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Flight Data Recorders: Past, Present, and Future

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Abstract—Devices that record data generated by an aircraft and its crew during operation are known as flight data recorders (FDR) and cockpit voice recorders (CVR). Data recorded by these devices enable the analysis of aircraft state and behavior from take-off to landing. The information provided by these devices is used to conduct inspections, investigations, training, and other measures by aviation experts following hazardous events or accidents. As of today, multiple instruction manuals covering the specifications of FDRs and CVRs have been presented by various organizations, experts, and scientists within the aviation industry. However, no consolidated research document that brings all this information together for regulatory and technical purposes has been published yet. Our objective is to carry out an in-depth study of FDRs for both manned and unmanned systems. We aim to examine the requirements used in the past, current technological advancements, and future intelligent FDR approaches, intending to advance FDR technology. Starting with manned aviation systems, we provide a comprehensive overview of general FDRs and then look at new challenges and the resulting requirements for unmanned aerial vehicles (UAVs). After reviewing all relevant resources, we present a roadmap for the next generation of FDRs.

Index Terms—Flight data recorder, International civil aviation organization, Federal aviation administration, Unmanned aerial vehicles, Intelligent FDRs, IoT networks

I. INTRODUCTION

IN 2019, the chief executives of Boeing stated in a testimony to the United States Congress discussing the B737 max, “If back then, we knew everything we know now, we would have made different decisions” [1]. Although today’s aircraft are designed based on information uncovered from past accidents, there is inadequate data to determine the complex events that lead to an accident [2]. The safety of a flight depends not only on the aircraft’s design and the onboard systems’ features but also on the support provided by the ground stations, the skills of the pilot, and air traffic control (ATC)[3]. At the same time, flight data recorders (FDR) and cockpit voice recorders (CVR) also positively contribute to flight safety. To determine the cause of aircraft accidents, both are used.

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On various occasions, they are referred to by different names, such as black boxes, digital FDRs (DFDR), solid-state FDRs (SSFDR), or accident data recorders (ADR) [4].

This study of FDR serves a variety of purposes, including new aircraft development, training assessment, maintenance, and diagnosing accident causation. Installing an FDR in a UAV is becoming increasingly difficult, given the ever-shrinking size of the aircraft design, power, and other constraints. In addition, unmanned aerial vehicle (UAV) technologies have evolved over time, and the strong interest in their use indicates that these technologies will be the future of the aviation industry for military and commercial purposes. The rapid growth of UAV technology exceeded the pace of regulators, standards development organizations, and researchers to develop standards, requirements, and other regulatory policies for FDRs.

This paper contributes to the research community by identifying research gaps that can be solved in the future to improve UAV FDR technologies and help regulators set standards for UAV FDRs, their integration, operations, and analysis. A literature review collected most of the legal requirements and technical aspects of FDRs, from general technologies to artificial intelligence (AI)-based approaches for UAVs. In this way, we consider FDR solutions that either send the recorded data with real-time monitoring and data transmission to a ground station or record all the parameters on board. We’ve created a comprehensive overview of FDRs, from manned to unmanned systems, and associated it with the current AI-based revolution. Some opportunities through current technologies are presented, as well as challenges that come along with them.

This paper bridges between regulatory aspects and the technical history of FDRs. More specifically, limited literature is available connecting the FDR devices from manned systems to unmanned systems. It becomes necessary to associate these aspects and understand the criticality of FDR devices from small-scale evolution to current standards building a single document where the readers can opt for vital information regarding FDR studies, including requirements of parameters, weight limitations, size restrictions, power constraints, and communication protocols. These research gaps allow us to contribute to the next generation of FDR by proposing UAV architectural frameworks.

The remainder of the paper is structured as follows: In the first section, the introduction and background comprehensively illustrate the scope of the work, some real application usage of FDR, and the general overview of FDRs. The paper describes the emergence of FDR over time in the second section. Later, the FDR’s background is illustrated in which the data acquisition system concept addresses estimations of parameters, input data, input sensor information, and their encoding and

decoding strategies in the third chapter. Moreover, this section includes a recording operational checklist, which defines the quality of recording and calibration checks on measured parameters. In the next part “Fourth Section”, the general standards and regulations of FDR are demonstrated, which covers a review of the regulatory considerations of FDRs and a comparison regarding regulatory requirements, which highlight some of the challenging hurdles in the industry. The fifth section considers FDRs of UAVs, which defines FDR requirements for a UAV and challenges while implementing those requirements. Furthermore, this section analyzes report accidents from various official accident information portals of U.S. public safety departments, i.e., the National Transportation and Safety Board (NTSB), accident and incidents by the Federal Aviation Administration (FAA), and the Aviation Safety Reporting System (ASRS) portal from the National Aeronautics and Space Administration (NASA). In the sixth section, we present a roadmap for the researchers to execute research for the FDRs of UAVs that includes an intelligent FDR model, which can record all the parameters of an aircraft smoothly and design a real-time data transfer system with an enhanced quality of recording followed by the conclusion part.

II. EMERGENCE OF FLIGHT RECORDERS

FDRs that conform to the latest version of the (ICAO) Annex 6 “Operation of Aircraft” are classified into two main categories, the first one is “crash-protected flight recorders,” and the second category is “lightweight flight recorders” [5]. The first category is crash-protected because it fulfills the requirements of FDR survivability of a mishap situation and satisfies crash requirements. The second category is generally considered non-crash FDRs, which are lightweight, compact systems sometimes referred to as Quick Access Recorders (QAR). QAR is portable using removable media, such as a USB drive or microSD card, to make the data accessible. Since they are lightweight, they may not meet future regulatory requirements similar to the first group. ICAO, Annex 6 describes crash-protected flight recorders as consisting of an FDR and the CVR, as well as an Airborne Image Recorder (AIR) and a Data Link Recorder (DLR). On the other hand, a lightweight recorder consists of a data recording system (DRS), an aircraft cockpit audio recording system (CARS), an AIR, and the DLR [6]. The CARS are specially used for operational purposes, such as training, analysis of incidents or accidents, and performance evaluation. On the other hand, the CVR is employed by accident investigators to determine the cause of an accident or incident.

By the mid-1950s, installing or incorporating FDR systems on commercial flights became necessary due to the lack of survivors or witnesses in several serious aircraft crashes [7]. Two models for FDRs were designed at that time, named General Mill’s (GM) Ryan Flight Recorder (RFR), a data recorder, and the Australian Research Laboratories (ARL) “Flight Memory Unit”, a voice recorder [4], [7]. For the RFR, the patent published by Minnesota State University by Prof. James J. Ryan provides a measurement of four data parameters, i.e., altitude, velocity, g-force, and time [8] which

was utilized by the GM recorders. These FDRs can record parameters for up to 300 hours by engraving data into a metal foil with a needle. The prototype of the ARL’s flight memory unit design was based on David Warren’s¹ theory of using the voice wire recorder aboard an aircraft, which combines a cockpit voice and data recorder. This type of data recorder can record cockpit voice and eight different instrumental readings per second for four hours [9], [10]. The ARL in Fisherman’s Bend, Australia discovered the first black box flight recorder in 1953.

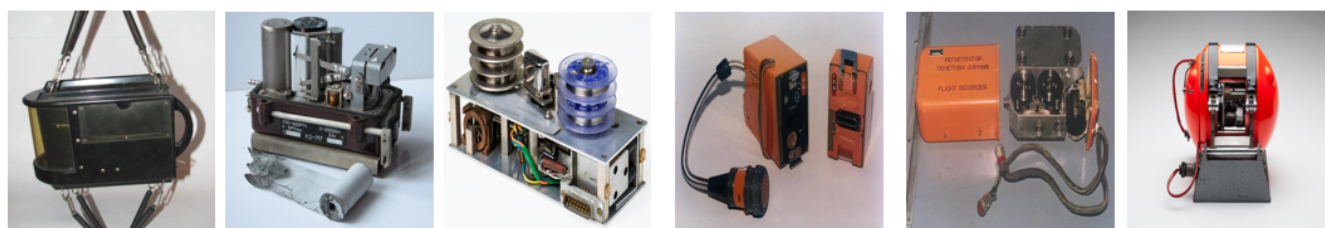
The first flight recorder used by a flight crew was based on ARL’s flight memory unit, which was also the first to be designed as a permanent instrument on an aircraft that can then help identify accidents by investigative organizations [11]. At the same time, while not the first FDR, the GM device was the first to emphasize the concept of impact protection and the first to implement a rigorous program of destructive testing for scientific purposes. The devices invented by Ryan and Warren were not simply flight recorders; these devices were designed and used primarily above all as accidental technologies (assisting in the investigation into aircraft accidents). Initially, the FDR could record only a few parameters; for example, the first FDR could only engrave five parameters on a non-reusable metal foil. The Czechoslovak military received some Soviet-made aircraft that had the first famous K2-717 (Baro-Speedo-Graph) recorder, which could record speed, time, and barometric altitude by engraving it with a needle on a floating paper strip [12].

In 1958, the aviation industry began to enforce basic specifications for aircraft that would facilitate the conduct of engineering studies. In addition, great efforts were made to manufacture FDRs in such a way that they could retain their original shape in the event of accidents, for example, in the event of a fire or other major damage to the aircraft [22].

Beginning in the 1960s, the Boeing 707, Caravelle, and DC-8 were the first jet aircraft to use FDRs. These devices used a mechanical stylus to engrave data into a metal foil; they are called metal foil and photo film recorders (MFPFR). In these types of FDRs, the data always come directly from basic aircraft sensors, such as accelerometers and control tubes, and the parameters are processed internally. At the same time, another technology was introduced that used a photographic film and a mechanical stylus with light beams to replace the metal sheet. They could only store five to six parameters in total, which means the number of parameters including magnetic heading and airspeed was also limited [23].

By 1965, as the need for accident investigation increased due to the number of airplane crashes, both metal foil and photographic film recorders could no longer meet the demands of examinations and fell behind. To meet the requirements, magnetic tape recorders were introduced that not only record conversations but also improve the number of parameters that FDR can record. The new innovation of the aviation experts was that the parameters were sampled, digitized, and then multiplex coded in a long frame (1 second), which means

¹Black Box Flight Recorder <https://www.dst.defence.gov.au/innovation/black-box-flight-recorder>, (accessed: 03/15/2023)



Evolution Year	Description	Key Characteristics
Pre-1930s	Early Flight Data Collection	Simple Mechanical Devices
1930s-1940s	Introduction of Crash Survivable Memory Units	Wire Based Technology
1950s-1960s	Analog Magnetic Tape Recorders	Broader Data Collection
1970s	Transition to Digital Recorders and CVR Integration	Solid State Memory
Late 20th Century	Enhanced Capabilities and Robust Design	Increased Data Capacity and Durability
Modern	Deployable Flight Data Recorders and Real-Time Data Streaming	Enhanced Survivability and Data Recovery



Fig. 1. FDR's Technology Devices Evolution [32] [33]

that the parameters were no longer stored in a single stream. In this type of recording, the magnetic tape helped to record the digital parameters, which were encoded as binary digits. Later, these types of recorders were called DFDRs[24].

