed) • 158 kW/m^2 for 20min (deployable)	• 158 kW/m2 for 15min (fixed) • 158 kW/m2 for 5min (deployable)	N/A
Low-intensity fire	• 260^{o}C for 10 hours (fixed) • 260^{o}C for 10 hours (deployable)	N/A	ATP: up to 85^{o}C SanDisk: up to 85^{o}C
Saltwater submersion	• Ability to be buoyant (deployable)	• Ability to be buoyant (deployable)	ATP: 3.28ft. for 72 hours SanDisk: 3.28ft for 72 hours
Fluid immersion	• A selection of fluids depending on Certification Authority for 48 hours (fixed and deployable)	N/A	N/A

Based on this study and the data gathered in Table 4 and Table 5, the following findings are considered of importance:

- Micro-SD cards are the preferred technology for the vast majority of sUAS because of their small size, low mass, high-speed performance (UAS sensors store data at ~200Hz), and high storage capabilities (up to 2 TB currently).
- In some sUAS models, the image and video data are stored separately from the flight data, thus utilizing two distinct memory units.
- The majority of sUAS use slot socket readers to attach the data recording devices to the sUAS electronic board. It is important to remark that these card readers are not designed to provide crash or fire protection to the flight data recorders.
- Some sUAS models encode their flight data files, making the recovery of this data more difficult in the event of an accident [11].
- It was found that some sUAS can fly without any "FDR" on it [11].
- It should be noted that the standards for micro-SD cards are not mandatory and are used to demonstrate the product's quality and performance.

4.3.2 Findings from mechanical tests performed on two commercially available micro-SD cards

NIAR performed a series of physical tests on two commercially available micro-SD cards (manufacturer 1 and manufacturer 2) recommended for use in sUAS to understand the devices' capabilities and limitations. The test conditions were selected to resemble those applicable to manned aircraft flight data recorders where possible. Based on the scope of the project, the evaluated test conditions were compression (static crush), low-intensity fire, and penetration resistance. A high-level summary of the results from these tests is presented in this section. For more details, refer to Section 3 of Appendix C.

Compression Tests: The tests were conducted at room temperature and ambient relative humidity. A 35kip test frame was used for testing. The frame was equipped with 22kip strain gauge load cells. The system can operate as a standard universal test machine. This configuration was used for testing. A pair of 2" cylindrical platens were used to compress the SD cards. Table 6 summarizes the test results for the preliminary tests conducted on the micro-SD cards for manufacturers 1 and 2. Based on the obtained results, a compression of 18.5% of the total thickness or a load of 3,060 lb. was used for the benchmark testing for manufacturer 1, and a compression of 22.4% of the total thickness or a load of 3,740 lb. was used for the benchmark testing for manufacturer 2.

Table 6. Micro SD card compression tests results – Preliminary tests.

		Manufacturer 1		Manufacturer 2	
Test #	Nominal Compression [%]	Max. Load [lb.]	Card Status	Max. Load [lb.]	Card Status
1	10	246.3	Readable	1,245.7	Readable
2	10	405.1	Readable	947.7	Readable
3	15	2,068.7	Readable	2,104.7	Readable
4	15	71.0	Readable	2,275.8	Readable
5	20	3,584.3	Readable	3,134.6	Readable

6	20	3,738.9	Failed	3,415.9	Readable
7	22.5	4,162.7	Readable	3,915.2	Failed
8	22.5	4,459.9	Readable	4,249.3	Readable
9	25	3,911.2	Failed	4,452.6	Failed
10	25	4,748.1	Failed	4,946.1	Failed
11	20	3,577.8	Readable	4,449.3	Readable
12	20	3,732.6	Failed	3,836.6	Failed
13	20	4,267.6	Readable	3,740.1	Failed
14	20	3,061.7	Failed	Null	Null
15	20	4,673.4	Readable	3,781.3	Readable
16	20	2,825.0	Readable	3,948.4	Readable

For benchmark testing, ten tests were conducted per card manufacturer. The results are summarized in Table 7. It is worth noting that none of the tested cards sustained visible damage. In other words, the physical appearance remained intact after the test, regardless of the compression level to which the cards were exposed and the status of the card after testing.

Table 7. Micro SD card compression tests results – Benchmark tests.

Manufacturer ID	**Benchmark Tests**	**Failed Samples**	**Number of Failed Samples/Stopping Criteria**	
			Displacement	Load
1	10	1	0	1
2	10	1	0	1

Low-Intensity Fire Tests: The two manufacturers of the SD cards used for this program already provide a range of temperatures for the operation of the devices. The temperature ranges from -25 to 85°C. In an effort to explore the limitations of the SD cards, NIAR evaluated temperatures above 85°C. A high-level summary of the results from these tests is presented in this section. For more details, refer to Section 3 of Appendix C.

Table 8 summarizes the test matrix corresponding to the preliminary tests conducted. Equal matrices were used for both SD card manufacturers.

Table 8. Micro SD card low-intensity fire tests matrix – Preliminary tests.

Test #	**Temperature [°C]**	**Soak Time [s]**	**Status**
1-2	85	180	Readable
3-4	95	180	Readable
5-6	100	180	Readable

7-8	110	180	Readable
9-10	125	180	Readable
11-12	150	180	Readable
13-14	175	180	Readable
15-16	200	180	Readable

The tests, as defined above, did not result in failure for either of the card manufacturers. Therefore, the conditions presented in Table 9 were evaluated.

Table 9. Micro SD card low-intensity fire tests results – Benchmark tests.

Test #	Temperature [°C]	Soak Time [s]	Status
1-4	150	900	Readable
5-8	150	1800	Readable
9-10	200	600	Readable

Penetration Resistance Tests: The penetration resistance tests were similar to the static crush tests. The main difference lies in the fact that the SD cards were loaded using a semi-spherical indentor as opposed to a flat plate. Different levels of compression were evaluated. Based on the preliminary tests' results, the benchmark testing parameters were individually set for each of the card manufacturers. Table 10 presents the results of the preliminary tests performed on the manufacturer 1 and manufacturer 2 devices. For benchmark testing, ten tests were conducted per card manufacturer. Table 11 summarizes the results of these tests. Similar to the static crush tests, none of the tested cards exhibit visible damage. Based on these results, a penetration resistance qualification load of 25 lbs is proposed. The proposed load level entails a minimum factor of safety equal to 1.4 with respect to the minimum failure load observed for the samples tested for penetration resistance.

Table 10. Micro SD card penetration resistance tests results – Preliminary tests.

