UAV Avionics Safety, Certification, Accidents, Redundancy, Integrity and Reliability: A Comprehensive Review and Future Trends

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***Abstract*—This paper underscores the significance of safety and reliability in the realm of Unmanned Aerial Vehicle (UAV) technologies, and how regulations play a pivotal role in ensuring their responsible use. We have analyzed safety incidents and trends both in Canada and globally, noting a decline in incidents attributed to enhanced regulations. Our comparative analysis of different UAV technologies identified batteries as the most reliable power supply, Global Navigation Satellite System (GNSS) as the most effective navigation system, and Light Detection and Ranging (LiDAR) as the optimal optical sensor due to regulatory compliance and system redundancies. We also examined the regulatory framework in Canada, comparing it with the risk-based approach of the European Union Aviation Safety Agency (EASA) and the efforts of Joint Authorities for Rule-making on Unmanned Systems (JARUS) towards global harmonization. Furthermore, we highlighted emerging trends in automation and flight control technologies, with a focus on European regulations shaping UAV automation trends. In conclusion, by adhering to best practices from other regulatory bodies, embracing emerging trends, and adopting a risk-based approach, Canada can promote the growth of the UAV industry while ensuring safety and reliability in UAV technologies.**

***Index Terms*—Unmanned aerial vehicles, Avionics Safety, Drone Certification, Accidents, Redundancy, Integrity, Reliability.**

NOMENCLATURE

ANSI	American National Standards Institute
AOR	Aviation Occurrence Report
ASRA	Aviation Safety Research and Analysis
AVOPS	Aviation Operations Centre
ATC	Air Traffic Control
ATM	Air Traffic Monitoring
ATS	Air Traffic Services
BVLOS	Beyond Visual Line of Sight
CADORS	Civil Aviation Daily Occurrence Reporting System
CAR	Canadian Aviation Regulations
CFR	Code of Federal Regulations
CSA	Canadian Standards Association
EASA	European Aviation Safety Agency
FAA	Federal Aviation Authority
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
INS	Inertial Navigation Systems
IPS	Indoor Positioning System
JARUS	Joint Authorities for Rule-making on Unmanned Systems
LiDAR	Light Detection and Ranging
NAAs	National Aviation Authorities
RCMP	Royal Canadian Mounted Police
SESAR	Single European Sky ATM Research
SFOC	Special Flight Operations Certificate
TC	Transport Canada
TCCA	Transport Canada Civil Aviation
TSB	Transport Safety Board
UAVs	Unmanned Aerial vehicles
UGVs	Unmanned Ground Vehicles
VFR	Visual Flight Rules
VLOS	Visual Line of Sight
VTOL	Vertical Takeoff and Landing

I. Introduction

Motivation: Unmanned Aerial vehicles (UAVs), commonly referred to as drones or Uninhibited Aerial Systems (UASs), are aircraft that can be operated without a human pilot onboard [1]–[4]. They can be remotely controlled or flown by a computer based in preprogrammed flight paths [5]. UAVs have a rich history, dating back to their use in reconnaissance missions during World War I. Today, UAVs are used in a wide range of industries and applications, such as surveillance, photography, mapping, search & rescue, and more which will be covered in subsequent sections [1], [3], [6]. With the introduction of drones, which refers to all unmanned vehicles that are controlled remotely, UAVs have become more popular and accessible.

The rise of UAVs has revolutionized the way we interact with the world around us. From aerial photography to military reconnaissance, UAV's have become an essential tool with a wide range of applications in many industries. However, this surge in popularity comes with an increased risk of accidents. In order to ensure safe and responsible UAV use, certification and regulation has become a crucial requirement for operators, government bodies, and the general public. In Canada, Transport Canada (TC) has set in place strict regulations to govern the operation of UAVs, and these regulations require pilots to obtain a pilot certificate. This certificate ensures that pilots have the necessary skills and knowledge to be able to operate their UAVs in a safe manner while following the rules that TC has set in place. All operations are conducted under Part IX of the Canadian Aviation Regulation (CAR) [7]. Pilots must always carry a valid drone pilot certificate when operating their drone. This drone pilot certificate serves as

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documented evidence of the pilots level of skill and expertise and helps mitigate the risk of accidents and misuse of the UAV. In circumstances where a drone pilot wishes to operate a UAV in Canada outside of the rules set in place in Part IX of the CAR, they can apply for a Special Flight Operations Certificate (SFOC).

Despite the numerous benefits of UAVs, there is also an inherent risk associated with their use. One of the most significant risks is the potential for mid-air collisions with other UAVs or piloted aircrafts and helicopters. Other risks include loss of control and intentional misuse of the UAV. Certification helps mitigate these risks by ensuring the pilot has the necessary training and knowledge to operate their UAV safely and in a responsible manner. Additionally, certification can help enforce the regulations set out by TC, which in turn helps maintain the integrity of the Canadian aviation system. In recent years, there have been several high-profile incidents involving UAVs that have highlighted the importance of certification and safe operation. Using TC's Civil Aviation Daily Occurrence Reporting System (CADORS) between November 5th, 2005, and December 31st, 2016, there were a total of 355 incidents that were reported in Canadian airspace with 66.5% of those involving UAVs. Of these 66.5% the vast majority of these incidents were reported by pilots operating piloted aircrafts [8]. These incidents have been steadily increasing every year since 2013. By requiring and enforcing certification and regulation, TC can help ensure that UAVs are operated safely and responsibly.

Scope: The goal of this paper is to review the significance of safety and reliability considering the context of UAV technologies as well as how regulations play a key role in ensuring their use. Safety incidents and their ongoing trends are investigated. Energy sources, the advancement of navigation systems, and sensing technologies are discussed in terms of regulatory compliance and system redundancies since they play a vital role in UAV safety and reliability. The paper also reviews the regulatory framework in Canada, European Union Aviation Safety Agency (EASA), and the efforts of Joint Authorities for Rule-making on Unmanned Systems (JARUS) towards global harmonization. The paper also presents the potential emerging trends in automation and flight control technologies.

Structure: The remainder of the article is organized as follows: Section II presents UAV safety occurrences, Canadian airspace classification, and UAV incidents in Canada and around the world. Section III lists UAV features, state of UAV technology, and advancements in safety and reliability. Section IV describes regulatory framework in Canada, Canadian pilot certification, and international regulatory frameworks. Section V presents a comparison of UAV technology based on safety and reliability. Section VI presents trade-off studies in UAV systems of energy sources, navigation systems, and optical sensors. Section VII illustrates potential future trends. Finally, Section VIII concludes the work.

II. Safety Occurrences

A. UAV Safety Occurrences

To understand the current state of UAVs incidents in Canada, it is important to understand how the incidents are recorded by Transport Canada Civil Aviation (TCCA). TCCA records up to date not only UAV safety occurrences but instead all safety occurrences in aviation. This information is organized into TCCA's database called the CADORS, allowing all parties to have access to safety information to promote the continuous improvement of safety in the space. All stakeholders of the safety occurrence are notified in a timely manner. CADORS was launched in 1985 and was used to capture information on civil aviation occurrences and capture Air Traffic Services (ATS) operations under the CAR, section 807.01 [9].This database is important as there is a lot of value in collecting information regarding aviation safety occurrences. Over the last five years, TCCA has received on average 45 aviation safety occurrences every day [9]. The information that is gathered by TCCA in CADORS is used to identify early potential hazards and loopholes in the current safety system. CADORS data is further used to follow up on specific events, develop safety communications and develop reports and studies on potential safety issues. The most common event that results in a UAV safety occurrence being recorded is due to UAVs entering areas of Canadian airspace in which they are not registered to fly.Understanding why this is an issue, comes first from examining why there are seven classes of Canadian airspace. Analyzing the safety occurrences that have happened in Canada, certain trends start to emerge. Canadian UAV safety occurrences appear to be most frequent in Ontario and British Columbia where UAV safety occurrences were growing exponentially, until 2017 at which point their number started to decrease [9]. This indicates that UAV regulations and safety technologies are resulting in reduced UAV safety occurrences [9]. Comparing trends in recorded UAV safety occurrences in Canada to what is being recorded worldwide it becomes clear that the same trend is being seen worldwide. This further indicates that UAVs are becoming safer as certifications, regulations and safety related technologies are developed.