In the 1970s, as technology evolved, these data recorders were replaced by SARPP-12 recorders capable of recording six analog parameters and up to ten discrete parameters on photographic film [13]. It can be assumed that the improvement and design of FDRs related to the sensors, signal processing techniques, and recording systems have always gone hand in hand with technology development [13]. The innovations and improvements in recording technology helped the FDR to record numerous parameters such as from analog to digital on tape and then to a solid state. An FDR must meet the following to be considered a viable device for detecting the causes of aircraft accidents: length of the recording, a group of relevant recorded parameters, the survival after an accident, i.e., no damage to the recorded data once the accident occurred, and the quick recovery of the crashed aircraft's data records [14], [15].

In 1985, as digital technology developed, magnetic tape recorders were replaced by solid-state recorders, which use solid-state memory cards for recording. The new types of SSFDRs offered greater resilience and reliability than mag-

netic FDRs. This allows up to 100 parameters to be recorded, although the memory card had been made smaller, the sampling frequency had been increased, and useful recording performance has been achieved by increasing the recording time of the models up to fifty hours or even more. For sound playback, not only has the possibility of digital sound recording been improved but the recording time has also been extended by a few hours [27].

The choice of aircraft and flight parameters is an essential factor that depends on the type and size of the aircraft and the equipment used. Before the 1980s, flight recorder manufacturers recorded different attribute sets. Later, ICAO recommended a list of 32 parameters that must be recorded in every aircraft and on every flight [16]. The considered parameters were air speed, anticipated flight speed, altitude barometric, vertical flight speed, pitch angle, flight time/course, rolling angle, and overloads in both axes i.e., longitudinal and perpendicular. The recorded parameters for on-board flights were also an engine revolution, position of aileron and elevator, various pressure measurements such as fuel, oil, and hydraulic system, some discrete signal measurements of aircraft settings including the status of landing gear, landing flap, the cutoff status of power electric generators, heat, or engine fire signals, etc. [17]. The length of the recording depends on the recording tape, the size

of the memory, and the customer's requirements. However, for assessing the cause of the accident, the recording of the last 30 minutes is often sufficient to extract the information needed [18].

To accurately reflect the situation causing the accident, quick recovery and ensuring the quality of data must be assured [19]. It is also important to consider and calculate the negative factors of the FDR system that may affect the recording or recording resolution during an aircraft accident. Usually, these forces are of a mechanical nature, e.g., overload, the impact force when hitting the terrain, the heat generated during a fire, the attack of sea salt during an accident in water, and some attacks of the aircraft itself like different liquids as well as fire extinguishing agents.

The survivability of an FDR during an aircraft crash in the ocean or on land is an important factor in the development of FDRs. The software framework and the quality of the data are also of great importance to the overall FDR system. Additionally, the size also influences other important factors of FDR design, including the size, power consumption, communication protocol, and installation on an aircraft of the FDRs. We described two models in the background part which emerged in the mid-1950s and provided crystallization of cultural impulse to FDR's study into an object of scientific and institutional analysis similar to the motivation provided by Greg Siegel[20].

III. BACKGROUND ON FDRS

As described in the section above, FDRs record all important parameters during the flight of an aircraft and are required by law [21]. In addition, CVRs are also an important component that records audio flight crew's voices, as well as other sounds inside the cockpit during the flight. In this article, the research is limited to FDRs as they are the core component necessary to draw technical conclusions about an incident.

As technological innovation advances over time and demands also increase, it has become insufficient for FDRs to process parameters internally in a limited amount of memory. In order to store all the information received from the sensors, a data acquisition unit was constructed to gather all the parameters before recording. Therefore, different types of devices have been developed, including Flight Data Acquisition Cards (FDAC), Flight Data Acquisition Units (FDAU), and Flight Data Interface Units (FDIU). They collect data from various sensor sources and then store it in the FDR, whose purpose is limited to just recording data [22]. However, this type of data unit can only be used in large aircraft for public transport. In smaller aircraft, the purpose of data acquisition is still fulfilled by the FDRs [25], [26].

For flight data monitoring, data acquisition technologies provided a huge benefit [28], [29], the FDRs were employed for recording the data, and that data may be utilized in the case of an accident. Data can be routed through various other types of recorders using a data acquisition unit, which is considered unprotected. The data is sometimes stored on a magnetic tape, optical disk, and/or a memory card constructed in a way so that it can be removed or replaced quickly. Generally, it is located

in the electronic equipment bay or in the cockpit. Other devices that function in the same way as the FDRs are the Quick Access Recorders (QARs). The data acquisition system serves as a data dispenser for both the FDR and the QAR. Also, the QARs have the advantage of input ports that meet the standard of the aircraft buses including (ARINC 429) hence they can receive more data [30], [31]. Using scalar measurement and aggregated data in [73], the authors performed quantile regression exploring the influential features that affect the maximum vertical acceleration during landing. They employed a sufficient dimension method to evaluate the performance of the model identifying nine important features and studying how they relate to hard landings. The authors proposed the CurveCluster+ in [74] approach which automatically identifies hard landing using the QAR data. The flight parameters are extracted in this method to perform analysis of the data and then provide a two-level hierarchical classification for harsh landing which reveals the reason for the incident.

There is another category of data recorder named Direct Access Recorder (DAR) which gets the data from data management units (DMU). These recorders are designed to allow the selection of parameters. This means that they not only select the parameters to be recorded, but also the recording mode, periodic recording, and recording triggered by certain accidents, e.g. exceeding a predefined threshold. Usually, these types of recorders are used for operations such as maintenance, research, and/or flight data monitoring [5].

A. Data Acquisition Systems

Data acquisition has a significant and critical role in collecting data for FDRs. The concept employs data acquisition computers that centralize and format the data input from several sensors and other instruments. Afterward, the data is transferred to the FDRs through an associated digital link such as ARINC 573 or 717 serial link [34]. The data acquisition system obtains the data from various sensors and avionic systems and then delivers the data to an FDR.

To obtain a continuous flow of data from the sensors to the FDRs, data acquisition units collect the data samples, and conditions and then digitize analogs signal that represent the aircraft functions. Particularly, the data acquisition unit (DAU) system involves the sampling of parameters and their digital encoding from actual physical values to recorded values [35].

The Data Frame Layout (DFL) depends on the recording method used in the data acquisition system, which entails the encoding method, parameter location, and bit numbers that were used to encode parameters[36]. Its function enables the conversion process from recorded value to physical value. The conversion function runs through a checklist of measuring and processing channels. Then, the calibration control reports are obtained in the DFL document to complete the process for essential parameters. Figure 1 represents a functional block diagram and a depiction of the memory organization, which every aircraft needs to carry to fulfill the requirement of regulators. The parameters output by the data acquisition system are decoded and a sequenced binary file with images in four-second intervals is obtained. Furthermore, these frames are

divided into four different one-second frames. In a one-second frame or “subframe,” the data is encrypted into 64, 128, 256, and 512 “words” of 12 bits each using the generation of FDR technology described above [37] [38]. An example is shown in Figure 2, obtained from a document from the European Union Aviation Safety Agency (EASA) which shows that the main element of the record is a “word” consisting of 12 bits. Several parameters can be stored in this word. A parameter is often recognized by the word and the binary and/or bit number in which it was coded. Then, these words are categorized into sub-frames, each containing one second of data. These subframes are mostly sizes 64, 128, and 256, etc., and four sub-frames construct one frame[40].

B. Operational Verification Checklist for Recording

To improve recording quality, some authentication checks are performed to verify the recorded parameters and to check the calibration of the measuring and processing channels. To verify the recorded parameters, evaluate the overall operation of the recording system, and improve the quality of the DFL data, a review of the recording parameters in the FDRs is performed. To get the authenticated model's performance and for validation, these checks must be performed only for FDRs, not for other devices such as QARs and DARs. The entire set of stored information can be copied and converted into engineering units for further analysis using a decoding software platform that must be programmed according to the DFL document. This process may involve the check of recorded parameters; for instance, parameter locations must be set according to the data frame layouts, authentication of conversions functions of regulatory parameters which are under consideration and their value range of operation, consistency in terms of different phases of flight, also coherence of parameter's pattern in several phases of flight, verification of unreadable data for a big length or cyclical areas, and finally sequential integrity of data recording.

The calibration of measuring and processing channels is to calculate the data quality evaluated by comparing the value of the parameter determined from the instruments and the recorded value. It is necessary to calibrate the measurement and processing of individual parameters for better data quality. The conversion functions given by the manufacturers are theoretical, and their test results performance is only calculated in the context of prototypes; hence the calibration results may differ from those of actual aircraft [39]. Moreover, the factors that affect the quality of measurement are described in the following Table I:

In the end, the sensors that save data for recorders might be different from those that feed data to the various flight instruments and other aircraft systems. As a result, the recorded value is likely to differ from the actual value. Suppose the allowable difference between the recorded value and the actual value is too large. In that case, two actions are initiated, depending on the nature of the problem: The first is to replace or repair the malfunctioning elements in the system. The second is to change the conversion functions in the DFL using a calibration procedure.

TABLE I
FACTORS AFFECTING THE QUALITY OF MEASUREMENTS[27]

Calibration Factor	Consequences and Explanation
Sensor Aging	Sensors can be subjected to various environmental constraints, such as temperature and high-pressure variations causing the system to drift from its initial calibrations.
Connecting of Additional Devices to Analog Input	Potentiometers or Synchronization transmitters may alter the electrical characteristics of transmitted signals in the context of amplitude and/or phase.
Assembling and Disassembly of Mechanical Elements	Sensor misalignment can occur as a result of significant overhauls or when undergoing an FDR systems retrofit, leading to potential issues with sensor calibration.

C. Calibration Process

As described earlier, the calibration of the measuring and processing channels is to obtain enhanced data quality, moreover, the quality of data is obtained after evaluating the comparison of the parameter's value as measured by instruments, with the recorded value. The calibration process of parameters' measuring and processing channels is provided that involves the generation of the baseline values, which then enter a sensor noting the output value of acquisition devices. If the data acquisition is performed by the recorders, it retrieves the corresponding recorder value [27].

The methods that generate the baseline values are created using one of the following strategies [40]: 1) Activation of Sensors: this process includes “sensor stimulation,” which refers to the input and sensation received when the sensor is activated after getting physical inputs, for instance, “calibrated pressure on pitot-static system port.” Also, it is responsible for reproducing the electrical signal input of a sensor, performed when sensor stimulation encounters complex situations such as engine temperature or different alarms. 2) System's Auto-Test Activation: the Inertial Reference System (IRS), whose functions internally adjust the parameters according to baseline values. 3) Instruments Indication Check: assessing all the instrument indications when there is no availability of internal test or if a sensor feeding recording system also feeds to cockpit indicators. To check the obtained value from the data acquisition system, a valid or compatible read-out system is connected for real-time value computation by utilizing the conversion functions similar to that provided by the data frame layout document. Note particular aircraft manufacturers only offer this calibration of measuring and processing channels before delivery [41].