	Manufacturer 1		Manufacturer 2	
Test #	Max. Load [lb.]	Card Status	Max. Load [lb.]	Card Status
1	25	Readable	25	Readable
2	25	Readable	25	Readable
3	30	Readable	30	Readable
4	30	Readable	30	Readable
5	50	Readable	50	Failed
6	50	Readable	50	Readable
7	75	Failed	40	Failed
8	75	Readable	40	Failed

9	100	Failed	40	Readable
10	100	Readable	40	Failed
11	125	Failed	30	Readable
12	125	Readable	30	Readable
13	150	Readable	35	Failed
14	150	Failed	35	Failed
15	175	Readable	35	Readable
16	175	Failed	35	Readable

Table 11. Micro SD card penetration resistance tests results – Benchmark tests.

Manufacturer ID	Benchmark Tests	Failed Samples
1	10	4
2	10	2

4.3.3 Findings from physics-based simulations of a variety of sUAS crash scenarios

NIAR performed a comprehensive evaluation of different crash conditions using high-fidelity numerical simulations. Leveraging previous knowledge and resources, an extensive simulation matrix that thoroughly assessed the crash survivability of sUAS FDRs was evaluated. Three sUAS configurations were used: Fixed-Wing (2.55lb) (F2.55), Quadcopter (2.70lb) (Q2.7), and Fixed-Wing (55.0lb) (F55). Each aircraft's corresponding Finite Element Model (FEM) included a Virtual Sensor (VS) representative of the physical FDR system. For the Quadcopter Q2.7 configuration, additional validation exercises were developed to characterize the behavior of the sUAS' FDR and electronic board (see Section 4 of Appendix C). Various impact targets were studied, including critical aircraft structures, ground vehicles, pedestrians, buildings, and different ground surfaces. Table 12 through Table 14 present the simulation matrix for the three sUAS configurations. For more details about the model development and simulation setups, please refer to Section 5 of Appendix C.

Table 12. F2.55 FEM simulation matrix.

Target	Impact Location	Impact Velocity	Analysis Code
G – Windshield	1	Cruise	A55-GF2.55-C1C
G – Wing	1	Cruise	A55-GF2.55-W1C
B – Vertical Stabilizer	3	Cruise	A55-BF2.55-V3C
B – Wing	1	Cruise	A55-BF2.55-W1C
C – Horizontal Stabilizer	1	Cruise	A55-CF2.55-H1C
C – Wing	1	Cruise	A55-CF2.55-W1C
R – Front Cowling	1	Cruise	A55-RF2.55-C1C
R – Blade	1	Cruise	A55-RF2.55-B1C
Operation Over People - Head	1	Static	A55-GCF2.55-H1S

Wall	N/A	Static	A55-WF2.55-xxS
Moving Vehicle - Windshield	1	Cruise	A55-MVF2.55-C1C
Surface Water	N/A	Static	A55-SWF2.55-xxS
Surface Soil	N/A	Static	A55-SSF2.55-xxS
Surface Concrete	N/A	Static	A55-SCF2.55-xxS

Table 13. Q2.7 FEM simulation matrix.

Target	Impact Location	Impact Velocity	Analysis Code
G – Windshield	1	Cruise	A55-GQ2.7-C1C
G – Wing	1	Cruise	A55-GQ2.7-W1C
B – Vertical Stabilizer	3	Cruise	A55-BQ2.7-V3C
B – Wing	1	Cruise	A55-BQ2.7-W1C
C – Horizontal Stabilizer	1	Cruise	A55-CQ2.7-H1C
C – Wing	1	Cruise	A55-CQ2.7-W1C
R – Front Cowling	1	Cruise	A55-RQ2.7-C1C
R – Blade	1	Cruise	A55-RQ2.7-B1C
Operation Over People - Head	1	Static	A55-GCQ2.7-H1S
Wall	N/A	Static	A55-WQ2.7-xxS
Moving Vehicle - Windshield	1	Cruise	A55-MVQ2.7-C1C
Surface Water	N/A	Static	A55-SWQ2.7-xxS
Surface Soil	N/A	Static	A55-SSQ2.7-xxS
Surface Concrete	N/A	Static	A55-SCQ2.7-xxS

Table 14. F55 FEM simulation matrix.

Target	Impact Location	Impact Velocity	Analysis Code
G – Windshield	1	Cruise	A55-GF55-C1C
G – Wing	1	Cruise	A55-GF55-W1C
B – Vertical Stabilizer	3	Cruise	A55-BF55-V3C
B – Wing	1	Cruise	A55-BF55-W1C
C – Horizontal Stabilizer	1	Cruise	A55-CF55-H1C
C – Wing	1	Cruise	A55-CF55-W1C
R – Front Cowling	1	Cruise	A55-RF55-C1C
R – Blade	1	Cruise	A55-RF55-B1C
Wall	N/A	Static	A55-WF55-xxS
Moving Vehicle - Windshield	1	Cruise	A55-MVF55-C1C
Surface Water	N/A	Static	A55-SWF55-xxS
Surface Soil	N/A	Static	A55-SSF55-xxS
Surface Concrete	N/A	Static	A55-SCF55-xxS

Loads, acceleration, and impulse transferred to the virtual FDR were analyzed. Based on the numerical simulation results, the maximum mechanical loads observed were 500.2N (112.45 lbf), 910.43N (204.67 lbf), and 559.6N (125.8 lbf) for the F2.55, Q2.7, and F55 sUAS, respectively. These peak loads have durations of less than a few milliseconds (0.5-3ms), which is difficult to replicate in a standard mechanical test. In addition, the maximum average accelerations observed for a time window of 0.5ms were 4,850g, 9,800g, and 17,500g for the F2.55, Q2.7, and F55 sUAS, respectively.

Figure 1 and Figure 2 present the load and acceleration values predicted with the high-fidelity numeric simulations.