The information in the CADORS database comes from the sources around the country such as NAV CANADA, Transport Safety Board (TSB), Royal Canadian Mounted Police (RCMP), aircraft operators, and government agencies. Of those entities, NAV CANADA provides about 80% of all the aviation occurrence information. The information is provided in an Aviation Occurrence Report (AOR) and sent to Aviation Operations Centre (AVOPS) through secure emails. Once received, the Aviation Safety Research and Analysis (ASRA) staff enter it into CADORS. Any missing information on the CADORS application is received by ASRA by consulting relevant sources. Finally, a quality assurance review is performed before it is finally published [9]. Fig. 1 illustrates the CADORS reporting process graphically. Once the safety occurrence has been published, analysts assign it to an event based on its details. The event can describe something that occurred to the aircraft or something that happened to the

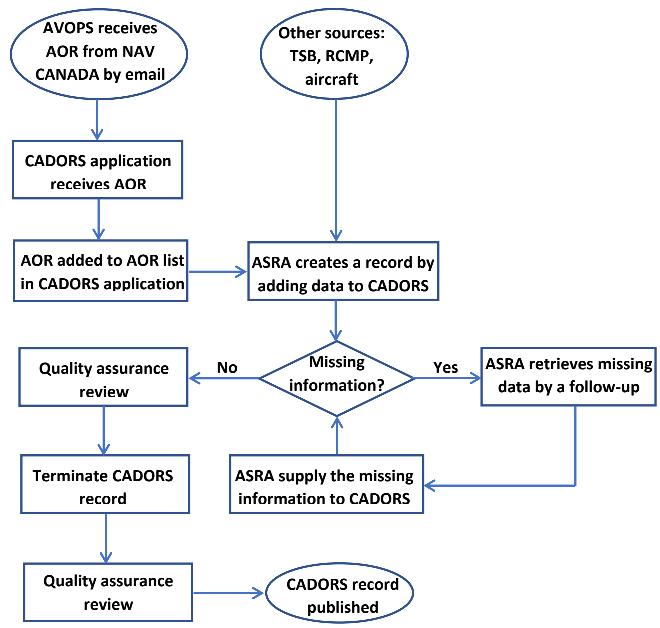

Fig. 1. Graphical Representation of CADORS Reporting Process [9].

aviation system. By assigning events to the safety occurrences, it allows CADORS to be easily categorized and improves the ability for the data to be analyzed. For the purposes of analyzing UAV safety in Canada, CADORS occurrences will be filtered for events which involve UAVs. Using the CADORS to analyze UAV data, the severity and frequency of safety occurrences in Canada can be analyzed.

B. *Canadian Airspace Classification: A to G*

Most UAV occurrences are reported because a UAV is found flying in classes of Canadian airspace without the required permission to do so. Canada has seven classes of airspace with each having its own rules about the types of aircrafts that can be used and the communication equipment that is required for the pilots to use. In all classes of airspace, NAV CANADA provides Air Traffic Control (ATC) and flight information to ensure safety in the air. Pilots can fly the aircraft based on the aircraft's navigation instruments or visually by using their sight. Depending on the airspace, NAV CANADA may restrict which of the two methods can be used by the pilot. Instrument Flight Rules (IFR) is defined as the pilot using only instrumentation on the flight deck of an aircraft, where Visual Flight Rules (VFR) is defined by the pilot using line of sight navigation which is based on what can be seen outside the cockpit [10], [11]. Beginning with Class G, this classification refers to uncontrolled airspace. This is where ATC services are provided, however pilots are responsible for keeping a safe distance from all other aircraft. Class G airspace goes to an altitude of 18,000 ft, and both VFR and IFR apply [10], [12].

Class B and A refer to controlled low-level airspace and controlled high-level airspace respectively. In class B, ATC gives pilots clearance to fly as well as instructions on how to maintain a safe distance from other aircraft. The altitude limits are between 12,000 ft and 18,000 ft and exist in areas close to an airport. Both IFR and VFR can be used in this Class. Class A is similar to class B in most respects however it accounts for all airspace above 18,000 ft. Aircrafts cannot use VFR when flying in Class A airspace [10]. Next, class C, D, and E are defined as Control Zone and Terminal Area for Busy Airport, Control Zone and Terminal Area for Moderate Traffic Airport, and Control Zone for Airports without Towers respectively. VFR and IFR apply to all aircraft flying in these zones. In class C, all aircraft need clearance to fly in this zone. In class D only aircraft using IFR require ATC clearance with aircrafts using VFR only needing to have an established radio connection with ATC. In class E, only aircraft using IFR need clearance and VFR do not. Class F is the final class and refers to restricted and advisory airspace. In restricted or advisory airspace, no aircraft can enter without the permission from the controlling agency. Airspace can be restricted due to specific security, safety, or military concerns. UAVs flying in Canada must follow rules put in place by TC. Furthermore, UAV activity must be done in Class G. If the UAV is flying in Class A-E airspace, the UAV must be registered with TC, the operator must hold an advanced operations pilots' certificate, and have a written authorization from NAV CANADA [10]. Unfortunately, UAV operators do not always follow these rules which is the reason for most recorded UAV safety occurrences in the past decade.

C. *UAV Incidents in Canada*

Using the CADORS database from TCCA, all the aviation safety occurrences that involved any type of UAV were filtered through and recorded over the past ten years from January 1st, 2013, to March 24th, 2023. For the purposes of this analysis, severe safety occurrences would be any occurrence that involved injury or fatalities. The data we obtained show that there have been no safety occurrences in Canada related to UAVs that could be classified as severe. Although it has been concluded that there are no severe UAV safety occurrences, there is one that does require more attention. In 2017, for the first time ever in Canada a small drone collided with a passenger plane above Quebec City's Jean Lesage airport [13]. Federal Transport Minister Marc Garneau confirmed that the aircraft had only sustained minor damage and that nobody was hurt. This incident could have been much worse if the drone had collided with the cockpit or the engine on this aircraft. "The incident could have been catastrophic" was said by Garneau when asked at a Montreal press conference. This incident resulted in a series of interim regulations being put in place, which were further approved in 2018. The updated regulations now state a minimum age for drone operators and a mandatory written test for UAV pilots who are now required to register their names and address on the drone itself. To analyze the spatial distribution of incidents in Canada over the past ten years, the UAV safety occurrences were grouped by province. Fig. 2.(a) shows percentage of UAV safety occurrences per province in Canada.