IV. GENERAL STANDARDS FOR FDR AND REGULATIONS

Regulators and standards development organizations define the requirements, manuals, and other resources for FDR development, installation, and operation. In this section, we cover some major regulatory organizations that develop standards for the FDR, CVRs, and their operation. Several versions, editions, and a few amendments in these texts can be found having shared goals to set the standards of the FDRs. For example,

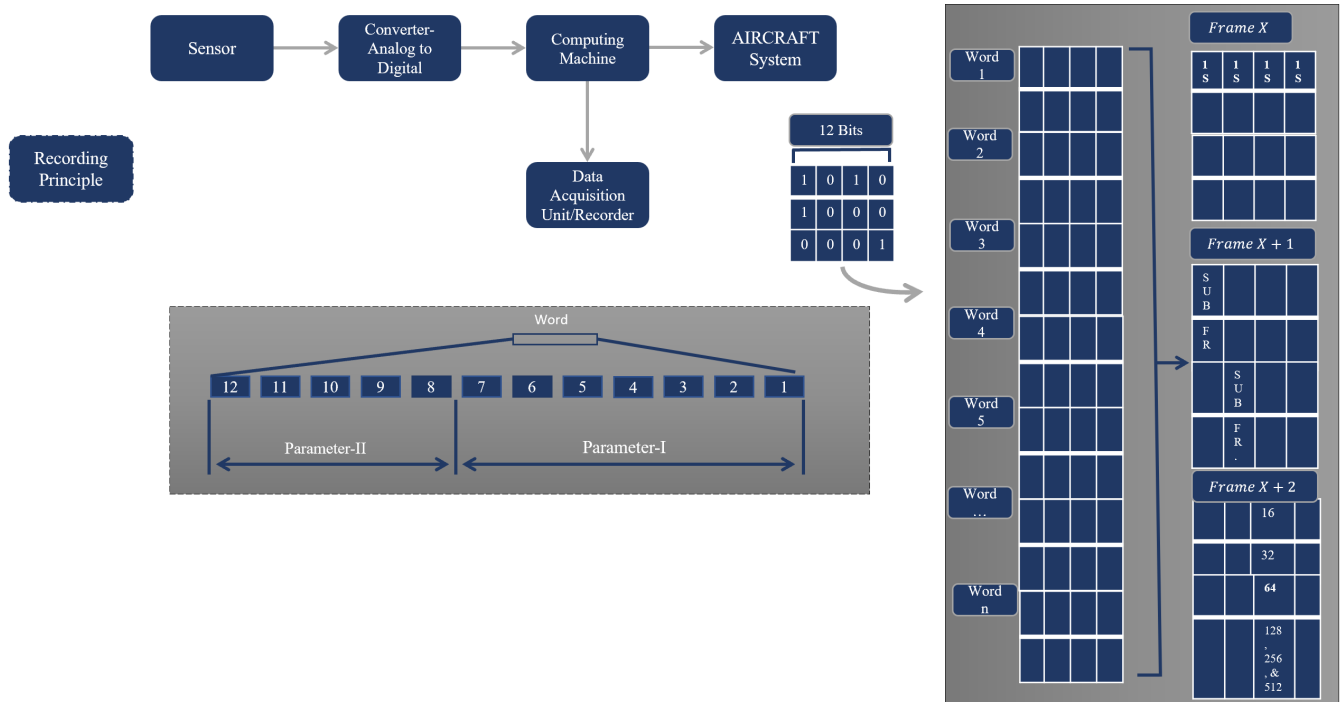


Fig. 2. Principle of Recording [42]

ICAO Annex 6 “Operation of Aircraft” Part-I, II, and III, (and its editions of flight data operation) also defines the FDR requirements, general standards, procedures, etc. These are considered the principal documents pertaining to FDRs. Table II lists a number of organizations from various countries that contribute to aeronautical and aerospace engineering research mainly assisting the aircraft operators in defining the requirements, and other resources for FDR development, installation, and operation, including the design of data frame layouts. The Joint Aviation Requirements - Operations (JAR-OPS) read-out manual is an excellent source to study FDR standards at the European Level; which is a joint aviation requirement for the operation of commercial airplanes. Another critical institution that defines regulations for FDRs is EUROCAE; their manuals are used to set the regulations in Europe [27]. In the U.S. the FDR regulation is prescribed in Federal Aviation Regulations, Part-125, “Certification and Operations”.

A. Brief Survey of Aviation-related Professional Societies, Associations, and Organizations

To cover the technical aspect of aircraft, such as operation, inspection, and safety-related standards, ICAO Annex 6 serves as a complete guide including recommended best practices. There are more Annexes defined by the ICAO. In this section, we shall specifically focus on Annex 6 as this mainly covers safe operating policies for aircraft operation. Additionally, Table II outlines a number of organizations, societies, and professional organizations that work for the sake of aviation safety, flight operation, and other space-related activities [43]. These organizations collaborate with international aviation

organizations and regulatory bodies to share best practices and safety information and take part in worldwide initiatives to raise aviation safety standards.

TABLE II
THE GOVERNING BODIES, PROFESSIONAL AVIATION ORGANIZATIONS, SOCIETIES, AND ASSOCIATION

Organization/Authority Name	Country with Headquarters
International Civil Aviation Organization (ICAO)	United Nations, Montreal, CA
Federal Aviation Administration (FAA)	Washington, D.C. USA
European Union Aviation, Safety Agency (EASA)	European Union Cologne, Germany
European Organisation for Civil Aviation Equipment (EUROCAE)	Paris Region, Saint-Denis, France.
Australian Transport Safety Bureau (ATSB)	Canberra, Australia
Civil Aviation Administration Of China (CAAC)	Dongcheng District, Beijing, China
Civil Aviation Authorities	Various Aviation Bodies
Joint Aviation Authorities (JAA)	European States
Experimental Aircraft, Association (EAA)	USA and Canada Based
Flight Safety Foundation (FSA)	USA and Canada Based
General Aviation Manufacturers Association (GAMA)	USA and Canada Based
International Air Transport Association (IATA)	USA and Canada Based
Society of Experimental Test Pilots (SETP)	USA and Canada Based
European Civil Aviation Conference (ECAC)	Council of Europe Neuilly-sur-Seine, France
European Organization for Safety of Air Navigation (EUROCONTROL)	41 Member States Brussels, Belgium

B. Regulatory Requirements and Operations

Section 2.4.1 of the ICAO Annex 6, Part-II, 10th edition, states the regulatory requirements concerning FDR operational guidelines and other similar devices such as CVR, AIR, and DLR for the issuance of an airworthiness certificate. It must be capable of recording parameters listed in Table A2.3-1 of Appendix 2.3 for various types of aircraft based on weight, size, and operations [44]. An aircraft with a maximum take-off mass of 5700 kg must be equipped with an FDR, regardless of the airworthiness certificate it holds. This has been defined in ICAO Annex 6, Part-I, and paragraph 6.3. There are specific recommendations and installation guides provided in attachment D to Annex 6, which describe the rules as follows: 1) the recording requirements, such as the number of parameters, data quality, etc., must be verified by standards that are approved by certifying authorities. 2) the manufacturer needs to provide operating instructions and procedure of installation, parameters source or origin 3) equations that relate counts to units of measurement followed by the manufacturer's test reports to the certifying authority. The equipment or instruments with their installation should be viable to the State of Registry (The State on whose register the aircraft is entered). Among them, section 2.4.16 "Flight Recorder" is dedicated to features and characteristics of FDR equipment, defining the essential information and providing a few notes for the FDRs [45]. For instance:

- The crash-protected flight recorders should consist of at least one of them; a complete FDR, a cockpit voice recorder, an airborne image recorder, and a data link recorder. As per the Appendix provided in ICAO, Annex, the images and information of data link possibly be recorded on the CVR either or the FDR.
- Similar to that of Crash-protected FDR, lightweight recorders must be comprised of one or more of an aircraft data recorder system (ADRs), cockpit audio recording system (CARS), airborne image recording system (AIRS), and data link recorder system (DLRS). The data link information can be recorded on either one of the following i.e., ADRs or CARS.
- Complete information regarding FDR guidelines and regulatory requirements can be found in Appendix 2.3 of the ICAO, Annex 6, Part II.
- The EUROCAE ED-112, EUROCAE, ED-56A, EUROCAE-ED-55, and minimum operational performance specifications (MOPS) are the primary documents illustrating the specifications that are applicable to crash-protected flight recorders for those aircraft for which the certification application is submitted to a Contracting State earlier than January 1st, 2016. The section EUROCAE ED-112A also describes the same content for crash-protected flight recorders on or after 1 January 2016.
- The ED-155 of the EUROCAE section shows the specifications regarding the lightweight flight recorder in the MOPS or the equivalent document.
- After November 7, 2019, contains requirements for States; concerning the usage of voice, images, data

recordings, and transcripts are provided in the ICAO Annex 6, Part-II, 10th Edition.

C. Current Standards for the Survivability of FDRs

The FAA and the EASA have set the current standards for the survivability of FDRs in their documents TSO C123A (CVR) and C124A (DFDR)². These standards mandate that FDRs must be capable of withstanding extreme conditions, such as high-impact crashes, intense fires (high and low intensities), and deep-sea submersion, to ensure the preservation of vital data for accident investigations. These tests include a low-intensity fire test, where the FDR must endure temperatures of 260°C for 10 hours, as well as an impact shock test, where the FDRs must withstand 3,400 Gs for 6.5 milliseconds in all directions, and a static crush test, where the FDRs must resist 5,000 pounds of pressure for 5 minutes on each axis. In addition, FDRs must undergo fluid immersion tests, where they are submerged in aircraft fluids, such as fuel and oil, for 24 hours, and water immersion tests, where they must remain submerged in seawater for 30 days. The FDRs must also demonstrate penetration resistance, as they must withstand a 500-pound weight dropped from a height of 10 feet with a 0.25-inch-diameter contact point. Lastly, FDRs must exhibit hydrostatic pressure resistance to remain operational at the equivalent of depths up to 20,000 feet.

D. Challenges

Depending on the application, the characteristics of an aircraft change. New types, designs, weight classes, and areas of use are constantly emerging, all of which have to be taken into account in the requirements for FDRs. Nevertheless, the requirements should still be implementable and future-proof. New challenges are constantly arising, such as the use of AI in aviation, urban aircraft mobility (UAM), or unmanned aerial vehicles (UAVs) in the national airspace, which must be taken into account and, if necessary, result in a reevaluation of the current requirements for FDRs. Since an aircraft is sometimes used over long distances and also across national borders, care must also be taken to ensure that the different requirements of the various jurisdictions and organizations do not conflict as far as possible. A significant challenge exists with respect to data volumes becoming more extensive and larger due to new technologies like artificial intelligence or new sensor technologies. UAVs, in particular, however, are expected to become smaller and smaller. As a consequence, it is a significant challenge to provide enough memory and to use it efficiently. This includes, for example, optimizing the recording interval, and recording resolution of different sensors.

V. FLIGHT DATA RECORDER FOR A UAV

This section explains the importance of a UAV and its benchmarks using its history, civil and commercial applications, future requirements, and a review of reported accidents

²Department of Transportation, Federal Aviation Administration Aircraft Certification Service-TSO C123A, C124A

in the United States from three different agencies to gather data that will allow us to understand which flight parameters and sensors are essential for lightweight FDR technologies.