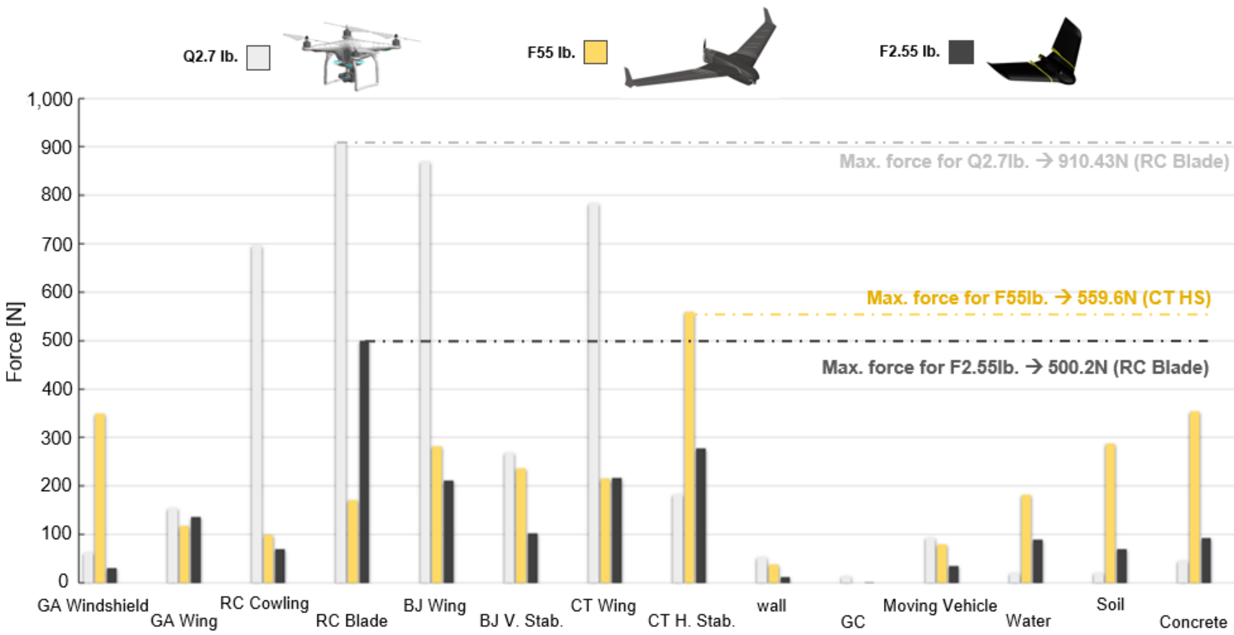

Figure 1. Virtual Sensor load results categorized by UAS type.

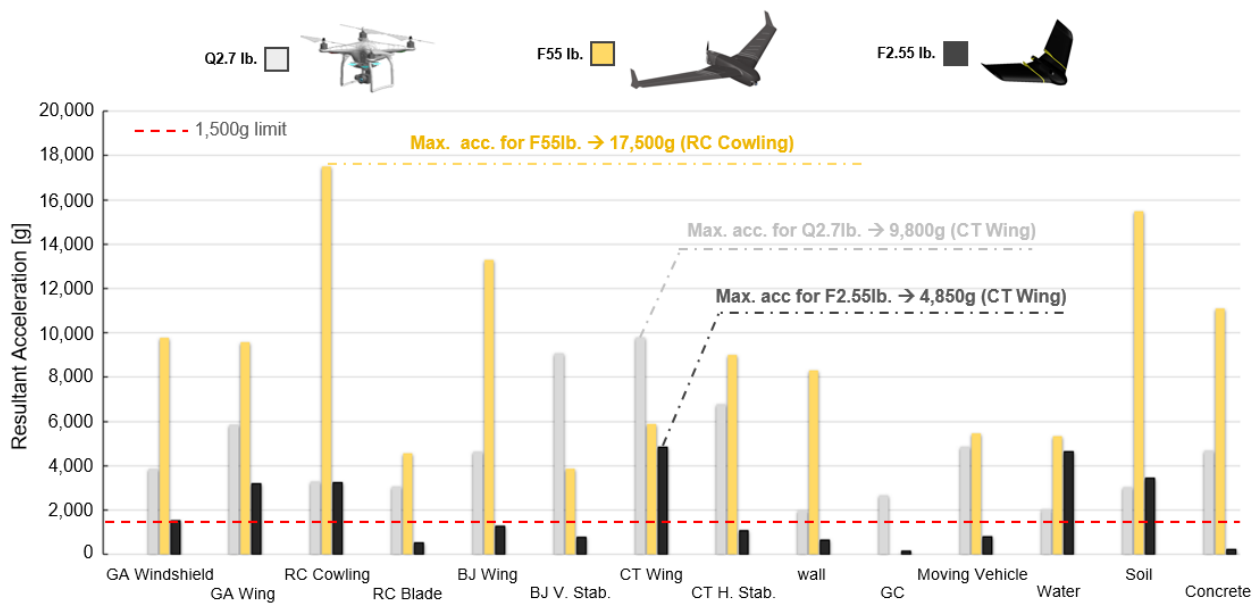

Figure 2. Virtual Sensor acceleration results categorized by UAS type.

4.4 Conclusions

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 sUAS operations has 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, NIAR has studied crash scenarios involving sUAS by utilizing advanced numerical models developed during previous ASSURE programs. First, 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. The cutting-edge numerical methodologies to analyze similar devices were reviewed and applied in several preliminary validation exercises and full-scale sUAS crash simulations.

The main conclusions from Task 3 are:

- FDR TSOs and standards have been continuously evolving to cover a broad range of aircraft. However, there are still gaps to be filled between lightweight FDRs and the technology being used for flight data recording in sUAS.
- Due to the size constraints and data recording frequency in sUAS, micro-SD cards are the preferred technology to record flight data. Further work needs to be done to standardize the use of these devices in different sUAS platforms. For example, some sUAS platforms use more than one FDR to store video, images, and flight data. Additionally, some sUAS platforms use different encryption languages to classify the flight data. Standardizing the flight data management would facilitate data retrieval in the event of a sUAS accident,

ultimately helping to generate more robust standards to enhance safety during sUAS operations.

- Manufacturers of micro-SD cards use metrics similar to those used in traditional FDRs to assess the survivability of these devices. However, there are still uncertainties about the limit values required to survive the hazardous conditions during a sUAS accident.
- By using physics-based simulations, NIAR was able to predict representative loads and accelerations at the FDR during a sUAS crash scenario. While these simulations provide a fair approximation of what an actual FDR would experience, it is important to develop more advanced physical testing to correlate the values predicted by the numerical analyses and to refine the models further. By following this approach, it will become possible to develop crash-survivable housings for these memory units using the critical values predicted from the simulations, thus increasing survivability in the case of a sUAS accident.
- It should be noted that only in 8 of 41 the resultant acceleration (during a time interval of 0.5ms) observed at the virtual FDR did not exceed the 1,500g limit imposed by the standards applied to these types of devices. This suggests that the time window used for micro-SD FDRs (0.5ms) may be very conservative for sUAS crash scenarios or that a higher limit should be considered for this type of aircraft.

4.5 Recommendations

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

1. Assess the survivability of sUAS FDR for other hazardous conditions not analyzed during this work, such as water/fluid immersion, low and high temperature, and hydrostatic pressure.
2. Note that in this work, the mechanical tests performed on the FDR were purely static. However, the loading conditions during a crash event are highly dynamic. NIAR recommends developing dynamic mechanical tests similar to the ones developed in [12] to understand the effect of the shock duration and magnitude on the FDR. While developing these dynamic tests, it is important to find the conditions that best represent an actual crash scenario involving a sUAS. The values obtained during this work should provide an insight into the conditions imposed during these tests.
3. Expand the numerical simulation matrix to study the influence of the FDR location within the sUAS on the loads and acceleration levels observed.
4. 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 and average acceleration windows for loading conditions representative of a crash scenario.
5. 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.