Looking at Fig. 2.(a), most of the UAV safety occurrences are recorded in British Columbia and Ontario which make up 65% of all occurrences over the past ten years. This

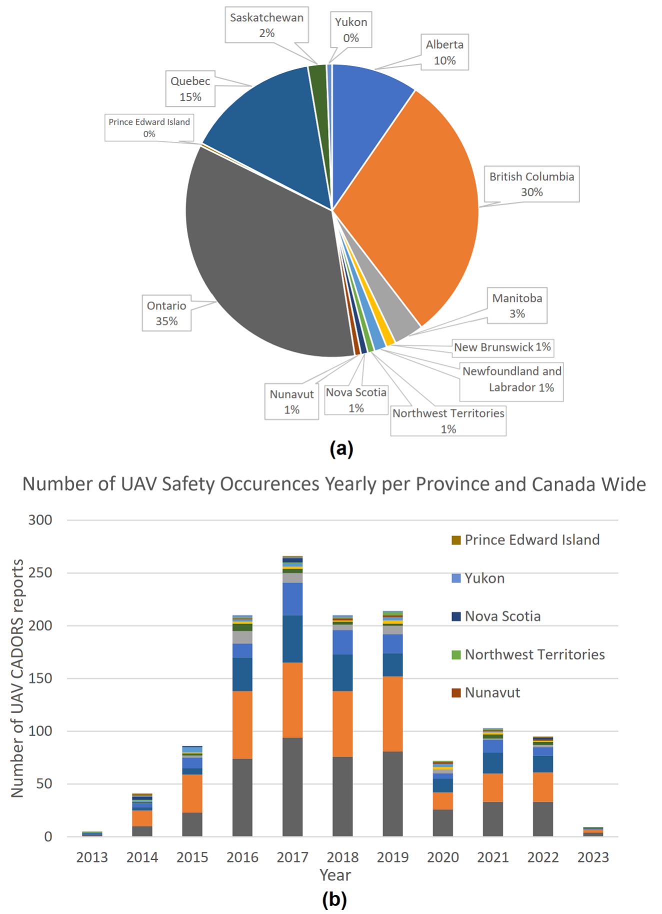

Fig. 2. UAV safety occurrences in Canada: (a) Percentage of Safety Occurrences per Province and (b) Total number of UAV Safety Occurrences between 2013 and 2023 [9].

finding reasonably aligns with the fact that British Columbia and Ontario have large populations and very active airspace. Quebec and Alberta come next as they produced the third and fourth most safety occurrences respectively, with a combined 25%. Finally, the last 10% of recorded safety occurrences comes from all the other provinces. Prince Edward Island produced the least number of UAV safety incidents with only four being recorded in the past ten years. Looking at the amount of recorded UAV incident reports per year since 2013 reveals general trends in UAV safety in the past decade. Fig. 2.(b) shows the number of UAV safety occurrences yearly per province and Canada wide (Fig. 2.(a) and (b) are using same province color and legend).

From Fig. 2.(b), the first observation that can be made is that between 2013 and 2017 there was an almost exponential rise in reported UAV safety occurrences nationwide. This is a result of the explosion in popularity of recreational drones. Pilots have spotted drones in their flight path more than 130 times in that five-year range. The data shows that the amount of UAV safety occurrences peaked in 2017, the same year that the incident at Quebec City's Jean Lesage airport occurred. After the new interim rules were put in place, and later became part of TC's regulations, the data shows that the amount of these recorded occurrences starts to decline. In 2020, the number of recorded incidents was the lowest it had been since 2014, this is likely in part due to the pandemic reducing air transportation activity. Although air transportation activities increased between 2021-2023, the levels of safety occurrences continued to decrease never rebounding back to their previous highs. This proves that the regulations that TC has put in place have been successful in promoting safety in Canadian airspace. The correction of incidents to an acceptable level after an exponential increase is attributable to the current regulatory landscape in the country. Canada's UAV regulations have resulted in a considerable improvement to aviation safety in Canada for all stakeholders which is an achievement that did not appear to be possible only five years ago.

D. *UAV Safety Occurrences Around The World*

As previously demonstrated, in Canada a great improvement has been seen in the number of UAV safety occurrences in recent years achieving acceptable levels. In 2018 the International Air Transport Association (IATA) stated in its safety report 2018 that there has been an increasing safety risk posed by drones due to the unpredictable nature of drone operators [14]. IATA's safety report stated that there was a significant increase in UAV related incidents from 2014 to 2018, with 50% of those reports coming from Europe [14]. Similar to reports in Canada, most of the reports occurred when a UAV was interfering with the trajectory of an aircraft. It must be noted that most worldwide safety occurrences are likely to go unreported as there is a lack of a standardized reporting system. As such it is difficult to understand the true scale of the safety threat of UAVs. In 2022, the EASA, issued its safety review for that year that showed a drop in recorded UAV safety occurrences in all categories [15]–[17]. The number of severe incidents involving a UAV reached zero in 2021. EASA credits the reduction in drone related incidents in Europe to advancements in object detection and avoidance technology as well as certification for drone pilots [15]. Another contributing factor is likely the reduction in the amount of tourist traffic in the European countries that occurred in 2020 and 2021. The reduction in the UAV safety occurrences seen in Europe since 2018 follows a trend similar to what has been seen in Canada since 2017. It may be too early to determine whether this trend continues in the coming years or if it will rebound to 2018 levels. To summarize, fewer UAV safety occurrences are being recorded in Canada and worldwide compared to previous peaks in 2018 as safety technologies and regulations begin to catch up to UAV popularity.

III. UAV Features and Safety Technology

A. *UAV Features*

Within the UAV industry there is a vast range of purposes and industries that utilize UAVs which then require an enormous amount of specialization and features. With the large amount of UAV requirements there are many ways UAVs can be categorized, however they can generally be categorized by their wing type. There are four main styles that are utilized, each of which have several uses and come in a large variety of sizes. These styles include single rotor drones, multi-rotor drones, fixed wing drones and fixed wing hybrid drones (tilt-rotors). First single rotor drones (Fig. 3.(a)) look and function like typical helicopters, they are fitted with one large rotor to provide thrust and a tail rotor for control and stability [15]. Single rotor UAVs are typically large, and gas powered allowing them to operate Vertical Takeoff and Landing (VTOL) flight, high endurance, and the ability to carry large loads. Single Rotor UAVs are limited due to their complex nature as they can be dangerous, require extensive training and are expensive. Multi-rotor drones (Fig. 3.(b)) hover like a helicopter; however, they utilize multiple rotors for lift and control during flight and are easily the most widely used type of drone due to their versatility. Multi rotor drones are battery powered and tend to be small, being able to be easily carried by a single person. Due to their additional rotors, they offer great stability, maneuverability, VTOL flight, inexpensive while being easily portable. With multiple rotors and their small stature there are several drawbacks such as low endurance, small payload capacity, low stability in wind and low flight speeds. With these traits multi-rotor UAVs offer a large amount of utility in a wide range of commercial industries such as photography, aerial inspecting, surveying, agriculture, delivery, and recreational use such as racing.

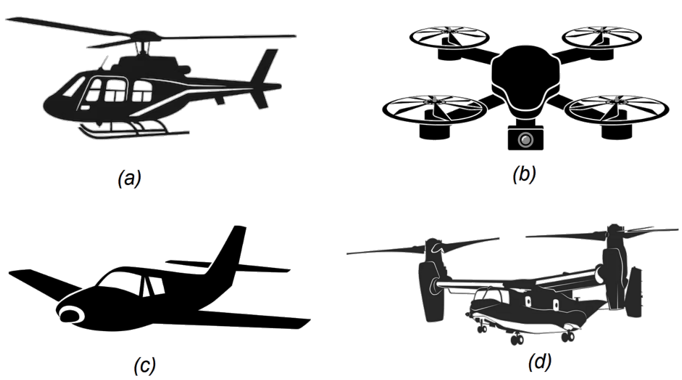

Fig. 3. Type of UAVs: (a) Single rotor, (b) Multirotor, (c) Fixed wing, (d) tilt-rotor.