A. Motivation and Importance Regarding FDRs for UAVs

Unmanned aerial vehicles (UAVs) are often known by various names, such as Unmanned Aircraft Systems (UAS) and/or Remotely Piloted Aerial Systems (RPAS). Over the past decade, UAVs developed by academia and industry have added new system complexities and introduced more data sources to be captured and stored by an FDR or CVR. The question now arises here, How can we ensure the safe and efficient management of new data while meeting all necessary requirements and avoiding any negative consequences? Traditional manned aviation already has existing standards for FDRs and CVRs as discussed above; however, these standards, under many contexts, are insufficient in enabling the ability to diagnose the cause(s) of a UAV's mishap or accident. A considerable increase and advances in computer technology have allowed the manufacturer to design a novel kind of FDR that can record all the parameters per the recommendation of the ICAO and others, despite the fact that the flight hours have become longer. These new FDRs are often referred to as "next-generation" or "extended-range".

A recent IEEE conference publication [46] focused solely on traditional aircraft raised the question for researchers and aviation experts: "which flying parameters are more helpful for recording." They provided an idea to construct two sets of parameters; the first set they regarded as a pilot awareness set, and the second one is a traditional data set used to help experts and investigators determine the cause(s) of a mishap, incident, or accident. The first set of parameters requires a great deal of effort to study past accidents and then build a model/system to ensure that we have a sufficient number of recorded parameters that could help identify the pilot's current situation during flight. For UAS, this is not the case, as there is no pilot onboard replaced by a remote pilot and/or automation. Looking at the growing number of UAVs and their applications, this will most likely also become a necessity for UAVs during the following decades.

Given that manned and unmanned aircraft are designed, employed, and maintained differently, a minimum standard parameter set is required for UAVs that can contribute to flight diagnosis. While each attribute can be valuable toward determining the cause of a system failure, but recording all features typically increases the size, weight, and power requirements of the FDR, which would limit the platforms capable of carrying it. To address the challenges, the following few sections will provide further analysis of the needs of FDRs for UAVs.

B. Introduction of UAV Applications

UAVs have become very popular in today's world as they can be deployed in environments inaccessible to humans and perform a variety of operations/missions. The potential applications are limitless: UAVs can be used for defense and civilian purposes. We can consider a UAV in the broadest sense

as a remotely controlled (RC) aircraft. However, it differs from an RC aircraft in its complexity, flight control system requirements, the use of onboard sensors, and, as mentioned earlier, the ability to fly beyond line of sight (BLoS). UAVs are also considered flying robots due to the above characteristics and have various levels of automation that conventional robots do not have [48]. Table III lists the applications of UAVs for civil and commercial purposes that are needed in today's world.

The UAVs can be further divided into two subcategories: fixed and rotary. For military missions, fixed wings are often employed because they can carry a larger payload and have similar characteristics to that of traditional airplanes. The term "rotary-wing aircraft" refers to aircraft that generate lift by means of wings or blades rotating around the aircraft, attached to a mast. In the case of UAS, several of these rotors often provide the necessary lift and stability. These aircraft often fulfill similar tasks as fixed-wing aircraft. However, they can also perform functions in urban or other areas where fixed-wing aircraft have difficulties navigating. Fixed-wing UAVs typically have higher speeds than rotary-wing UAVs, and like their manned counterparts, have a more extended flight range.

Today's UAV manufacturers offer a variety of sizes, payload capacities, and ranges depending mainly on their area of applications, mission length, wingspan, and a number of sensors. Figure 3 illustrates the classification of UAVs. We classified them based on some parameters such as size, weight, application, mission, and user. Figure 4 shows the typical protocol of the UAV system obtained from the University of York document [47].

UAV technology is increasingly needed for a variety of applications, especially those where the environment is inaccessible to humans and/or deemed unsafe. Assuming that human pilots in manned aircraft are exposed to danger regardless of the flight or mission, using UAVs in missions can help reduce risk factors and keep human pilots out of harm's way. Considering the safety of manned aviation systems, these systems are being developed more carefully and at a higher cost than UAVs [48]. Designs frequently seek to ensure UAV survivability, but this is not always practical for small or medium-sized UAVs. There exists a trade-off between unmanned and manned systems in terms of unmanned system size, range, cost, payloads, specifications, and mission scope. Table III illustrates civilian uses in various situations.

C. General FDR requirements of UAV and Parameter Classification

The requirements for safe UAV operation are essential in every application domain. The rapid development of many applications requires specific guidelines, regulations, and standards depending on the type of UAV and its use. The development of requirements for an FDR must take into account different properties, such as the type of UAV, the size of the UAV, computing power, the quality of the data, the application area, the survival standards, and more. Comparing a conventional aircraft and a UAV, the FDR in a manned system must differ from that of a UAV. ICAO Annex 6, Operation of Aircraft Volume III

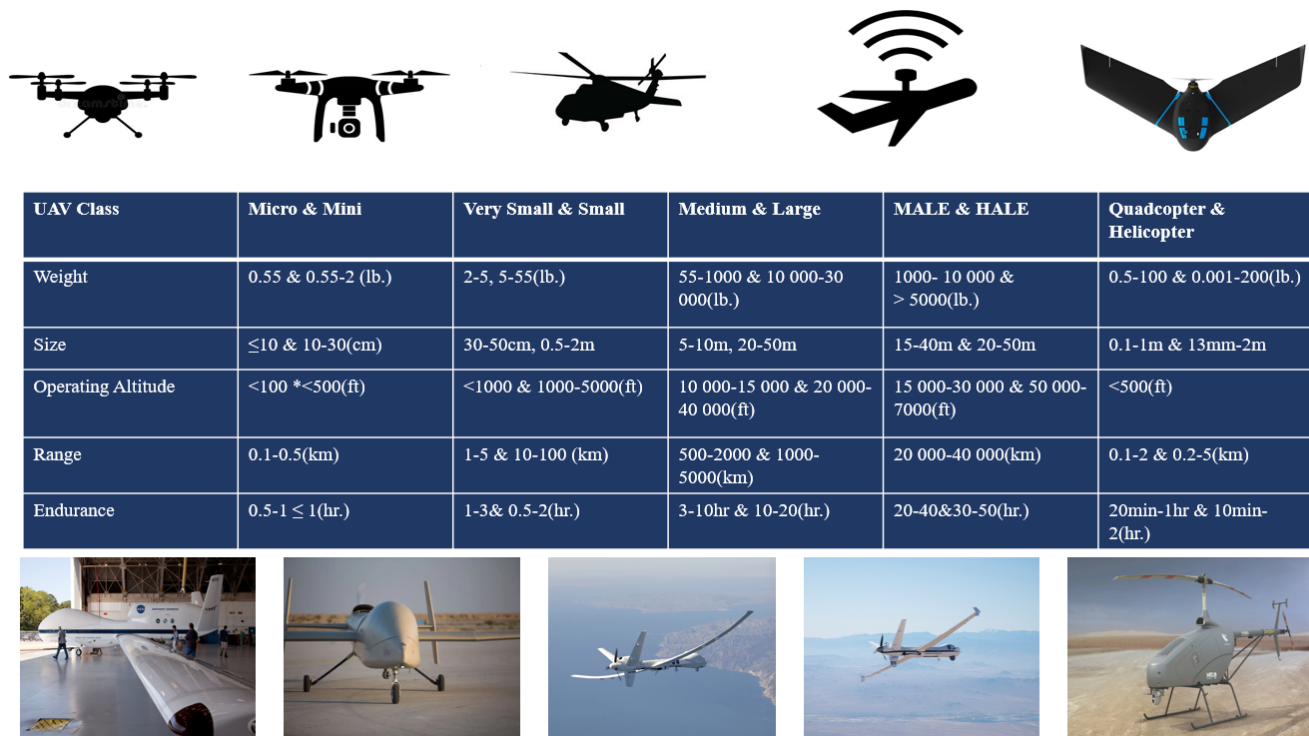


Fig. 3. Classification of UAVs[48]

outlines the requirements for traditional aircraft systems. The question now arises whether the parameters are identical for UAVs. To answer this question, our study conducted a brief literature review to determine the requirements for the FDR of a UAV. In addition, the ICAO Type I, Type II, and Type IIA Annexes describe that an aircraft must record parameters such as aircraft configuration, flight path, operation, altitude, engine power, and speed (for a list and aerodynamic drag devices, see Type, II, and Type II-A) to determine the flight characteristics of the flight [43] [44].

By regarding the selection of parameters for manned systems, aviation industry experts have enough data from accident reports. If maintenance experience, rationality, systematics, and a complete set of parameters are available, then the selection of mandatory parameters for recording purposes is achievable since there is real-time evidence [48]. According to a few publications in the proceeding of the First Symposium on Aviation Maintenance and Management [50], we can divide these parameter sets into the six classes shown in table IV.

Descriptions of these classes are as follows:

- Aerodynamic Parameters: Environmental or surrounding conditions can be obtained from aerodynamic parameters, such as the motion of the flight.
- Motor/ Engine Data: We can deduce the operational status and the engine's current status from this class, for instance, engine RPMs, engine temperatures, etc.
- Control Input Data: This category provides the total input from the pilot or UAV's flight control system.
- Status and Alarming of Airborne Equipment: The data coming from this category deals with the status and fail-

ure of this equipment, which includes electric, hydraulic, navigation, etc.

- Configuration Data: This category addresses the storage of UAS configuration parameters such as aileron deflection, rudder, elevator, landing gear position, etc. For example, if a fly-by-wire (FBW) control system is used, the key value of each phase for every channel is recorded as well, to show the information concerning the overall response of the control system.
- Peripheral Information: This category provides records and remarks about flight data such as GMT, flight index, and takeoff weight, etc.

FDRs are crucial to be installed for training, maintenance, accident investigation, and for the design of future FDR generations, including airworthiness certification. However, the calibration process of FDRs for small UAVs is often neglected and there is a lack of standardization for parameter sets.

UAVs are not only utilized for military operations but also for various civilian missions, leading to potential conflicts with general aviation platforms. FDRs play an important role in this aspect, as they help to meet safety and maintenance requirements through the parameters they monitor. Table IV provides a classification of these parameters (sample parameters), allowing for monitoring of the UAV's status and equipment, as well as assisting with training and investigating accidents. However, not all of the parameters listed by the ICAO's Annex 6 apply directly to UAVs, and further research is required to establish standards for UAV parameters, the actual range of parameters, and recording intervals, etc., to

TABLE III
LIST OF UAV CIVIL AND COMMERCIAL APPLICATIONS [49]

Category	Applications
Maps, Surveying, and Aerial Photos	Survey Structural Technologies, Real Estate, Bathymetry, Archaeology, and Heritage
Infrastructure	Monitoring of Pipelines, Bridges, and Building Inspection with their Support, Roads, Railway Tracks, Canal Inspection, Power Plants, Support in Construction, and Landfills
Agriculture	Physical Interaction with Farming and Cultivation, Harvesting, and Planting
Law Enforcement and Public Safety	Rescue Missions and Search, Counter-Privacy, Private security, Firefighting, Fires in Forest, Border Patrol, Environmental Protection, Medical Support
Emergency Response	Quick Response in Natural Disasters, Artificial (Man-made) disasters, Usage in Epidemics
Transportation and Logistics	Cargo and Food Delivery and Private Transportation
Mining and Energy Eng.	Exploration of Natural Fossil Fuels, Support in Mining
Communication	Employment in Communication Relays, Conventional Wireless Communication Networks, TVs Broadcasting, Network Coverage, Internet, and Other Support in Emergency
Journalism and Cinematography	News Coverage and Motion Photography
Wildlife Management	Protection of Animals with Counter-Poaching, Pest Control, Monitoring of Bird Lives and for Scientific Research on Animals, and Monitoring of Sea Creatures.
Hobbies, Arts, Research Activities	Recreational Activities, Flight Research, UAV as a Hobby, photography
Miscellaneous Missions	Other Missions in Safe Operations of Civil Airspace

check more parameters, please refer to ICAO Annexes and EUROCAE parameter characteristics for flight data recorders in [44] and [45]. The classification in this study is based on our findings and previous literature.