5 TASK 4 DELIVERABLE

5.1 Overview

The incorporation of UAS into the NAS marks a significant transition in the field of aviation, compelling a comprehensive reassessment and modification of existing aviation protocols, with a particular emphasis on flight safety devices such as FDRs and CVRs. This section provides an overview of Task 4 (see appendix D), which amalgamates findings and insights from Tasks 2 and 3, and enhances the report from Task 2 with relevant findings. It hopefully establishes an integral framework for the comprehension and management of the details involved in the integration of UAS into the NAS.

The historical backdrop of aviation has been significantly marked by the use of FDRs and CVRs, ensuring flight safety and facilitating post-incident investigations. However, the transition from manned to unmanned systems introduces unique challenges, particularly due to the varied operational profiles, autonomy levels, and technological capabilities of UAS. Task 4 of the ASSURE A55 project examines these challenges, offering a nuanced understanding of the requirements needed for effective UAS integration into the NAS.

A critical component of this task is the branching of FDR requirements into data and parameter requirements, including the types of data, refresh rates, and the pivotal aspect of crash survivability, which encompasses the media used for data recording. The examination of manned flight data monitoring standards, augmented with UAS-specific data, lays the groundwork for understanding the optimal data recording rates that balance information depth, cost, and power requirements.

The significance of crash survivability, especially for small Unmanned Aircraft Systems (sUAS), cannot be overstated. The increasing utilization of UAS amplifies the probability of accidents, necessitating the development of crash-survivable FDRs. These devices must maintain integrity under challenging conditions to provide invaluable data for accident investigation, analysis, and the creation of enhanced safety measures.

An intriguing aspect of Task 4's findings is the examination of SD cards' viability as data storage media, particularly for sUAS. Given their lightweight, compact nature, minimal power requirements, and substantial data storage capacity, SD cards emerge as a practical solution for UAS data storage needs. However, the exploration into the crash survivability of these SD cards opens avenues for future research, particularly in improving their resilience and ensuring the integrity of stored data in post-crash scenarios.

In essence, Task 4 of the ASSURE A55 project provides a comprehensive lens through which the integration of UAS into the NAS can be viewed, highlighting the nuanced requirements of FDRs specific to unmanned aviation. From the evolution of aviation standards to the exploration of data parameters, crash survivability, and the potential of SD cards, this task lays down a critical foundation for future research and policy design, ensuring the safe and efficient integration of UAS into the broader aviation ecosystem.

One of the salient features of the ASSURE A55 Task 4 report is its observation of UAS operations across various domains, from fixed-wing and rotary-wing UAS to UAM and autonomous operations. Each domain presents distinct challenges and requirements for flight data recording, underscoring the necessity for a multi-faceted approach to standard development. The recommendations provided are not one-size-fits-all but are instead designed to address the specificities of each UAS type and operational context, highlighting the comprehensive and nuanced circumstances found within the UAS landscape.

A portion of the Task 4 report is dedicated to discussing the implications of autonomy levels on FDR requirements. As UAS operations evolve towards higher levels of autonomy, the nature and volume of data that need to be recorded change dramatically. The report delves into the minutiae of capturing data from autonomous systems, especially those reliant on deep learning algorithms and computer vision, pointing towards future research directions that aim to enhance the transparency and explainability of autonomous decision-making processes. This focus on autonomy is crucial, as it represents one of the most dynamic and rapidly evolving facets of UAS technology.

Task 4 attempts to address the practical challenges associated with implementing the proposed FDR requirements, especially for smaller UAS where SWaP constraints are significant considerations. The discussion on the ease of implementation hopefully offers a grounded perspective on the feasibility of these requirements, balancing the ideal against the practicable. This pragmatic approach ensures that the recommendations are not just theoretically sound but also viable in real-world applications.

The overview of Task 4 encapsulates a forward-thinking approach to UAS integration into the NAS. The report acknowledges the current state of UAS technology and operations but is firmly oriented towards the future, anticipating advancements in autonomy, data storage technologies, and UAS applications. This forward-looking perspective is crucial for developing standards and recommendations that not only address today's challenges but are also adaptable to tomorrow's advances.

The overview of Task 4 of the ASSURE A55 project presented here provides an encapsulation of the key themes, challenges, and considerations involved in identifying flight recorder requirements for UAS integration into the NAS. From the specific understanding of UAS operations and the impact of autonomy to the practical challenges of implementation and the forward-looking approach to standard development, the report lays a foundation for future research, policy formulation, and the safe, efficient integration of UAS into the aviation ecosystem. As the UAS landscape continues to evolve, the insights and recommendations from Task 4 hope to help play a role in shaping the future of unmanned aviation.

5.2 Background

The concept of documenting flight data for safety and investigative purposes has its roots in the early days of manned aviation. The initial generation of flight recorders in the 1950s employed analog systems to capture fundamental flight parameters and cockpit conversations. Subsequent technological advancements have significantly enhanced the capabilities of these devices, concluding with the introduction of solid-state memory recorders. These devices, capable of storing an extensive array of flight parameters and hours of audio data, offer increased reliability and robustness.

FDRs and CVRs have become indispensable in aviation safety, furnishing crucial data that has led to numerous safety improvements and regulatory developments. The evolution of these devices mirrors the aviation industry's pursuit of augmenting the capacity to reconstruct pre-incident events, thereby mitigating the recurrence of accidents.

The last few decades have witnessed the rapid development and deployment of UAS, propelled by technological advancements and an expanding spectrum of applications. Contrary to manned aircraft, UAS operate without an onboard human pilot, being either autonomously controlled by onboard computers or remotely piloted from a Ground Control Station (GCS). The diversity in sizes, capabilities, and operational uses of UASs introduces unique challenges and opportunities, particularly concerning safety protocols and airspace integration.

The seamless integration of UAS into the NAS is entangled within a complex matrix of regulations and standards promulgated by various national and international entities. Domestically, the FAA spearheads the regulatory framework for UAS operations, drawing upon existing standards for manned aviation while addressing the distinctive facets of unmanned flight. Internationally, entities such as ICAO and the EUROCAE play pivotal roles in shaping global UAS policies.

Current regulations for manned aircraft FDRs and CVRs, such as those delineated in the Federal Code and technical standards like EUROCAE's ED-112A, serve as foundational elements. However, the distinct operational dynamics, control mechanisms, and the potential for autonomous operation inherent in UAS necessitate a thorough reexamination of data recording paradigms, storage methodologies, and recorder survivability standards.

The regulatory landscape for UAS is characterized by a mosaic of national and international standards, each with its nuances and specifications tailored to different aspects of UAS operations. This intricate regulatory tapestry underscores the importance of a coherent and unified approach to UAS regulation, which is pivotal for ensuring the safe and efficient integration of UAS into the NAS. It is imperative that new regulations and standards for UAS, particularly regarding flight data recording, are developed in a manner that ensures compatibility and interoperability across different domains, thereby facilitating seamless global UAS operations.