Fixed wings (Fig. 3.(c)), unlike rotor-based UAVs, utilize their wings to generate lift to achieve flight functioning like airplanes. Fixed wing UAVs provide a great amount of utility in the widest range of sizes and may be gas or battery powered. Fixed wing UAVs either require a runway or landing strip or lighter models may be thrown by a user. Fixed wing UAVs maneuverability is limited due to the lack of hover and VTOL capabilities. Fixed wing UAVs excel in that they have long flight times, can carry larger payloads, fast flight speeds and stability in high wind speeds, however they require large spaces and require more training. They are often used for Aerial mapping, utility inspection, surveillance, agriculture within the commercial sphere and within the military they can be used for reconnaissance, situational awareness, aerial fire support, precision targeting support for ground, air, and sea forces as well as decoys. Finally, Fixed-wing hybrid VTOL drones (Fig. 3.(d)) refers to UAVs with fixed-wing UAVs with the added benefit of being capable of VTOL and hover flight. They achieve VTOL and hover flight by either rotating its rotors or its wing to change the pitch of thrust. Fixed-wing hybrid VTOL drones offer many of the same uses of fixed-wing VTOLs while eliminating some of its problems, however, they are more expensive and increase the weight and complexity of the aircraft.

B. State of UAV Technology

1) UAV Power Sources: Batteries are a common power source for drones, with various types available, Lead acid (Pb-acid), Nickel cadmium (NiCad), Nickel Metal Hydride (NiMH), Alkaline, Lithium Polymer (Li-Po), Lithium Ion (Li-Ion), Zinc Oxide (Zn-O2), Lithium-air (Li-air) and Lithium-Thionyl-chloride (Li-SOCl2) [18]–[20]. Criterias that are important for considering a battery type include power density, energy density, weight, volume, cycle life, cost, safety, and maintenance. Li-Ion batteries are popular for electric vehicle applications because they can deliver high energy and power per unit of battery mass, have a long cycle life, and are more compact and efficient than other rechargeable batteries. However, they are also more expensive than other battery types. These factors are critical in determining the UAVs effectiveness as they may influence the UAV's cost, range, endurance, size, payload capacity, acceleration, and lifespan before replacing the battery. Power density determines the UAV's acceleration, energy density determines the UAV's range and endurance, while life cycle determines the number of recharges before the battery must be replaced.

UAVs can also be powered by combustion engines, which include petrol and diesel engines. These engines comprise several parts, such as a combustion chamber, pistons, fuel injectors, intake, and exhaust valves. Despite the differences between petrol and diesel engines - such as spark plugs in petrol engines and self-ignition in diesel engines under high pressure, both types of engines are generally less efficient and more harmful to the environment due to emissions [18], [21], [22]. Combustion fuels have a significantly higher energy density compared to Li-Ion battery with diesel fuel having an energy density of 12,666.7 Wh/kg and petrol 12,888.9 Wh/kg while Li-Ion batteries only displaying an energy density of 250 - 340 Wh/kg [18]. While Combustion engines have a more effective fuel source allowing for better UAV performance, they are only able to be used on larger vehicles due to the more complex and resilient machinery required [18]. Solar power energy is another energy source utilized in UAVs. Electrical current is harnessed from the light radiated by the sun in two different fashions, namely, there is the photovoltaic (PV) effect and Concentrated Solar Power (CSP) [18]. PV solar energy directly transforms the energy from the sun's light into current with the use of solar panels while CSP solar energy concentrates the heat generated by solar rays to run a steam turbine. UAVs utilize PV solar energy to either power UAVs or to extend the range of battery powered UAVs. To generate sufficient power to operate UAVs, the solar panels need to be as large as possible. To achieve this, solar powered UAVs require large, fixed wings to function.

As renewable fuel vehicles gain popularity, researchers are investigating alternative power sources to batteries, one of which is fuel cells (FCs). FCs are classified into different types, such as Proton Exchange Membrane (PEM) FC, Phosphoric Acid FC (PAFC), Solid Acid FC (SAFC), Alkaline FC (AFC), High-temperature FC (HTFC), and Electric storage FC (ESFC) [18]. PEMFCs are like batteries, with two electrodes separated by a membrane and connected through an electrolyte. FCs have an energy density of up to 150 times that of a Li-Po battery. Advancements have led to the development of drones powered by FCs, which have advantages such as no direct pollution, no sound, high energy density, and almost instant recharge [18], [23]. However, FCs require a high-power density, rapid response to loads, and a hydrogen supply infrastructure. Each type of FC has its advantages and disadvantages, and their implementation in drones must consider the weight, size, and range limitations caused by hydrogen storage tanks. FC technology would be very useful for drone operation, however, is not heavily utilized now due to the challenge of existing infrastructure such as hydrogen storage to support its use. Table I presents comparison of different 5kg payload capacity UAV considering different fuel sources.

TABLE I
COMPARISON OF DIFFERENT 5KG PAYLOAD CAPACITY UAV WITH DIFFERENT FUEL SOURCES [18].

Product Name	Li-Po Battery DJI M600	Hydrogen FC (1kW)	Gasoline	Solar Airbus Zephyr 8
Specific Energy (Wh/kg)	9.99	646	2,600	435
Flight Time (min)	20	250	120	20160
Weight (kg)	10	6.5	4.9	60
Payload (kg)	5	5	5	5
Discharge / Charge (min)	92	Refuel Time	Refuel Time	Constant Charge
Cost (USD)	5,699	13,410	1,550	3,000,000

2) UAV Navigation Technology: Within UAV navigation, collision and obstacle avoidance systems are crucial for ensuring safe and certified operations. Autonomous positioning is often necessary for station-keeping and loitering [1], [24]–[26]. UAVs rely on a combination of Global Positioning Systems (GPS) and Global Navigation Satellite Systems (GNSS) receivers, Inertial Navigation Systems (INS), Light Detection and Ranging (LiDAR) scanners, ultrasonic sensors, visual cameras, and Simultaneously Localization and Mapping (SLAM) techniques for navigation. A localization navigation system is used by autonomous UAVs to determine their position and orientation in real-time. This system typically utilizes sensors and cameras such as LiDAR, radar, and GPS to measure the vehicle's movement and surroundings, and processes these data to determine the UAV's location. The information obtained from the localization navigation system is then used by the UAV's control system to plan and execute movements or tasks [25], [27]–[30]. Unmanned Ground Vehicle (UGV) navigation refers to guiding UAVs from one location to another and often involves the use of various sensors and technologies such as GPS, LiDAR, and cameras to determine the UAV's location on a known trajectory that has been previously established. This type of navigation is commonly used in military reconnaissance and search and rescue operations [5], [27], [31]. GPS/GNSS is widely used in UAVs for various applications such as reconnaissance, surveillance, surveying, mapping, and geophysics exploration [1], [26]. GPS plays a critical role in UAV navigation systems by determining the position, speed, and altitude of the vehicle. GPS is often used in combination with an INS to provide comprehensive navigation solutions. Autonomous UAVs rely on GPS to provide highly precise information for control purposes, and GPS is also used in earth observation measurements to accurately reference geographically collected data. The precise time stamps provided by UAV GPS are valuable in collecting information [26].