D. FDR Design and Operation Requirements

A growing need for UAVs in various industries requires establishing FDRs design and operation requirements for these aircraft. This subsection aims to explore certain considerations that must be taken into account while designing and operating the FDRs of UAVs, which include technical requirements, regulatory guidelines, and potential challenges described as follows.

1) *Power Constraints*: Long-range UAV missions often require significant stored energy to ensure successful completion. There is always a trade-off between various characteristics, such as range, payload, altitude, communication power, and mission endurance. Power requirements must be assessed to ensure safe UAV operation and real-time data transfer. To meet these requirements, either a lightweight FDR with data recording capabilities and a set number of parameters can be implemented, or a real-time data transfer strategy must be developed to transmit the data.

TABLE IV
CLASSIFICATION OF FDR PARAMETERS IN SIX CATEGORIES [50]

Aero-dynamic Parameter	Motor/Engine Data	Control Input Data	Status and Alarming of Airbone Equip.	Configuration Data	Peripheral Information
Altitude	Rotor Speed	Stick Input	Electric	Aileron Deflection	GMT
Airspeed	Gas Exhaust Temp.	Flap/Slat Control	Hydraulic	Rudder	Flight Index
Angle of Attack	Fuel Consumption Rate	Speed Brake	Navigation	Elevator	Weight-Takeoff
Angle of Slideslip	—	—	Environment Control	Landing Gear Position	Synchronization
...

2) *Size Restriction in Small UAVs*: FDR in small UAVs, micro and mini UAVs, poses a challenge. An alternative solution is to implement a real-time data transfer mechanism to receive flight data, requiring seamless network connectivity. Another possibility is to develop a nano FDR that records minimal operational standard parameters of UAVs.

3) *Weight and Payload*: In the preliminary design phase of a UAV FDR, it is important to consider the weight requirements, including the take-off weight and installed payload, for both fixed-wing and rotary UAVs. For smaller UAVs, the number of parameters can be limited, and a lightweight FDR may suffice. On the other hand, installing an FDR with a parameter set may be mandatory for larger UAVs with a high take-off weight and payload capacities to ensure safe and efficient operation, that complies with regulations and provides critical information. Thus, a lightweight FDR can be considered in the design phase.

4) *Airspace Regulatory Requirement*: The requirements of airspace access for UAVs must also specify the FDR requirements of the air vehicles operating within those airspaces. These related regulations must be proposed within the given course to meet the growing application needs of UAVs. The ICAO, FAA, and EUROCAE continuously collaborate to set the standards regarding the UAV regulatory aspect considering the UAV design type, altitude, frequency spectrum, and airspace operating permissions. In this regard, two surveys provide the current state of regulation concerning UAV operations [51], [52].

5) *Encoding and Decoding Strategies*: The parameter encoding and decoding are performed in the DAU unit, where all parameter sampling processes of the actual physical and recorded values occur. The DFL document outlines the recording methods, parameter locations, encoding methods, number of bits for encoding parameters, and types of encoded data. The process is then reversed for decoding purposes. During this review, new encoding methods may be implemented to reduce the computational complexity of the algorithm employed by the FDR.

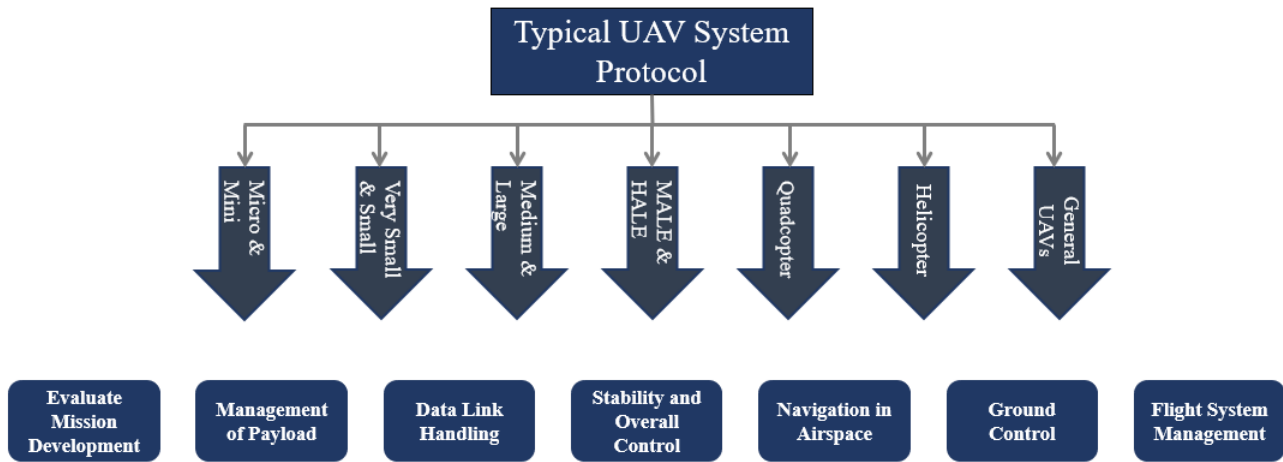


Fig. 4. Conventionally UAVs Protocol by Evans AR[47]

6) *Quality of Data Recording*: The quality of data recording plays a crucial role in flight data analysis by the operators. Regarding the data quality, ICAO Annex 6, Part-I refers to “the remedial action must be taken if the recording of the mandatory parameter is not recorded correctly”. Also, the ICAO Annex 6 [45], EUROCAE ED-55/ED-112 and ED-112A specify that the “significance period of poor quality data” can lead to severe consequences while analyzing the data³. This is the same case that can be applied to UAVs while recording the data; the data quality standards should be similar for UAVs. The poor data quality can be due to loss of information, overlapping of the time period, or anachronism. For the UAVs, as the number of vehicles will be in millions, the standards for the quality of data must be taken into reconsideration.

7) *Requirements Based on Autonomy*: Many different subsystems establish the flight capability of a UAS. These systems perform tasks such as detection and avoidance, flight planning, fault identification and recovery, and many others. NASA presents [53] multiple domains where autonomous processes can be applied and would benefit the overall system. Depending on which and how many of these tasks are performed autonomously, a UAS can be categorized into one of several levels of automation, according to NASA [54]. These autonomous systems present new challenges for FDRs as additional data needs to be recorded compared to conventional aircraft. In general, it can be stated that all data used to make an autonomous decision should be recorded. This usually includes sensors for sensing and surveying the environment, such as LiDAR, ultrasound, and cameras. This results in new challenges. Current estimates suggest that autonomous cars will generate up to 3 Gbit/s at low autonomous levels and up to 40 Gbit/s at high autonomous levels [55]. Even if the use case is different, these values can also be applied as a rough estimate of the data volumes of autonomous UAVs.

The decisions of autonomous systems, often implemented with technologies such as neural networks, are black boxes, making decision interpretation substantially difficult, which means that the set of recorded attributes must be sufficient to interpret and comprehend decisions made by the system’s automated elements.

Figure 5 depicts the need for installing an FDR in different types of UAV classes. Depending on the size of a UAV, for instance, micro, mini, very small, and small UAV types, the data recording requirement can be fulfilled by a minimum set of parameters due to its size and power limitations. Because there is commercial employment of UAVs where it is not applicable to install the FDR onboard hence real-time data transfer scheme can be introduced, which can provide us with the data at the distributed sensor network node. We can integrate the features of FDR in the flight control system of UAVs both can work as a common goal for the command center and data transfer purposes. On the other hand, it is fully suggested to integrate the FDR in large UAVs such as Medium, Large, and other UAVs sizes. The integrated Internet of Things (IoT) devices in today’s world are proven to be the best solution for this purpose having better energy efficiency and robust communication links among the overall network [56], [57].

E. Current FDR Technologies for a UAV

At the moment, the lack stands for parameters set for UAVs despite efforts by aviation governing bodies to identify the parameter requirements of FDRs for UAVs, the significance in the aerospace industry, and research on FDR standards that are lagging behind. The lack of a standard parameter set for UAVs can make it difficult to compare data from different UAVs or to conduct meaningful research on FDR standards. Additionally, without standard parameters, it can be difficult to ensure that all necessary flight data is being recorded, which can compromise the safety of the UAVs. The reason might be UAVs’ unmanned nature hence the need for associated

³NPA 2019-12 - Installation and maintenance of recorders – certification aspect, EASA, November 13, 2019 <https://www.easa.europa.eu/en/document-library/notices-of-proposed-amendment/npa-2019-12>

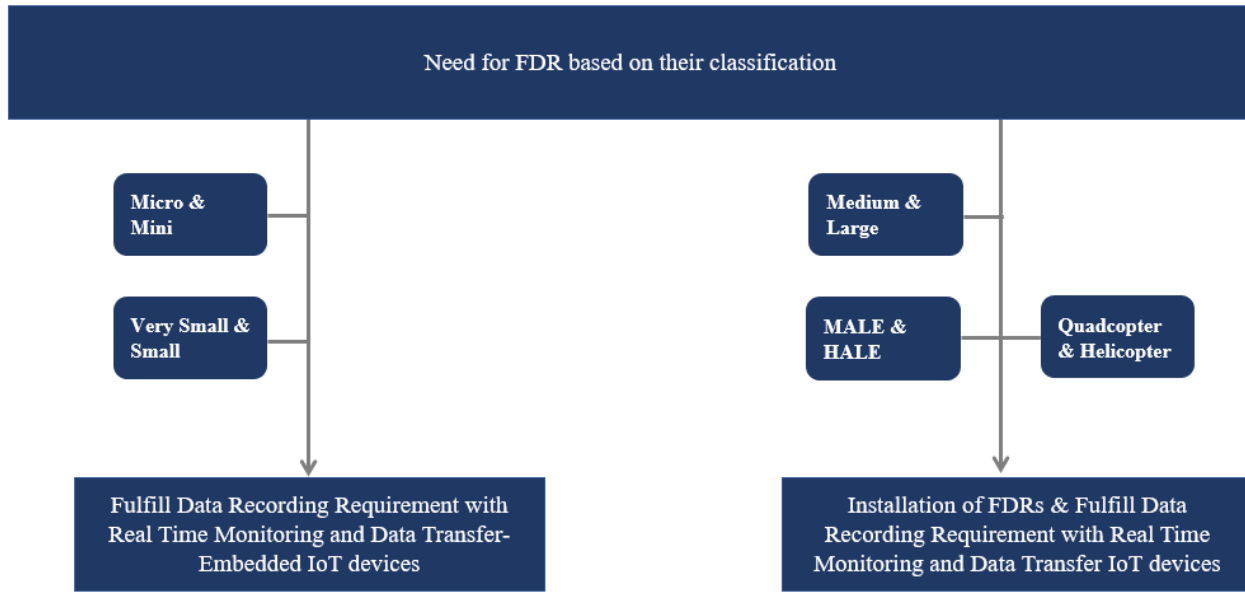


Fig. 5. Need for FDR based on Classification of UAVs

research get less compelling and there is no crew on board, the difference among type, is primitive usage (if compared with today's UAVs) except for military missions. Hence, forming a standard be challenging and subsequently requires less attention than its counterpart. Preferably, the rapid development and mentioned technological challenges constitute less attention to the regulators to define the FDR parameter identification set. Therefore, a comprehensive set of recording parameters is required in order to enhance safety and serve various purposes, such as airworthiness development, accident investigation, and training. The current lightweight FDR technology is provided as follows with their specifications.