In the realm of manned aviation, FDRs and CVRs play a crucial role in enhancing flight safety by enabling detailed post-incident analyses, which in turn inform safety improvements and regulatory updates. For UAS, the principles underlying the necessity for flight data recording remain the same, yet the implementation presents unique challenges. Given the diversity in UAS operations—from small drones used for recreational purposes to larger systems deployed for commercial or scientific missions—the requirements for flight data recording must be adaptable, ensuring that they are relevant and applicable across the spectrum of UAS operations.

One of the most defining characteristics of UAS technology is the potential for high levels of autonomy. As UAS continue to advance towards greater autonomy, the data recording requirements must evolve accordingly. Traditional FDRs focused primarily on capturing physical flight parameters, but for highly autonomous UAS, there is a need to record data that reflects the decision-making processes of the onboard autonomous systems. This includes not just the outcome of such decisions but also the inputs and algorithms that led to those decisions, presenting a complex challenge for data recording and analysis.

The survivability of flight data recorders in the event of an incident is a critical consideration for both manned and unmanned aviation. For UAS, ensuring the crash survivability of FDRs is complicated by the vast array of potential operational scenarios and crash dynamics. Additionally, the integrity of the recorded data is paramount. This not only involves the physical robustness of the recording devices but also incorporates aspects such as data encryption, secure transmission, and storage, particularly for UAS that rely on real-time data telemetry to a ground station.

The integration of UAS into the NAS necessitates the development of comprehensive, flexible standards that can accommodate the rapid advancements in UAS technology and the diversification of UAS applications. These standards must address the core aspects of flight data recording, including the types of data to be recorded, the frequency and resolution of data capture, and the crash survivability of recording devices. The standards must be developed with a forward-looking perspective, anticipating future technological developments, and ensuring that they remain relevant and effective in enhancing UAS safety and operational efficiency.

5.3 Findings

The comprehensive analysis conducted under Task 4 of the ASSURE A55 project reveals a multi-layered understanding of the requirements necessary for the integration of UAS into the NAS. These findings outline the critical areas of focus, challenges encountered, and potential pathways for establishing effective and robust flight recorder standards for UAS. The insights gleaned from this analysis are helpful in shaping future directives for UAS integration, ensuring safety, compliance, and operational efficiency.

5.3.1 Data and Parameter Requirements

A crucial aspect of the findings relates to the identification and categorization of data and parameter requirements for UAS flight recorders. This includes a detailed examination of the types of data essential for comprehensive flight analysis, such as altitude, airspeed, heading, engine performance, and flight control inputs, among others. The refresh rate or the frequency at which this data should be recorded was also scrutinized, highlighting a balance between capturing detailed flight data and managing storage and power constraints inherent in UAS operations.

5.3.2 UAS-Specific Augmentations

The research underscores the necessity of augmenting traditional flight data parameters, drawn from manned aviation standards, with UAS-specific data. This augmentation addresses the unique operational characteristics of UAS, such as autonomous decision-making processes, real-time telemetry data transmission, and specific control inputs pertinent to UAS operations. The inclusion of these UAS-specific parameters ensures that the flight recorders can capture a comprehensive dataset reflective of the unique operational subtleties of UAS.

5.3.3 Crash Survivability

A significant portion of the findings is dedicated to the aspect of crash survivability of flight recorders in UAS. The analysis emphasized the need for flight recorders to maintain integrity under adverse conditions, ensuring that valuable data can be retrieved for post-incident analysis. The survivability criteria extend beyond physical robustness to encompass data integrity, security, and accessibility, particularly in scenarios where data is transmitted in real-time to a ground station.

5.3.4 Autonomy Levels and Recording Requirements

The findings elucidate the direct correlation between the levels of autonomy in UAS operations and the flight recorder data requirements. As UAS operations turn towards higher autonomy levels, the complexity and volume of data to be recorded increase, necessitating advanced data management strategies. This includes the recording of algorithmic decision pathways, sensor fusion logs, and autonomous system responses to operational contingencies, presenting a complex challenge in data recording and analysis.

5.3.5 Implementation Challenges

The practical challenges associated with implementing the proposed flight recorder requirements for UAS were thoroughly examined. These challenges are particularly pronounced in smaller UAS, where SWaP constraints impose significant limitations. The findings highlight the trade-offs between the comprehensiveness of data recording and the practical limitations of UAS platforms, advocating for scalable and adaptable recorder standards that can accommodate a wide range of UAS types and sizes.

5.3.6 Regulatory Harmonization and Future Directions

The analysis underscored the critical need for regulatory harmonization both nationally and internationally, to ensure seamless and safe UAS operations across different jurisdictions. The findings advocate for collaborative efforts among regulatory bodies, industry stakeholders, and academic institutions to develop cohesive and forward-looking recorder standards that align with the evolving landscape of UAS technology and applications.

5.3.7 SD Cards as a Viable Data Storage Solution

An interesting revelation from the research pertains to the viability of using SD cards as data storage media for UAS flight recorders. Given their lightweight and compact nature, along with significant storage capacities, SD cards emerge as a practical solution for UAS data storage needs. However, the findings also point to the necessity for further research into enhancing the crash survivability and data integrity features of SD cards to make them a reliable choice for UAS flight recorders.

5.3.8 Future Research Areas for Improving Crash Survivability

The findings from Task 4 highlight several key areas for future research aimed at improving the crash survivability of UAS flight data recorders. These include the expansion of numerical simulations to better understand the impact of the Vehicle System (VS) location on loads and accelerations experienced during a crash. Future studies are also encouraged to explore the optimization of material use and design for prototype crash-protected flight data recorders, ensuring they meet the stringent demands of various UAS operational scenarios.

5.3.9 The Importance of Standardized Data Formats

The findings also emphasize the importance of establishing standardized data formats and communication protocols for UAS flight data recording. The current lack of standardization can lead to challenges in data interoperability and analysis, particularly in a post-incident investigation. Standardizing data formats would facilitate easier data sharing and analysis across different platforms and systems, enhancing the overall effectiveness of UAS flight data recorders in contributing to aviation safety.

5.3.10 The Role of UAS in Urban Air Mobility (UAM)

Task 4's findings also delve into the specific requirements of UAS operating within the emerging domain of UAM. Given the unique operational context of UAM, including operations within densely populated urban environments, the findings suggest additional parameters that might be relevant, such as cabin pressure altitude and loss of cabin pressure for passenger flights, to ensure the safety and comfort of those onboard passengers. This highlights the adaptive nature of flight recorder requirements in response to the diverse applications of UAS technology.