3) UAV Optical Sensor Technology: Red Green Blue (RGB) cameras are commonly used in UAVs for capturing high-quality images and videos of an area. RGB cameras capture visible light wavelengths that humans can see and are used to create 2D or 3D maps of an area, monitor crop growth, and capture aerial footage for film and video production. RGB cameras have the advantage of being lightweight, affordable, and easy to use. They also provide high-resolution images, making them ideal for detailed analysis and documentation of an area. However, they may struggle to capture details in low light or in highly reflective or dark environments. Infrared (IR) cameras are another type of sensor used in UAVs for capturing thermal images of an area. Infrared cameras detect infrared radiation, which is emitted by all objects and provides a temperature profile of the area being imaged. Infrared cameras are used in various industries including agriculture, construction, and search and rescue missions. They are particularly useful for identifying hotspots, detecting leaks in pipelines, and monitoring crops for irrigation and pest control. Infrared cameras can operate in low light and can penetrate through smoke and fog, making them ideal for night-time and low-visibility missions [1], [26], [32].

Hyperspectral sensors are also used in UAVs for capturing images of an area at hundreds of different wavelengths. Hyperspectral sensors can capture information on an area's vegetation, water, and mineral content, and can identify specific objects or materials that may not be visible to the human eye. Hyperspectral sensors are used in various industries, including agriculture, geology, and environmental monitoring. They can be used to monitor plant health, detect changes in land use and vegetation, and identify areas with mineral deposits. Hyperspectral sensors can be expensive and require complex processing, but they have the advantage of providing detailed information about an area that cannot be obtained by other sensors [33]–[35]. LiDAR is a form of remote sensing technology that uses rapid laser pulses to capture data points and create precise and accurate maps of an area [36]. LiDAR drones have a wide range of applications, including tracking the progress of construction, conducting safety inspections, estimating resource stockpiles, mapping power lines, and reconstructing accident scenes. LiDAR technology has the advantage of working in the dark and penetrating through vegetation, making it suitable for various use cases where photogrammetry systems may struggle to capture detailed objects. However, photogrammetry is still commonly used due to its accessibility and ability to create detailed models overall. With the decreasing cost and weight of LiDAR, it is expected that LiDAR adoption may expand to new industries and use cases in the future [36].

C. Advancements in Safety and Reliability

The UAV industry is continuously evolving every year. As a result, safety and reliability must advance to ensure their continued success. Advancements in safety and reliability are focused in four main areas: autonomy, navigation systems, sensors, and power supply. Advancements in all these four categories work cohesively to ensure safety and reliability. It is imperative that progress in these categories is made to keep up with the rapid advancements in UAV technology and percent the safety of UAVs from being overshadowed. Drone autonomy has been increasing in the development of UAVs and has been directly responsible for the rise of hobbyist drone pilots. Advancements in autonomy have led to the improvement of remote-control capabilities, and minimal human intervention. Human error poses a risk to UAV operation, as a result mitigating unexpected human error can greatly reduce the probability of risk. As previously mentioned in 2.2 State of UAV Technology, the LiDAR-based drone is pushing the boundaries of UAV autonomous technology, it can self-navigate through environments unmapped by GPS [26], [37]. This technology is expected to continue to improve and mitigate associated human error. Autonomous UAVs are dependent on advancements in navigation technology.

Navigation systems are continuing to advance the safety and reliability of UAVs. All modern UAVs are equipped with advanced navigation systems such as GPS and ground-based sensors which allow the drones to navigate remotely or autonomously. UAVs are equipped with sensors that calculate the distance between the UAV and surrounding objects to avoid collisions [38], [39]. It is common to see drones hover and maintain a certain altitude, this is a result of the altitude hold function. The altitude hold function is controlled by a barometric pressure sensor, ultrasonic sensor and a throttle stick which work cohesively to allow the drone to maintain or shift its position during operation [38], [40]. Modern navigation systems are connected seamlessly to cloud computing services such as Amazon Web Services (AWS), which analyzes and processes data from drone operation. This can be beneficial in avoiding recurring errors that may have an effect on safety. Navigation systems help drones avoid obstacles and collisions and improve flight stability while ensuring more reliable operation. Sensors are the backbone of the UAVs navigation systems and autonomy [38]. The improvement in navigation systems and autonomy are directly linked to the advancements in sensor position and accuracy. Sensors improve the UAVs environmental awareness and help them detect challenges posed by its operation environment, such as temperature changes, air pressure and humidity. UAVs can use cameras and ultrasonic sensors to detect obstacles and avoid collisions. Advancement in sensors can further lead to more effective autopilot and battery management. Advancing battery management systems with sensors can optimize and prevent overheating and other issues [38]. Sensor technology has made UAVs safer and more reliable.

The power supply for UAVs is what allows it to operate, as a result advancement in the UAVs power supply is critical for safety and reliability. Most UAVs use lithium-ion batteries because they are highly energy dense, lightweight and have excellent rechargeable properties. As power supply solutions advance, UAVs will be capable of flying for longer periods of time. Many modern UAVs have a redundant power system to ensure that UAVs will not fall out of the sky if power in the main supply fails. In addition to having redundant power systems, many of them also have systems such as auto landing or return home features which would activate in the event of a critical failure or power loss. Power management systems in modern UAVs are a critical feature of the power supply. This system monitors the power usage of individual UAV components and can adjust power allocation accordingly to maximize the efficiency of the power supply [38]. Power management systems will continue to advance and become more efficient. Power supply technology will continue to advance and improve the safety and reliability of UAV technology as a result.

IV. Regulatory Framework in Canada

UAV operations are regulated in Canada through the CAR Part IX – Remotely Piloted Aircraft Systems [7]. The regulation is subdivided into subparts for small remotely piloted aircraft which are defined as having a maximum take-off weight of between 250g (0.55 lbs.) and 25 kg (55 lbs.), defined in Subpart 1. Regulation for operation of larger UAV, or unique operating condition is defined in Subpart 3. Before 1996, when CAR Part IX was codified, old regulations had a much more complex structure. Fig. 4 shows new Part IX regulatory structure the difference between the old and new regulatory structure in Canada. Key elements of the previous regulation remain, such as the SFOC. However, the new regulation simplifies exemptions and UAV distinctions into 2 categories of operation, weight class and VLOS status, making for a more robust and expansive legislation. Note that the maximum weight threshold was lowered from 35 kg to 25 kg in the new iteration of the Canadian regulations. This regulation only deals with the operation of UAVs, defining when and where small UAVs can fly, as well as the certifications a pilot must possess for each operation type [41], [42].

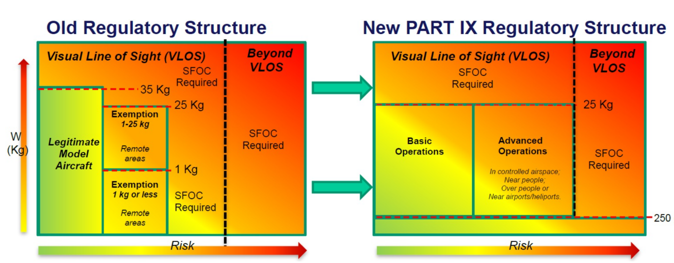

Fig. 4. New Part IX Regulatory Structure [43].