Lilium Jet chose to use the L3Harris Extra Light Data Recorder (xLDR) for electric vertical takeoff and landing (eVTOL) aircraft [58]. The eVTOL is an aircraft configuration that uses electrical power for vertical hover, takeoff, and landing lies under the UAM potentially designed for urban air transportation. The standard version of FDRs manufactured by L3Harris are used in fifteen aircraft models because they are lightweight and meet the requirements and recommendations of the global governing bodies. Larger aircraft typically use two FDRs, such as the CVR and the FDR. However, on an eVTOL, only the FDR is used to collect data from the sensor due to the vehicle's smaller size. Crashworthiness is an essential factor in assessing survivability in the event of a crash. The xLDR can withstand pressure depths of 6000 meters, operating temperature -55°C to $+70^{\circ}\text{C}$, static crush 1000 lbs., and fire protection up to 1100°C for fifteen minutes. In designing the eVTOL, careful consideration must be given to the aircraft's weight along with all other components. The xLDR is designed to survive in the event of an accident.

FDR-01 [59], designed by UAV Navigation, is another

lightweight recording device that can be installed on manned and unmanned vehicles. Additionally, this can be integrated into a maritime platform that records all the data from the sensors and control commands, such as servos, ECU, etc. Similarly, it can record the instruction or control commands acquired from the GCS.

Other nano, macro, and small recorder devices are provided by DTS-Ultra Small Slice [60] recording devices designed especially for small drones. These devices are modular in design and include a microprocessor, excitation, and full signal conditioning. They can survive accidents, handle vibration, operate in various weather conditions, and provide data recording in low-pressure environments like high altitudes. These devices meet military standards such as MIL-STD-810E, a globally accepted manufacturing, and environment testing standard. The environmental specification for this type of device is operating temperature ranges between -40°C to 60°C (-40°F to 140°F), an altitude of 15240m (50000 ft) at -40°C and the vibration range is random, which exceeds 810-E standard vibration. They can be employed in various UAV applications.

The Hensoldt Group has developed a lightweight crash recorder (LCR) [61] that has received European Technical Standard Order (ETSO) certification for aircraft equipment from the European Aviation Safety Agency (EASA). These lightweight recorders, such as SferiRec LCR-100, are suitable for lightweight aircraft such as UAVs, drones, business jets, and helicopters due to their low weight, volume, and power consumption [61]. Previously, data acquisition and recording functions were distributed among different devices. Still, these functions are now performed in a single device containing the complete autonomous operation package. Because of its size

and lightweight, it has become possible to fit it into small aircraft. A high-resolution camera (Flight Eye-FE 320) is integrated into the lightweight recording devices in cooperation with KAPPA Optronics GmbH [60].

F. Survey of Reported Accidents

This section examines reported aviation accidents from three well-known organizations in the U.S., which typically record all fatal accidents and survival rates for drone accidents. One can report accident and incident data to the National Transportation and Safety Board⁴ (NTSB) or the FAA⁵ if one's drone crashes, and there is also a voluntary portal, the Aviation Safety Reporting System (ASRS)⁶, from NASA. The information obtained from the following three sources is evaluated to assess the importance of incorporating a lightweight FDR into UAVs.

While experts can identify many potential hazards, there could be a variety of causes (primary, secondary, and tertiary) that can contribute to a UAS incident or accident⁷. These UAVs sometimes crash due to programming or human error, but also due to weather events, high winds, lithium-ion polymer battery (LiPo) fires, and other technical problems⁸.

1) *National Transportation and Safety Board (NTSB)*: The NTSB is an independent public safety department for investigating traffic accidents in the U.S. that determines the causes of accidents and makes safety recommendations. The NTSB also investigates marine, rail, pipeline, and hazardous material transportation accidents. The responsibility of the NTSB includes preventing accidents and improving transportation safety. It also issues guidelines and protocols for safety recommendations to prevent the recurrence of an incident or accident. In this article, we have analyzed aviation accident data to summarize the number of reported accidents and evaluate the significance of this study [62].

Figure 6 shows all accidents involving UAVs worldwide and in the U.S. The data was taken from the NTSB's online accident portal. In 2006, only one accident was reported, which has been common for many years. It can be seen that the number of reported accidents has been increasing since 2018.

2) *Accident and Incident Data by FAA*: The FAA continuously conducts and sponsors research to enhance commercial and recreational aviation safety. To analyze accident history, data is extracted from the Accident and Incident Data portal by the FAA. Figure 7 shows the number of accidents from 2010 to 2014. We found limited data on this portal to depict the number of accidents. In 2011, there was a noticeable spike in the number of reported accidents. Fortunately, in the subsequent years from 2011 to 2014, the number of accidents decreased [63].

⁴<https://www.nts.gov/Pages/AviationQuery.aspx>

⁵<https://www.asias.faa.gov/apex/f?p=100:446:::NO:446>

⁶<https://asrs.arc.nasa.gov/>, (accessed: 02/10/2023)

⁷An Overview of Human Factors in Aviation Maintenance http://www.atbs.gov.au/media/27818/hf_ar-2008-055.pdf

⁸Operation and Certification of Small Unmanned Aircraft Systems <https://www.regulations.gov/document/FAA-2015-0150-4721>

UAS Accidents and Incidents per Year according to NTSB

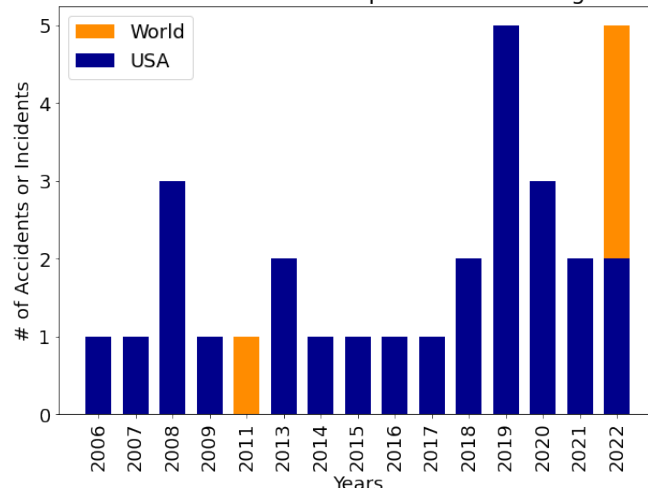


Fig. 6. UAV Accidents and Incidents in the World and U.S. per Year according to NTSB

UAS Accidents and Incidents per Year according to the FAA

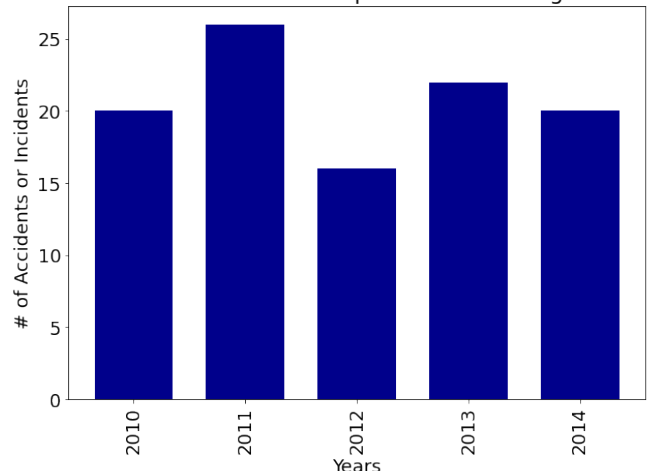


Fig. 7. UAV Accidents and Incidents per Year according to the FAA

3) *Aviation Safety Reporting System by the NASA*: The NASA-administered ASRS also referred to as the "NASA Report" or "NASA Form," has introduced a voluntary participation portal for the reporting of aviation accidents. This program is designed to ensure and improve aviation safety. The ASRS plays an important role in contributing to improving safety and preventing accidents. Data is collected from operators, pilots, and others involved in aviation accidents. In addition, the data is available to the FAA, organizations, and the aviation industry for scientific purposes and is used to promote aviation safety worldwide. Therefore, we have collected their data to determine the number of reported accidents for our studies.

The FAA occasionally gathers accident data from the Aviation Safety Reporting System (ASRS) portal. This collaboration helps ensure the reporting of any aviation safety incident or situation in which aviation safety may have been compromised. This program is similar to the Voluntary Safety Reporting Programs (VSRP) but differs from its counterparts

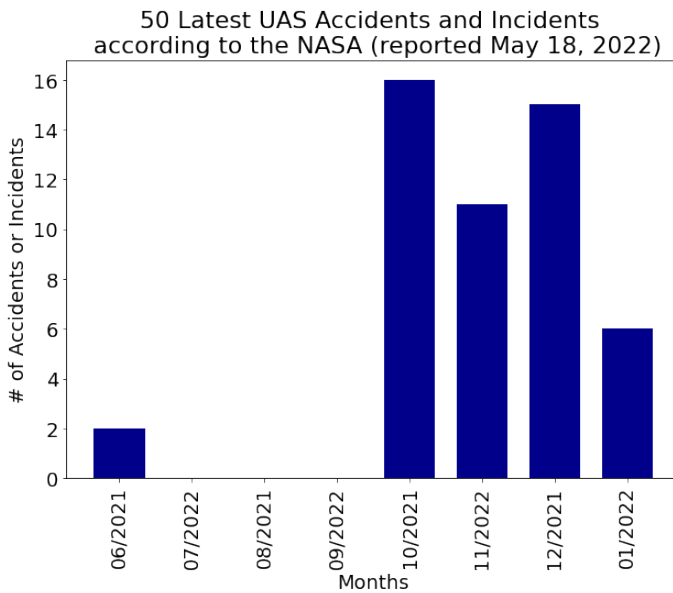


Fig. 8. 50 Latest UAS Accidents and Incidents according to the NASA (reported May 18, 2022)

in structure [64]. Figure 8 shows the fifty most recent accidents in the U.S., as shown in the NASA ASRS system portal, which includes a monthly report from June 2021 to January 2022. The third quarter of 2021 shows no accidents of a UAV. However, from October 2021, the number has increased significantly. Especially in October, November, and December, an exceptionally high number of accidents can be observed. This could be due to more challenging weather conditions in the fall and winter.