The findings from Task 4 of the ASSURE A55 project provide an overview of the current state and future directions for flight data recording in UAS operations. From the nuanced requirements based on UAS types and levels of autonomy to the practical challenges of implementation and the need for regulatory harmonization, the findings lay a solid foundation for future advancements in UAS flight data recording. As UAS technology continues to evolve and find new applications, these findings will serve as a critical resource for stakeholders across the aviation industry, guiding the development of standards, policies, and technologies that enhance the safety, efficiency, and integration of UAS into the global airspace.

5.4 Conclusions

The comprehensive analysis conducted as part of Task 4 within the ASSURE A55 project has yielded significant insights into the complexities of integrating UAS into the NAS. This section encapsulates the core conclusions derived from the examination of FDR requirements, crash survivability standards, and the central regulatory framework that will govern UAS operations. These conclusions provide a strategic roadmap for advancing UAS integration, ensuring alignment with safety protocols, operational efficiency, and regulatory compliance.

One of the principal conclusions of this task is the imperative need for a thorough reevaluation and adaptation of existing FDR standards, traditionally designed for manned aviation, to accommodate the diverse spectrum of UAS operations. The analysis underscores the necessity for UAS-specific data parameters that account for the unique operational profiles, including autonomous decision-making processes and real-time telemetry data transmission. This necessitates a paradigm shift in how flight data is captured, stored, and analyzed, emphasizing the need for a flexible and scalable approach to FDR standardization for UAS.

The findings highlight the importance of augmenting traditional flight data parameters with UAS-specific considerations to capture the full operational dynamics of unmanned flights. The conclusion underscores the need for a comprehensive data set that not only facilitates post-incident analysis but also aids in the continuous improvement of UAS safety and operational protocols.

A critical conclusion from the task is the paramount importance of crash survivability for UAS flight recorders. The findings illustrate the need for robust standards that ensure the physical integrity of FDRs under adverse conditions, enabling the retrieval of vital data for post-incident analysis. The analysis extends to the integrity and security of data, especially for UAS that rely on data telemetry, underscoring the need for encrypted and secure data transmission and storage protocols to safeguard sensitive information.

The findings further stress the critical importance of standardizing data formats across UAS flight data recording systems. A standardized data format will facilitate easier data retrieval, analysis, and sharing across different platforms, enhancing the efficiency of post-incident investigations and contributing significantly to the advancement of UAS safety measures. The conclusion advocates for industry-wide collaboration to establish such standards, ensuring interoperability and consistency in data handling and analysis practices.

A significant takeaway from the task is the advocacy for a collaborative approach to the development and implementation of FDR standards for UAS. This encompasses partnerships between regulatory bodies, UAS manufacturers, operators, academia, and other stakeholders to ensure that the developed standards are comprehensive, practical, and reflective of the collective expertise within the UAS community. Such collaborative efforts are essential for fostering innovation, ensuring widespread adoption of standards, and ultimately enhancing the safety and efficiency of UAS operations.

Lastly, the analysis conducted as part of Task 4 of the ASSURE A55 project provides a foundational framework for the future of flight data recording in UAS. The conclusions drawn underscore the complexity of integrating UAS into the NAS and highlight the versatile approach required to develop effective FDR standards. As the UAS industry continues to evolve, these insights will play a crucial role in shaping the regulatory, technological, and operational landscape, ensuring the safe, efficient, and integrated use of UAS in airspace systems worldwide.

5.5 Recommendations

Between Tasks 3 and 4, the combined recommendations are as follows:

1. The set of parameters provided herein are adopted from the general aviation requirements. To verify the feasibility of those parameters for the UAS, further experiments are recommended including tests in real-world settings. requires an experimental work approach or in real-world settings. It is recommended that further research should be conducted to check and assess the recorded samples and their quality.
2. The methods used in encoding and decoding for recording those parameters can be verified to check the differences between actual physical values and recorded values. This can also help to extract the data easily for further data analysis.
3. For the autonomous UAS missions, it is recommended to know the LOA to define the exact set of FDR parameters requirements.
4. Standard file format for recording should be established to analyze all data recorded irrespective of the manufacturer.
5. Ground control station large enough to accommodate 2 or more people, should be treated as cockpit for current manned aircraft, hence, existing requirements (14 CFR § 23.1457 – Cockpit Voice Recorders) should be adopted.
6. For handheld ground control stations, all communications amongst flight crew (Pilot-in-command, persons manipulating controls, and visual observers) should be recorded.
7. Assess the survivability of sUAS FDR for other hazardous conditions not analyzed during this work, such as water/fluid immersion, low and high temperature, and hydrostatic pressure.
8. Note that in this work, the mechanical tests performed on the FDR were purely static. However, the loading conditions during a crash event are highly dynamic. NIAR recommends developing dynamic mechanical tests similar to the ones developed in [12] to

understand the effect of the shock duration and magnitude on the FDR. While developing these dynamic tests, it is important to find the conditions that best represent an actual crash scenario involving a sUAS. The values obtained during this work should provide an insight into the conditions imposed during these tests.

9. Expand the numerical simulation matrix to study the influence of the FDR location within the sUAS on the loads and acceleration levels observed.
10. 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 and average acceleration windows for loading conditions representative of a crash scenario.
11. 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.

These comprehensive recommendations serve to guide industry stakeholders in advancing UAS flight data recording capabilities, addressing prevailing challenges, and fostering future innovations that elevate the safety, efficiency, and regulatory alignment of UAS operations.

6 FINAL CONCLUSIONS

The in-depth examination and analysis conducted across Tasks 2, 3, 4, and 5 have culminated in a series of significant conclusions that collectively inform the future path of FDR development for UAS. This final section synthesizes the overarching themes, challenges, opportunities, and strategic directions highlighted in each task's conclusion, offering a holistic view of the path forward in enhancing the safety, effectiveness, and regulatory compliance of UAS through advanced FDR capabilities.

6.1 Evolutionary Trajectory and Historical Context

A foundational conclusion across the tasks is the recognition of the evolutionary history of FDR technologies from their origins in manned aviation to their current and potential applications within UAS operations. This historical context sets a blueprint for UAS FDR standards, emphasizing the transition from analog to solid-state recording technologies and highlighting principles such as data fidelity, storage capacity, and survivability. These principles, deeply rooted in the legacy of manned aviation, are equally pertinent to UAS operations and form the foundation of future FDR development for unmanned systems.

6.2 Regulatory Landscape and Harmonization

The complex and often fragmented regulatory landscape that currently governs UAS operations emerges as a critical area of focus. The need for regulatory harmonization and the development of UAS-specific recorder standards is a recurring theme, underscoring the urgency to address the unique operational profiles, autonomy levels, and technological capabilities of UAS. Harmonization efforts are essential not only for aligning with existing regulations but also for anticipating and adapting to future advancements and operational paradigms in UAS technology.