In accordance with Subpart 1 of CAR Part IX, every small remotely piloted aircraft operating in Canada must be registered with the Ministry of Transportation (901.03), with the pilot also requiring a pilot certificate (901.54). Division III of Subpart 1 outlines general operating and flight rules, which mandate operation under a Visual Line of Sight (VLOS). This means that a pilot or visual observer must always have unaided visual contact with the UAV during flight, which greatly limits the operations of these aircraft (901.11). Also outlined in this section are prohibited airspaces, flight safety regulations, and necessary documentation. Regulation 901.25 imposes a maximum flight altitude of 122 m (400 ft), or 30 m (100 ft) above any building or structure. Division V of Subpart 1 sets out regulations for advanced operations, which are defined for small remotely piloted aircraft for operation in (1) controlled airspaces, (2) at distances of less than 5 m (16.4 ft) from any person, (3) within 3 nautical miles from airports or 1 nautical mile from a helipad. This requires pilots to have an additional supplementary pilot certificate for advanced operations (901.62). Subsequently, Division VI imposes requirements for manufacturers that make UAVs intended for advanced operations. Regulation 901.78 states that manufacturers must make available to UAV owners (1) a maintenance program that provides instructions and inspection program, (2) any mandatory actions the manufacturer issues with respect to the system, (3) operating manual that includes safe ranges of weights and centers of gravity, minimum and maximum altitudes and velocities for each flight phase, effects of foreseeable weather conditions, unsafe characteristics of the system that could result in injury, procedures for operating system in normal and emergency conditions, and assembly / adjustment instructions. Under regulation 901.79, the manufacturer must also keep records of results, and reports relating to product verification for a period of 2 years after the date of manufacturing of the system [7], [41].

Subpart 3 of CAR Part IX addresses special flight operations for remotely piloted aircraft systems which include the operation of (1) UAV having maximum takeoff weight more than 25 kg (55 lbs.), (2) operation beyond VLOS, (3) operation at altitude greater than outlined above. For such an operation, pilots must have a SFOC-RPAS in accordance with regulation 903.02 if they are able to prove to the Minister the ability to perform the operation without adversely affecting aviation safety or the safety of any person.

A. *Canadian Pilot Certification*

In accordance with regulations 901.54 and 901.62 pilots wishing to fly UAV between 250 g and 25 kg must possess a pilot certificate. TC defines two certificates, Pilot Certificate Basic Operations and Pilot Certificate Advanced Operations, which can both be attained through a TC administered online exam. As the names suggest, candidates for advanced certificates need to demonstrate a much higher aptitude for concepts through a separate exam and must already have a basic operations certificate, mirroring licensing for other forms of transportation such as automobiles [13], [43], [44]. Examinations for both basic and advanced certificates cover almost the entirety of CAR Part IX, and sections from other parts including Part I: General Provisions and Part VI: General Operating Flight Rules. Pertaining to RPAS airframes, powerplants, propulsion and systems, candidates must have knowledge of proper RPAS handling, care and securing, electrical systems, redundancies and critical items, ground control stations, datalinks, batteries, autopilots, payloads, electrical motors, launch and recovery systems, and other systems onboard UAVs [43]. For this exam, candidates must show understanding of many other concepts including air law, air traffic rules, procedures, human factors, meteorology, navigation, flight operations, flight theory and radiotelephony [43]. Both basic and advanced pilots need to register their UAVs with TC in accordance with regulation 901.06, which can easily be done through TC's Drone Management Portal [45]–[50].

Basic pilots can begin conducting operations once they receive their certificate, unlike advanced pilots who must pass a flight review. This is a process where a flight reviewer, who are TC approved UAV pilots, assess the pilot's ability to safely operate the drone [47]. During this examination, pilots must demonstrate skill and knowledge including providing a satisfactory site survey, properly identifying airspace, obstructions, and terrain features, retrieve and interpret weather information, select a safe and efficient take-off location and flight route, and organize and arrange material and equipment in a manner that makes the items readily available. In addition, the pilot must be able to describe emergency procedures, complete all pre-flight inspection/checks, maintain a stable airspeed, cruising altitude, and heading, navigate by applying systematic navigation techniques, and orient the UAV to the direction of flight. The pilot must also be able to correctly program the UAV for a "return to home" if it is equipped with that function, select a power setting and altitude appropriate for the lost link situation, and promptly recognize when a lost link has occurred. Other skills and knowledge required include the ability to perform the tasks of identifying and recording their present position, estimating the approximate available flight time that will remain with the fuel/power on board upon arrival at the destination, and without delay contacting the appropriate facility to provide information on the "fly away" if needed. Additionally, the pilot must use an organized and efficient procedure to land, comply with all arrival clearances and instructions, complete appropriate checklists, note landing time, and secure the UAV [43]. Lastly, advanced operations can only be done by TC approved UAV [49]. This program is called RPAS Safety Assurance and requires manufacturers to make a declaration which states that their UAV is in accordance with advanced operations technical requirements. TC provides a complete list of all RPAS Safety Assurance compliant UAV for pilots looking to conduct advanced operations.

1) Special Flight Operations Certificate (SFOC): In accordance with CAR 903.02 any pilot seeking to conduct UAV operations that fall outside of the definitions for basic and advanced operations must have a SFOC. This certificate is mandatory for foreign operators, special events, flying near military airports, flying beyond visual line-of-sight, drones over 25kg (55lbs.), higher altitudes, hazardous payloads, and flying more than five drones at once [51], [52]. Applications for an SFOC consist of the purpose, dates, alternate dates, and times of the operation, along with the manufacturer and model of the system, complete with three-view drawings or photographs of the aircraft, performance, operating limitations, and equipment. A safety plan for the proposed area of operation and an emergency contingency plan must be described, as well as a detailed plan for how the operation is to be carried out. The names, certificates, licenses, permits, and qualifications of crew members, including pilots, visual observers, and UAV maintenance personnel must also be given. Instructions for system maintenance and how that maintenance will be performed must also be included. Descriptions of weather minima for the operation, separation and collision avoidance capability and procedures, normal and emergency procedures for the operation, and ATC services coordination, if applicable, must also be provided. Lastly, any other information requested by the Minister relevant to the safe conduct of the operation must be submitted [41].

B. Certification

As mentioned above, all advanced operations require RPAS Safety Assurance, which is governed by CAR Standard 922. This standard seeks to set out the minimum technical requirements that each UAV manufacturer must meet to be safety certified in Canada. Current codified sections refer only to operations in controlled spaces, and operations near people. Under regulation 922.04: Operations in Controlled Airspace, the UAV must have a lateral positional accuracy of ± 10 m (32.8ft) and an altitude accuracy of ± 16 m (52.5ft). Regulations 922.05 and 922.06 relate to minimizing injury to any persons near the UAV during operation by stating that the occurrence of any single failure of the UAV that may result in severe injury to a person within 30 m (98.4ft) or 5 m (16.4ft) horizontally must be shown to be remote. Furthermore, the systems, controls and associated monitoring and warning must be designed in a way as to minimize UAV pilot errors that could create additional hazards.

Under Division II of Standard 922: Technical Requirements – Operations within VLOS, only the regulations have been published and codified by TC and the Government of Canada. Sections dealing with certification for basic operations (922.02), operations over critical infrastructure (922.03), and all of Division III: Technical Requirements – Operations Beyond Visual Line of Sight (BVLOS) are labeled as reserved, which means that they are still under development by TC [53]. With this ongoing development worldwide, National Aviation Authorities (NAAs) have come together to create an advisory committee to consider and draft certification and regulation bases which can be used as a framework for national policy. The JARUS is an ICAO-recognized group that aims at drafting regulations to cover all aspects of unmanned aircraft systems operations [54]. Its members include several NAAs including TC, Federal Aviation Authority (FAA) and the European Union Aviation Safety Agency (EASA). JARUS 2019 report "Recommendations for Certification Specification for Unmanned Aircraft Systems" is the backbone for the development of many UAV certification regulations worldwide [55]. Subsequent sections discuss JARUS recommended regulations for certification of UAV.