VI. PROPOSED FDR FRAMEWORK, OPPORTUNITIES, AND CHALLENGES

This section illustrates the challenges to FDR technology that require airlines to upgrade existing FDR technologies for a number of reasons, including meeting new regulatory requirements, addressing obsolescence, weight, size, and performance issues, or collecting additional data. As mentioned earlier, this is not a problem for general aircraft technology, but more data is needed for UAVs, so changes need to be made to the FDR considering the modularity and scalability of UAVs. Consequently, a framework for designing a lightweight FDR for UAVs is proposed to address parameter requirements and other challenges.

To make modifications to FDR technology, a proposed framework must follow a strategy depending on the needs and nature of the aircraft. Also, while designing the newer version of FDR it must follow the characteristics illustrated in figure 9, which demonstrates the characteristics from older FDR technology to the newer version hence collecting adequate data for investigation and meeting the standard requirements.

A. General Aircraft FDR Technology

Opportunities exist for improvements to aircraft onboard recorders. A single data analysis program or database can be

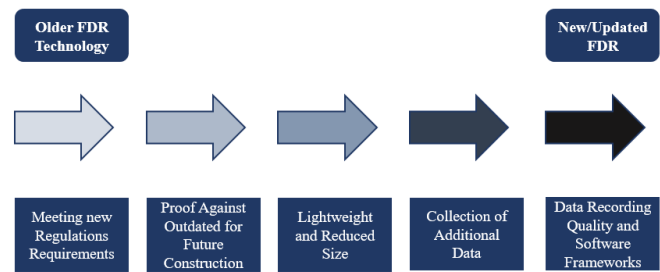


Fig. 9. FDRs' Improvement over Time

introduced to reduce the number of maintenance tasks where the data is gathered from various data recorders. This will simplify gathering and analyzing data and make it easier to analyze technical conditions using recorded data. After an aircraft has landed, the recorded parameters are transferred by radio to the servers chosen to gather this information and stored at a specific airport. This procedure would be automatic and remove the need for service workers (in the case of autonomous systems) to act as an intermediary and the time required to complete the data analysis. To fulfill this requirement, the aircraft must establish reliable and robust communication continuously with the ground base nodes of the networks. These kinds of networks are required across the globe. This kind of network already exists and is regarded as the IoT network operational in various applications sectors. The above-mentioned suggestions do not cover all potential solutions for the general aircraft category. However, they support the premise that there is room for improvement in the design of recorders, particularly for the software used to track the values or behavior of parameters in "online" mode. For instance, an airborne mission data recorder can directly provide the parameter data from an aircraft directly to the ground server. Moreover, the recorders' development will progress in response to newly developed requirements that will emerge in connection with the already existing technical possibilities after examining the historical impact of demands on modifications in recorders (including their software).

B. Data-Driven FDR Technology for UAVs

FDR's massive amount of data has challenged aviation experts regarding accessibility and analysis. To tackle this issue, modern data-driven frameworks are employed to perform data mining, an analytical process aiming to uncover patterns and relationships within large datasets. Data mining aims to support the knowledge discovery process, where fundamental insights are extracted and transformed into actionable information using AI/ML technologies [65]. These techniques enable aviation experts to effectively analyze the vast amounts of data generated by FDRs and make informed decisions based on their findings. This section presents a unique design for constructing a UAV FDR that meets the requirements outlined in the previous section, including parameter specifications, power limitations, data integrity, and communication protocol design. Furthermore, we demonstrate how machine

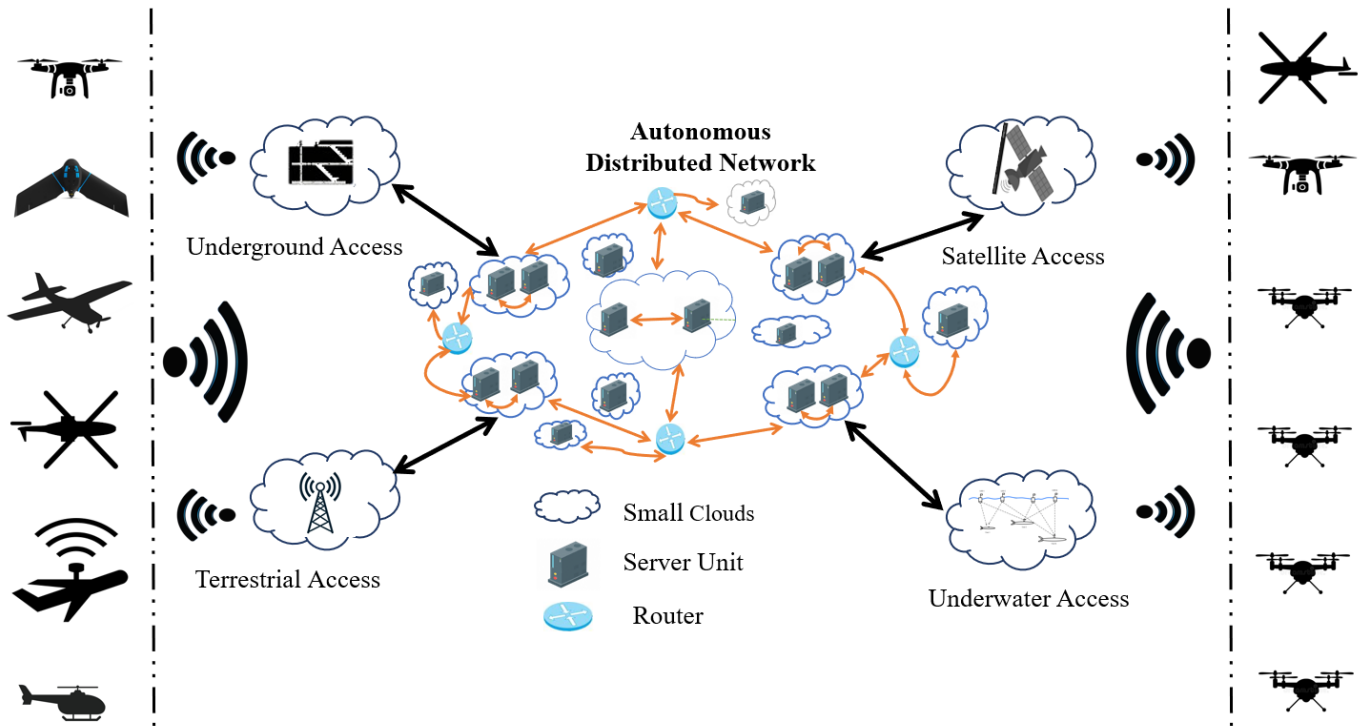


Fig. 10. Distributed Autonomous IoT network for UAVs

learning approaches can be implemented to enhance its performance. The authors in [75] employed Gaussian Mixture Model (GMM) based clustering to digital flight data which detects some flights with unusual data patterns. These different flights mean there's more risk because regular flights tend to follow similar patterns, while unusual ones stand out. Aviation and safety experts can review these patterns in the flight in depth which provides the risk assessment and they named this approach "Cluster AD-DataSample".

1) *Intelligent FDRs for UAV*: Based on [66], [67] and [68], we propose an FDR framework for UAVs and highlight the significance of machine learning algorithms in contributing to knowledge discovery (KD) and its potential as a promising AI approach. Additionally, we discuss the importance of designing software agents, also known as intelligent or autonomous agents, in various computing environments. These agents function independently or collaboratively with other entities in the system and possess the unique ability to employ learning and intelligence to achieve their assigned tasks or goals autonomously. The behavior of these agents can vary based on changes in the environment and can adapt dynamically. Today, software agents are widely used in various applications, including autonomous driving cars, traffic control systems, autonomous missions, email filters, and complex environments.

Programming frameworks that use software agents differ from other models, such as remote procedure calls and client models used in distributed processing. Autonomous agents can provide various services simultaneously, adopting the server role while acquiring services at other times, hence acting as a client. These agents also possess autonomy, which is

overall different from classical servers. There are enormous benefits of using agent-operated programming methods, such as reduced network load (i.e., it does not need a connection all the time with the user), which means agents can reconnect to their creator when the network is available, a decentralized structure, and asynchronous processing.

These agents need to work together to form a multi-agent system because a single agent can't handle complex problem-solving. Thanks to the distributed nature of networks, they work to solve the problem of data cooperatively. The knowledge is available and distributed among participant agents in a multi-agent system via node-to-node communications networks.

Participant agents typically have their own goals, and contact is made only when the information exchange is required or it may contribute to solving the problem of the overall system. In the context of FDR's comprehensive mechanism, three kinds of agent layers collaborate, the first one is the general agent layer, the second is the task handling layer, and the third is the database layer. In the general layer, individual agents such as electrical, mechanical, and decision agent, interacts with the flight control system of UAV, and DAU agents. The task-handling layer is a communication medium responsible for all communication between agents. The database layer saves the information every agent utilizes and the task handling layer.

The single agent-based system can be easily connected to a multi-agent subsystem for developing multi-agent systems. Most complex systems are distributed in nature and work together via node-to-node communication, and the knowledge needed to solve a problem is distributed among the agents.

Each agent can contribute to a coordinated solution for the overall distributed problem. It is possible only when the participant agents are fully cooperative and communicative with each other to solve the commonly distributed problem similar to the approach used in [66] but for UAVs. We believe that a multi-agent-based approach will be suitable for intelligent FDR design because it has several benefits over a single agent-based system, as UAVs can cooperate with each other in airspace for data and knowledge sharing. Table V provides the KD methods for constructing an intelligent FDR model. In this article, we have created an intelligent FDR model based on a learning algorithm and employing KD techniques, which is a database of previous flights. We have provided a framework for this model. This will help a UAV make decisions by using the data given to the model.

Initially, data can be gathered from both flights with and without incidents. This data can then be analyzed to identify specific sequences of events or patterns that may indicate the causes of unsafe flight conditions. As described in the literature [66], this technique can also be applied to unmanned vehicles, eliminating the need for an onboard pilot. Implementing a real-time data transfer system is crucial in this scenario, as it can detect previously unknown occurrences or events during flight, thereby providing early warnings to the UAV.

In the proposed method, the DAU must be installed on the UAV along with the participating agents, which interact with the UAV's flight control system. Meanwhile, the other participating agents in the network are ground-based computing systems. The task-handling layer is responsible for maintaining communication among the agents. The KD box stores the information utilized by the agents and the task-handling layer. Figure 10 presents the structure of an autonomous distributed framework where communication can be made through various types of networks in the UAV. This demonstrates the interconnectivity of IoT communication network devices with various contributing networks, ranging from satellites to underwater/underground networks, facilitating data transfer across networks.