6.3 Technological Advancements and Data Integrity

The rapid evolution of UAS and recording technologies presents a dual-edged challenge, offering innovative approaches to flight data recording and retrieval while also introducing challenges in data integrity, encryption, and transmission reliability. The capability of UAS to transmit real-time telemetry data necessitates stringent standards to ensure that remotely stored data can fulfill investigatory and safety purposes as effectively as data stored onboard. Additionally, the advancements in autonomous navigation and decision-making algorithms highlight the need for recording systems that capture the complex decision-making processes of onboard AI systems, ensuring transparency and accountability in autonomous UAS operations.

6.4 Stakeholder Engagement and Collaborative Development

The indispensable role of stakeholder engagement in the FDR standardization process is a core conclusion across the tasks. The collaborative approach to standard development is emphasized, involving active participation from regulatory bodies, industry stakeholders, academic researchers, and safety organizations. This collaboration ensures that the developed FDR standards for UAS are comprehensive, practical, and reflective of the diverse needs and perspectives within the UAS community.

6.5 SD Cards as Practical Data Storage Solutions

An intriguing conclusion from the analysis is the potential viability of using SD cards as a practical data storage solution for smaller UAS. Given their lightweight, compact size, and significant storage capacities, SD cards are recognized as a feasible option for data storage in smaller UAS. However, further research into enhancing the crash survivability and data integrity features of SD cards is highlighted as a crucial area for future investigation.

6.6 Standardization and Modular Approach to FDR Development

A critical insight derived from the comprehensive analysis is the necessity for a standardization in FDR requirements that are adaptable and flexible enough to cater to the diverse range of UAS types and operational contexts. The modular approach to standard development, as suggested in the conclusions of the tasks, advocates for a framework where core FDR requirements are universally defined, with additional specifications tailored to specific UAS categories such as fixed-wing, rotary-wing, and UAM systems. This approach ensures that FDR standards are not only robust and inclusive but also dynamic, capable of evolving alongside UAS technology and applications.

6.7 Addressing the Challenges of UAM Integration

Another significant conclusion pertains to the integration of UAS into the burgeoning field of UAM. The unique operational challenges and safety considerations associated with UAM, particularly in densely populated urban environments, necessitate additional FDR parameters and standards tailored to this domain. Parameters pertinent to passenger safety, environmental controls, and cabin pressure are highlighted as crucial for UAS operating within the UAM ecosystem, underscoring the need for continuous adaptation and refinement of FDR standards to encompass new and emerging UAS applications.

6.8 Future Research and Policy Initiatives

The conclusions also lay out a roadmap for future research and policy initiatives aimed at advancing FDR technology for UAS. Key areas for future investigation include the development of crash-survivable FDR housings, the optimization of data recording rates, the exploration of advanced data storage solutions such as SD cards, and the enhancement of autonomous systems' transparency through explainable AI. Policy and legislative efforts are called for to support these research initiatives, advocating for standardized data formats, enhanced data security protocols, and the integration of UAS into the NAS in a manner that aligns with safety and regulatory requirements.

In synthesizing the conclusions from Tasks 2, 3, 4, and 5, this overall conclusion section encapsulates the challenges and opportunities in developing FDR use for UAS. From the context of FDR technology and the call for regulatory coordination to the need for adaptable standards, enhanced data security, and collaborative innovation, the insights garnered provide a blueprint for the future of FDR development in unmanned aviation. As the UAS sector continues to expand and diversify, the strategic directions outlined in this report will hopefully serve as guiding principles, steering the advancement of FDR technology to ensure the safe, efficient, and integrated operation of UAS within the global airspace ecosystem.

7 FINAL RECOMMENDATIONS

This section delineates actionable recommendations derived from the extensive research and analysis conducted across Tasks 1 through 4. These recommendations are categorized into "Main Recommendations" for immediate implementation, "Needs Further Development" for areas requiring further exploration, and "Future Research" for advancing the field.

7.1 Main Recommendations

Adopt FDR Parameters from Deliverable 4: Industry stakeholders should adopt the FDR parameters outlined in Section 5 of Deliverable 4 as the basic standard for UAS FDR development, ensuring these parameters are integrated into FDR systems designed for diverse UAS platforms.

Standardize Data Formats: Establish a universal file format for FDR data recording across the UAS industry to promote data interoperability and streamline analytical processes, facilitating uniform data analysis and interpretation regardless of the UAS manufacturer.

Allow SD Cards for Small UAS FDRs: Recognize and allow the use of SD cards as a viable data storage solution for FDRs in smaller UAS, considering their compact size, significant storage capacity, and ease of integration, while ensuring the durability and data integrity of these storage media are validated for operational use.

Enhance Encoding and Decoding Techniques: Rigorously evaluate and optimize encoding and decoding methodologies used in FDR systems to ensure the accurate capture of flight data, minimizing discrepancies between recorded values and actual flight conditions.

7.2 Needs Further Development

Define FDR Parameters for Autonomous Missions: Determine the specific set of FDR parameters required for missions involving high levels of UAS autonomy, tailoring these parameters to capture the nuanced operational data of autonomous systems and to facilitate comprehensive post-mission analysis.

Collaborate on Regulatory Harmonization: Engage in collaborative efforts with regulatory bodies, including the FAA, ICAO, and EUROCAE, to harmonize FDR standards and regulations for UAS at both national and international levels, ensuring global consistency and interoperability in UAS operations.

7.3 Future Research

Assess FDR Survivability: Conduct in-depth studies to evaluate the survivability of sUAS FDRs under various hazardous conditions not previously analyzed, such as water/fluid immersion, extreme temperature variations, and exposure to hydrostatic pressure, to enhance the resilience of FDR systems.

Develop Dynamic Mechanical Tests: Create dynamic mechanical testing protocols that accurately simulate the conditions of a crash involving sUAS, to better understand the effects of shock duration and magnitude on FDR integrity and to refine FDR design for enhanced crash survivability.

Expand Numerical Simulations: Broaden the scope of numerical simulations to investigate the influence of FDR placement within sUAS on the loads and acceleration levels experienced during crash scenarios, utilizing these insights to optimize FDR placement and design for maximum protection.

Build Robust Finite Element Models: Utilize results from dynamic tests to construct advanced FEMs of sUAS FDRs, employing these models to simulate crash conditions and inform the development of more durable FDR designs that can withstand the rigors of operational use.

By addressing these recommendations through targeted actions, future research, and collaborative efforts, the goal is to create an environment conducive to the safe, efficient, and integrated operation of UAS within the National Airspace System. These strategic directions are intended to guide stakeholders across the UAS ecosystem in realizing the full potential of UAS technologies in a manner that enhances safety, operational excellence, and societal benefit.