1) General Regulations: JARUS defines the applicability to these regulation recommendations as any UAV which does not exceed 3,175 kg (7,000 lbs.) maximum takeoff weight (MTOW) for VTOL aircraft, and 8,618 kg (19,000 lbs.) for aircraft without VTOL capabilities [56], [57]. The manufacturer must define the limitations of operation under normal and emergency conditions. Operation conditions must consider environmental factors such as temperature, humidity, wind, and rain when determining limits. Not exceeding limitations must be a part of the integrated flight system on the UAV. In the case that the UAV is designed in a modular fashion, or intended to be disassembled and transported, the manufacturer must provide complete disassembly/assembly, storage, and handling documentation. Furthermore, incorrect assembly must be avoided by proper design and the transportation must not adversely affect the airworthiness of the UAV. The manufacturer is required to provide comprehensive documentation of testing data or system compliance within established operating limits, in order to verify adherence to both earlier and later compliance specifications.

2) UAV Operations: The manufacturer must determine the boundaries of the approved flight envelope, clearly demonstrating areas of safe flight, flight under abnormal conditions, and flight under emergency conditions. Different UAV flight envelopes are as depicted in Fig. 5. The regulation outlines various requirements wherein the manufacturer seeking certification for the operation of UAV must demonstrate compliance. Among these requirements are the determination of minimum speeds for each flight configuration and phase, minimum performance requirements for take-off and other critical flight phases, minimum climb and rate of descent performance, landing area requirements, approach and landing speeds, and procedures, as well as controllability and stability requirements for the UAV. All performance parameters must be determined for normal, abnormal, and emergency conditions to demonstrate safety considerations by the manufacturer.

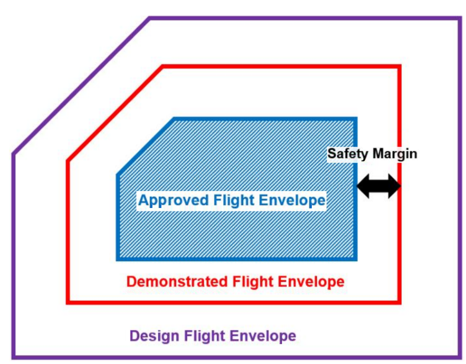

Fig. 5. UAV flight envelopes.

3) UAV Structures: Regarding UAV structure, the manufacturer must establish a structural design envelope which describes the range and limits of the design. The manufacturer must consider flight and ground loading conditions, mass variations and distributions over the applicable center of gravity envelope and loads in response to control inputs. Flight load conditions must be established and must ensure that all critical loads are established, vibrations and buffeting does not result in structural damage within the boundaries of the flight envelope, and flight loads resulting from likely failures are determined. Furthermore, structural design loads from taxi, takeoff, launch and handling must be determined. Under this regulation proposal, the manufacturer must develop and implement inspections or procedures to prevent structural failures which could be catastrophic. For UAV with pressurized compartments, the aircraft must be designed to be capable of continued safe flight in the event of rapid depressurization.

Critical parts are described as any part of a UAV, the failure of which would endanger continued safe flight, landing or emergency recovery. For any such parts, the manufacturer must establish a critical parts list. Procedures must be established for these critical parts to determine compliance with quality assurance requirements. Moreover, the manufacturer must establish a unique safety factor for critical design values that are uncertain, as well as for parts or assemblies that are likely to deteriorate before normal replacement or are prone to significant variability due to uncertainties in manufacturing processes or inspection methods. To determine the safety factor, the applicant must consider quality controls and specifications that account for the type of application, inspection method, structural test requirement, sampling percentage, and process and material control. Finally, the applicant must multiply the highest applicable safety factor for each part of the structure by using the limit load and ultimate load. If there is no limit load, the applicant is expected to use the ultimate load alone.

4) UAV Design and Construction: The manufacturer must ensure that the flight control systems operate smoothly and effectively, with trim systems designed to prevent inadvertent operation. Take-off and landing devices must provide stable support, account for system failures and environmental factors, and absorb kinetic energy. If necessary, the UAV must demonstrate aborted take-off capability, and must be able to keep landing devices in place. For operations on water, the design must ensure adequate buoyancy to support take-off and landing. The UAV must be designed to minimize the risk of fire initiation due to anticipated energy dissipation or ignition of flammable fluids. This is to be minimized through adequate fire or smoke detection and notification to the operator and if possible or the application of self-extinguishing or utilizing fireproof materials. In areas where the likelihood of lightning exposure is high, a UAV that is being certified for operation must have measures in place to protect it from the destructive effects of lightning. For UAVs that are not certified for such conditions, restrictions on flight, including take-off and landing, must be put in place to prevent them from being exposed to lightning. Electrical and electronic systems on a UAV must be designed to protect against lightning. Systems that are essential for safe flight and landing or emergency recovery must be designed to function properly during and after lightning exposure, with normal operation recovery in a timely manner. Systems that significantly reduce the UAVs capability or the crew's ability to respond to adverse conditions must also recover normal operation after lightning exposure. In case an emergency procedure requires a forced landing or controlled crash into a specific area, the following rules must be followed: (a) The UAV design should include enough features to minimize the risks arising from potential debris, fire, or explosions that could spread beyond the designated landing or crash zone. (b) The Flight Manual for the crew must provide information about the forced landing or controlled crash area's characteristics.

5) UAV Systems and Equipment: UAV equipment, systems and networks must be protected from intentional unauthorized electronic interactions (cybersecurity). All on-board power generation, storage and distribution must be designed to supply the power required for all approved operating conditions and ensure that no single failure will prevent the system from supplying the essential loads for continued safe flight. The manufacturer must ensure that equipment with high-energy rotating parts must be designed or installed in a way that prevents damage to other systems or structures in the event of failure. If recording is required, the system must accurately record and safeguard the necessary data including emergency events. The UAV must also have emergency recovery capabilities and procedures in place to prevent fatal injuries to people on the ground or in the air, as well as damage to critical infrastructure.

6) UAV Crew Interface and Other Information: This regulation outlines requirements for the remote pilot station and associated equipment in operating a UAV. The remote pilot station must be designed to support command and control of the UAV for the intended operations and qualify against expected environmental conditions. The equipment must also be designed to minimize errors that could result in additional hazards, and physical security must be considered. Additionally, the manufacturer must provide a UAV flight manual containing information such as operating limitations and procedures, performance information, loading information, and instrument marking and placard information necessary for the safe operation of the UAV. The manual must also include limitations for transportation, reconfiguration, and storage. Installed systems must provide the remote crew with necessary information to operate the UAV during each phase of flight, and not inhibit primary displays of flight or powerplant parameters. These systems must also be designed to ensure continued safe flight and landing or emergency recovery in the event of a single failure or probable combination of failures.