TABLE V
KNOWLEDGE DISCOVERY TECHNIQUES FOR INTELLIGENT FDRS DESIGN [66], [68], [76]

Knowledge Discovery Approaches	Reinforcement Learning (RL)	Ensemble Method and Rule-Based
Probabilistic and Statistical Methods, Q-Learning	Model Based	Association Rule
Classification based on Bayesian Techniques, Inductive Logic, Pattern Discovery, Data Cleaning, Transfer Learning, Support Vector Machine (SVM), Support Vector Regression (SVR)	Deep Q-Learning	Random Forest
Genetic Algorithms	Q-Network	AdaBoost
Deep, Artificial, Recurrent, Convolutional, and Long Short-Term Neural Networks	Deep Q-Network	Decision Tree
Combination of two techniques, for instance, Hybrid Approaches by integrating two or more above-mentioned methods	Flat Hierarchical-RL, Meta RL, HRL	Expert System

2) *Communication Protocol Design*: The need for robust and reliable communication emerges in the design of intelligent FDRs. UAVs have already integrated transmitters and receivers, which are used by various ground or airborne control stations to control UAVs. Numerous techniques have been suggested for designing the communication protocol for UAVs [70], which are not fundamentally different from current terrestrial communication networks, provided they are implemented correctly. Various types of networks can collaborate to construct the IoT network, from satellite to underwater acoustic communication networks. The question arises, "how do these communication networks cooperate in the design of UAVs, whether for military or commercial purposes, in aiding the real-time data transfer and current status of UAVs responsively". The aeronautical telecommunication network (ATN) is intended to deliver full duplex, high data rate, and seamless connectivity among the aerial vehicles, aircraft, ground control station (GCS), Aeronautical Administrative Communication (AAC) and various aviation-related services suppliers Aeronautical Operational Control (AOC), Aeronautical Passenger Communication (APC) and local governing authorities which provide ATC and flight information services (FIS). These types of networks cooperate to form a common ATN, which is operated as a single, cohesive, and virtual data network.

3) *Radio and Electromagnetic Spectrum*: The growing need for internet connectivity for various purposes and needs in everyday life has made it possible to propose new spectra for conventional and future-oriented communication networks. It is, therefore, necessary to elaborate on the communications spectrum used by UAVs for specific missions, whether for military or civilian purposes. Radiofrequency (RF) is one of the parts of the electromagnetic spectrum often used in a specific frequency range, which is then called frequency bands. Their range lies between 3KHz to 300GHz all current wireless connectivity networks benefit from the RF spectrum, such as analog radio, navigation of aircraft, radio employed in marine, amateur radio, television broadcasting, mobile networks, and satellite communications. The international organization that regulates the generation, transmission, and receiving of RF bands is referred to as the International Telecommunication Union (ITU) [71]. The international body is responsible for preventing interference among users and collaborates with each country's national interest with respect to its laws. Moreover, the organization headquartered in Geneva, Switzerland, monitors and provides recommendations for the shared global usage of the radio spectrum and then promotes international cooperation while assigning the satellite orbits. The selection of RF frequency is crucial in designing the communication system (continuously sending or receiving the data). RF or electromagnetic is a traditional source of communication among UAVs, ground control stations (GCS), satellites, and other contributors throughout the network. As shown in Figure 11, the overall methodology and functioning of the intelligent FDR with real-time data transfer are depicted.

Laser beam communication as a data link can also be used between aircraft, UAVs, and satellites as well. A white paper from the University of Oxford [72] initiated the Hy-

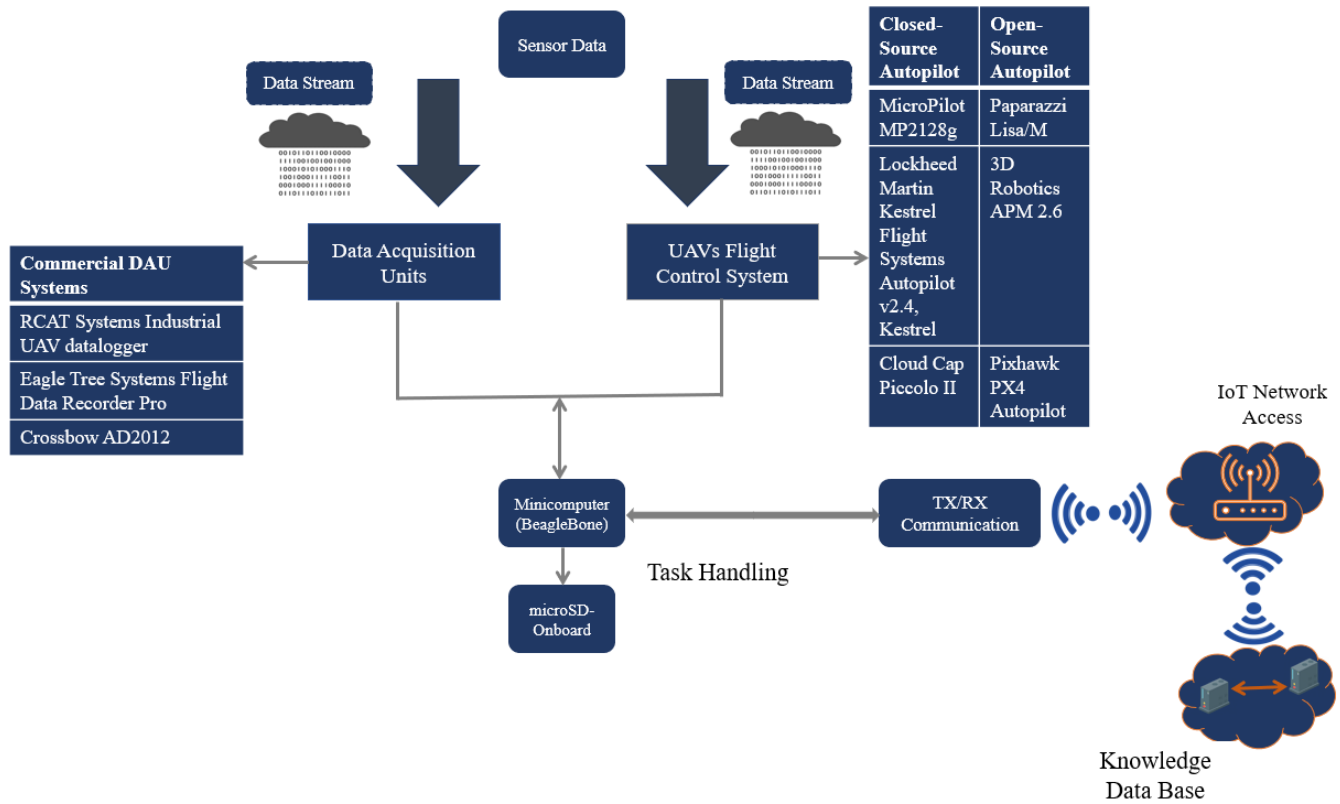


Fig. 11. Proposed FDR Model for UAVs

perion Project, which researches laser communication among aerospace network participants. Because most utilization of RF, the exponential growth of UAVs, and the number of satellites cause bandwidth allocation problems in communicating with any type of aircraft. On the other hand, laser communication is limited to a few kilometers (Km) hence distance constraints are present during the propagation of signals. Therefore, it is suitable for small UAVs to employ laser communication, reducing the load of bandwidth capacity of RF frequency. Moreover, communication from and to UAVs, satellites, and other skies is done mainly through the employment of RF applications. The following frequency bands are commonly employed for the goal of communication [48], [69]

- K_u - Frequency range- 12-18 Ghz, Area of Applications: Satellite Altimetry and High-Resolution Mapping (HRM)
- K_a -27-40Ghz, Area of Applications: Airport Surveillance and Very HRM
- K - Frequency range- 18-27 Ghz, Use: Water Vapor Absorption (Rare)
- S - Frequency range- 2-4 Ghz, Applications: Medium Use in Surveillance, Terminal Traffic Control, and Weather Purposes
- L - Frequency range- 1-2Ghz, Area of Applications: En-route Traffic Control and Surveillance
- C - Frequency range- 4-8 Ghz, Area of Applications: Tracking and Weather detection of Airborne
- X - Frequency range- 8-12 Ghz, Area of Applications: General Tracking, Marine radar, Missile Guidance, Map-

ping, and Airborne intercept

- HF - Frequency range- 3-30 Mhz, Current Deployment in Radar Surveillance
- VHF - Frequency range- 30-3002 Mhz, Application: Long Range Surveillance
- UHF - Frequency range- 300-1000 Mhz, Application: Long Range Surveillance

Based on the application area, we can use these frequency ranges for the data link and familiarize ourselves with the current status of the UAV. In the autonomous distributed network, the data is transferred and saved through different clouds, servers, and routers. For instance, the FDAU of the UAV can be associated with any link of a communication network to acquire the data collected by FDRs and spread it throughout the network. In this way, we have enough data for many purposes, i.e., training, designing, investigating accidents, and performing preventive maintenance. Additionally, we shall identify the recording resolution of each parameter, measurement range, recording interval, and accuracy of parameters with its maximum sampling.

C. Data Sharing Phase in IoT Networks

This section provides a data-sharing mechanism among the small UAVs throughout the IoT-based autonomous network. The possible assumptions we have made through our understanding are in two phases. The concept of a timestamp is essential to be introduced for the given data to a data store or the collection of data in the KD and keeping records

of information online. This concept signifies the particular data storage at different times. Firstly, the data generated from UAVs can be classified into two categories, i.e., UAVs' mission data and UAV's flight data. However, storing both data is essential for mission and flight current characteristics. In this study, our research is based on the FDRs of UAVs regarding flight data. Therefore, we use the data link layer of a communication system for opting flight data and then store it at any node of the wireless communication network.

1) *Phase-I*: Sending information from a UAV itself is a challenge in observing the device's computational resources. The sensor's data streams are processed to the FDAU; then it's transmitted through a communication channel. The relevant data can be saved to a particular owner of the UAVs or the GCS of that drone or to any network.

2) *Phase-II*: For the classification based on Figure 5 in micro, mini, very small, and small UAVs, we assume the flight data is generated and saved either on-board or the real-time data policy is integrated into it. The sensors' data is processed per FDR's methods used in general aviation and then transferred to a network node. Each data frame enters a server with a timestamp that records every data. It also can check the data in the server, and repeatedly data can be omitted from this process. Different UAVs can fly at different times; the timestamp also remembers the data coming from a particular drone at different intervals.

The association between UAV's flight control system and FDAU with IoT communication network are the remaining portions of the proposed intelligent FDR design for sending the real-time data of UAV parameters. A simulation platform can be generated with this design and then enlarged to a hardware design for testing and to check the feasibility of the methods, which we shall consider in the following research phase.

VII. CONCLUSION

This paper studied FDRs for conventional aircraft systems and UAV systems. We provided a brief introduction about FDRs illustrating the necessity to install them in any air vehicle. Starting from previously used technologies and the initial phase of FDRs, we captured the whole picture of FDRs and briefly discussed data acquisition system theory, operational verification checklist, and the calibration process. An overview of the technical development of FDRs is given and how these technologies evolved. Our research focused on the regulation of the FDRs by aviation organizations, professional societies, and governing bodies. These entities develop standards and guidance materials, which are subsequently translated into laws that all airlines and aviation industries are obligated to follow. The next section starts with a detailed introduction to UAVs which covers the background and paramilitaries of a UAV, identifies the parameter and operational requirements, and then provides the state-of-the-art of current lightweight FDRs. To establish the significance of this study for future generations of FDRs, we conducted a comprehensive review of UAV-related accidents reported by prominent U.S. government agencies, including the NTSB, the FAA, and the NASA accident portal. We elaborated a road map to design

intelligent FDR with the help of the autonomous distributed communication network. The roadmap and recommendations proposed in this article will undoubtedly help any aircraft deal with mishaps and provide sufficient data that can be used for further safety improvements and other purposes.

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