Table 15 encapsulates the strategic recommendations derived from the overall analysis, aimed at advancing the development, implementation, and standardization of FDR technologies within the UAS sector. These recommendations are designed to guide industry stakeholders, regulatory bodies, and the research community in enhancing the safety, efficiency, and regulatory compliance of UAS operations.

Table 15. Final Recommendations by Category.

Category	**Recommendations**
Main Recommendations	**Adopt FDR Parameters from Deliverable 4**: Integrate Deliverable 4's FDR parameters as the UAS FDR standard. **Standardize Data Formats**: Establish a universal file format for FDR data. **Enhance Encoding and Decoding Techniques**: Optimize FDR data encoding and decoding methods.

	Record Ground Control Communications: Implement recording protocols for all ground control station communications. **Allow SD Cards for Small UAS FDRs**: Recognize SD cards as a viable data storage solution for small UAS FDRs.
Needs Further Development	**Define FDR Parameters for Autonomous Missions**: Tailor FDR parameters for high-autonomy UAS missions. **Verify Encoding and Decoding Methods**: Investigate and improve FDR data encoding/decoding. **Collaborate on Regulatory Harmonization**: Work with regulatory bodies to harmonize UAS FDR standards globally.
Future Research	**Assess FDR Survivability**: Evaluate sUAS FDR resilience under various hazardous conditions. **Develop Dynamic Mechanical Tests**: Create protocols to simulate sUAS crash conditions. **Expand Numerical Simulations**: Investigate the influence of FDR placement within sUAS on crash survivability. **Build Robust Finite Element Models**: Construct advanced FEMs to inform durable FDR designs.

8 REFERENCES

Apostolidis, A., Pelt, M., & Stamoulis, K. P. (2020, January). Aviation Data Analytics in MRO Operations: Prospects and Pitfalls. In 2020 Annual Reliability and Maintainability Symposium (RAMS) (pp. 1-7). IEEE.

Bailey, T. (2006, January). Flight Data Recorders: Built to Survive. Avionics News, 38-47.

Clough, B. T. (2002). Metrics Schmetrics! How The Heck Do You Determine A UAV's Autonomy Anyway?

Dergachov, K., Bahinskii, S., & Piavka, I. (2020). The Algorithm of UAV Automatic Landing System Using Computer Vision. In 2020 IEEE 11th International Conference on Dependable Systems, Services and Technologies (DESSERT).

Došilović, F. K., Brčić, M., & Hlupić, N. (2018). Explainable Artificial Intelligence: A Survey. In 2018 41st International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO) (pp. 0210-0215).

Dub, M., & Parizek, J. (2018). Evolution of Flight Data Recorders. Advances in Military Technology, 13(1).

EUROCAE. (2013). Minimum Operational Performance Specification for Crash Protected Airborne Recorder Systems.

EUROCAE. (2009). Minimum Operational Performance Specification for Lightweight Flight Recording Systems.

Federal Aviation Administration. (2018, October 11). Technical Standard Orders (TSO). Retrieved from https://www.faa.gov/aircraft/air_cert/design_approvals/tso/

Federal Aviation Administration. (2007, April 10). Technical Standard Order: Flight Data Recorder Systems. Retrieved from https://rgl.faa.gov/Regulatory_and_Guidance_Library/rgTSO.nsf/0/e040550c3ab32300862572c200113975/$FILE/TSO-C124b.pdf

Federal Aviation Administration. (2013, December 19). Technical Standard Order: Cockpit Voice Recorder Equipment. Retrieved from https://rgl.faa.gov/Regulatory_and_Guidance_Library/rgTSO.nsf/0/c464478183dcbdc686257c450067e591/$FILE/TSO-123c.pdf

Federal Aviation Administration. (2000, June 15). Advisory Circular: Advisory Circular Checklist. Retrieved from https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_00.2-13.pdf

Federal Aviation Administration. (2010, August 17). Advisory Circular: Airworthiness and Operational Approval of Digital Flight Data Recorder Systems. Retrieved from https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_20-141B.pdf

Federal Aviation Administration. (2016, July 22). Advisory Circular: Airworthiness and Operational Approval of Cockpit Voice Recorder Systems. Retrieved from https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_20-186.pdf

Heinrich, S. (2017). Flash Memory in the Emerging Age of Autonomy.

Higgins, J., & Branscomb, K. (2022). Literature Review for ASSURE A55 – Identify Flight Recorder Requirements for Unmanned Aircraft Systems (UAS) Integration into the National Airspace System (NAS). Federal Aviation Administration Report A11L.UAS.101_A55.

House of Representatives Congress. (2015, December 30). 49 U.S.C. § 1114 - Disclosure availability and use of information. Retrieved from https://www.govinfo.gov/app/details/USCODE-2015-title49/USCODE-2015-title49-subtitleII-chap11-subchapII-sec1114

House of Representatives Congress. (2011, December 30). 49 U.S.C. § 1154 - Discovery and use of cockpit and surface vehicle recordings and transcripts. Retrieved from https://www.govinfo.gov/app/details/USCODE-2011-title49/USCODE-2011-title49-subtitleII-chap11-subchapIV-sec1154

Li, K., Zhang, K., Zhang, Z., Liu, Z., Hua, S., & He, J. (2021). A UAV Maneuver Decision-Making Algorithm for Autonomous Airdrop Based on Deep Reinforcement Learning. Sensors (Basel).

Office of the Federal Register National Archives and Records Administration. (2011, December 31). 14 CFR 129 - OPERATIONS: FOREIGN AIR CARRIERS AND FOREIGN OPERATORS OF U.S.-REGISTERED AIRCRAFT ENGAGED IN COMMON CARRIAGE. Retrieved from https://www.govinfo.gov/app/details/CFR-2012-title14-vol3/CFR-2012-title14-vol3-part129

Office of the Federal Register National Archives and Records Administration. (2010, December 31). 14 CFR 135 - OPERATING REQUIREMENTS: COMMUTER AND ON DEMAND OPERATIONS AND RULES GOVERNING PERSONS ON BOARD SUCH AIRCRAFT. Retrieved from https://www.govinfo.gov/app/details/CFR-2011-title14-vol3/CFR-2011-title14-vol3-part135

RTCA Inc. (2001). 0Y4DKM6A. Washington, D.C.

Thompson, H. M. (2022). A Vision of Future Crash Survivable Recording Systems. Allied Signal, Redmond, WA.

Walker, G. (2017). Redefining the Incidents to Learn From: Safety Science Insights Acquired on the Journey From Black Boxes to Flight Data Monitoring. Safety Science, 99, 14-22.

Young, L., Yetter, J., & Guynn, M. (2012, June 15). System Analysis Applied to Autonomy: Application to High-Altitude Long-Endurance Remotely Operated Aircraft. Infotech@Aerospace Conferences.