C. International Regulatory Frameworks

1) European Union Aviation Safety Agency (EASA): The regulation of UAV operation in European countries is mandated through EASA and is done proportionally to the associated risk of the specific operation [58], [59]. Their current regulation separates operations into "open", "specific", and "certified" risk levels which come with differing levels of authorization and bureaucracy. Like Canadian regulations, registration is not required for UAV $<$ 250 g (0.55lbs.) and required for all else. EASA believes that this regulation framework both prioritizes the safe integration of UAV into the aviation system as well as fosters innovation and a competitive

UAV industry in Europe. The open category allows low-risk drone operations that do not involve aviation authorities, even for commercial purposes. Operators and pilots do not need licenses or approvals, and the focus is on simple operations for small and medium-sized enterprises to gain experience. To fly in this category, drones must be flown within VLOS, below 150 m altitude, and outside specified reserved areas. Flying over crowds is not allowed, but flying over unrelated individuals in populated areas is permitted. Although airworthiness approval is not required, industry standards can be used, and UAV with safety features like parachutes and software redundancy that are already available [60], [61]. The open category is further subdivided into 3 subcategories: A1, A2, and A3. A1 is defined as flight over people but not assemblies, A2 as flight close to people, and A3 flight far from people. UAV weight below 250 gm has a subcategory of A1. No flight over uninvolved people (minimize duration if it occurs) and no training is required. UAV weight between 250 and 500 gm has a subcategory of A3. No flight over assemblies of people and the operator should read carefully the user manual as well as complete training and pass nationally defined exam. UAV weight between 500 gm and 2 kg has a subcategory of A3. No flight over uninvolved people and no flight over assemblies of people. The operator should read carefully the user manual and complete training and pass a nationally defined exam. UAV weight between 2 and 25 kg has a subcategory of A3. No flight near or over people Flight at least 150 m away from residential, commercial, industrial areas and training is required.

The specific category is for operations that require additional limitations or higher capability of the equipment and personnel, beyond the open category. Operators are required to perform a safety risk assessment and identify mitigation measures, which will be reviewed and approved by the applicable national aviation authority, unless the operator is approved to approve its own safety risk assessment. The safety risk assessment covers airworthiness, operating procedures and environment, personnel competence, and airspace issues. The level of safety for airworthiness is based on acceptable industry standards, and the competence of the involved staff, established through specific training or licensing. An operations manual is required to define the operating procedures, airworthiness level, personnel competence, and the type of airspace. The specific category is required when an operation poses significant aviation risks to persons overflown or involves sharing airspace. Examples of conditions resulting in specific categories include BVLOS flight, UAV with MTOW $>$ 25 kg, flight at altitude $>$ 120 m [62], [63].

The certified category is intended for operations that pose the highest risk, such as future drone flights carrying passengers like air taxis. The third component of the regulatory framework is similar to the regulations for manned aircraft because when drone risks are similar to manned aviation risks, they need to be classified as certified operations and treated accordingly with multiple certificates issued. For drones weighing over 150kg, a Type Certificate, individual certificate of airworthiness, and individual noise certificate needs to be issued. Design and production organizations need to be approved, and certification specifications are adopted for different configurations [64].

2) Federal Aviation Administration (FAA): The United States' FAA regulates UAV in a very similar manner to Canada, with its regulations codified under the Code of Federal Regulations (CFR) Title 14 Part 107: Small Unmanned Aircraft Systems. The regulations contained in this part are for operating UAV that weigh less than 55 pounds, in Class G airspace, within VLOS, at or below 400ft, and during the daytime. Regulations prohibit UAV from flying at speeds above 100mph and over people, although this may be permitted depending on the level of risk presented by the operation to individuals on the ground [65]. Operations over persons on the ground are separated into 4 categories of operation (numbered 1 through 4). Small, unmanned aircraft falling under Category 1 may fly over people as long as they weigh 0.25kg (0.55lbs) or less and have no exposed rotating parts. Category 2 and 3 operations have specific eligibility and operating requirements for unmanned aircraft that weigh more than 0.25kg (0.55lbs) but do not have an airworthiness certificate under Part 21. Category 3 has further restrictions, including not allowing small, unmanned aircraft to fly over open-air assemblies of human beings, except in specific cases like being inside a stationary vehicle or a covered structure that can provide protection [66], [67].

Category 4 allows small, unmanned aircraft with an airworthiness certificate under Part 21 to operate over people, provided that they meet additional requirements to ensure continued airworthiness and reliability. Note that a brief, one-time transiting over a portion of an assembled gathering, which is incidental to a point-to-point operation unrelated to the assembly, does not count as sustained flight over an open-air assembly [66]. CFR 14 Part 21 relates to certifications procedures for products and articles and is the governing regulation which certifies manned and unmanned aircraft. UAV wishing to undergo category 4 operations must receive type certification, product certification, and airworthiness certification to comply with regulations, similar to manned aircraft [68], [69]. Whilst 14 CFR Part 107 is only applicable to UAV weighing less than 25kg (55lbs), to fly a UAV that exceeds this limit, the pilot may apply for an exemption under 49 US Code (USC) Section 44807: Special Authority for Certain Unmanned Systems. The application for this exemption consists of concepts of operations, operations manual, emergency procedures, checklists, maintenance manual, training program, flight history, and safety risk analysis. If the proposal includes complex operations such as flying over or near people, BVLS, or multiple UAV operations, a safety risk analysis is required. To apply for operational approval for specific airspace, the operator must apply for a Certificate of Waiver or Authorization (COA) [70].

V. Comparison of UAV Technology based on Safety and Reliability

UAVs have gained popularity due to their versatility and affordability. When assessing UAV technology based on safety and reliability, several factors must be considered. These include flight stability, redundancy, collision avoidance, battery life, and remote control. Generally, UAVs that prioritize safety and reliability are more expensive than those that do not. However, the extra cost may be justified in industries where safety and reliability are paramount, such as military or commercial settings. Subsequent sections explore UAV technologies that improve the aforementioned factors, which are crucial for the future of UAVs. By enhancing UAV safety and reliability through these technologies, we can ensure safer and more dependable use of UAVs in various applications.

A. Flight Stability

The evolution of flight stability in UAVs has been an ongoing process of improving the design and functionality of the aircraft [5], [71]. Initially, UAVs were manually controlled by human operators using remote controls or onboard controls. However, this required a lot of skill and attention to maintain a stable flight path [71]. As technology advanced, autopilot systems were developed to assist in maintaining stability during flight. With the emergence of UAV autonomy, flight stability has been further improved. Autonomous UAVs use a combination of human-directed and autonomous drone operations to achieve a higher level of independence [5], [71]. This has led to the development of Intelligent Outer-Loop Control (IOLC) systems that can operate autonomously or semi-autonomously without predefined guidance from human interaction. The IOLC is capable of monitoring and controlling not only the UAV's critical functions but also its communications, sensor payload, and other subsystems, which enables it to meet complex mission goals [72]. Additionally, advancements in sensors and Artificial Intelligence (AI) have enabled UAVs to adapt to changing environmental conditions in real-time, which has further improved flight stability. For example, UAVs can now detect and avoid obstacles during flight, which helps prevent crashes and maintain stability. Overall, the evolution of flight stability in UAVs has been driven by advances in technology and the need for greater autonomy in unmanned aircraft. As technology continues to advance, we can expect to see even more improvements in flight stability and overall UAV safety and reliability.

B. Redundancy

Redundancy is an important aspect of UAV technology that ensures the reliability and safety of the aircraft. Redundant systems, such as having multiple motors or power sources, make the UAV more reliable because they can help maintain the UAV's operation in case of a system failure. For example, when implementing LiDAR technology onto a UAV, it requires more power resources to compensate for the power need and added weight of the LiDAR sensors. To ensure safety and reliability in operations, modern UAVs that implement LiDAR technology are designed with redundancies. The Sky front Perimeter 8 gasoline-electric hybrid multi-copter is an example of a UAV with a redundant system. It has both hybrid and electric engines for both motors, which provide complete engine redundancy for safety. Flight navigation systems on autonomous UAVs must comply with JARUS worldwide regulations to adapt to software or hardware failures and maintain an acceptable level of safety. Fail-safe technology is crucial for any drone to be reliable. One common redundancy is identifying the drone's position. In case of GPS failure, autonomous drones must be equipped with an Indoor Positioning System (IPS), such as Bluetooth antennas, Wi-Fi, digital cameras, or LiDAR, which can identify the UAV's location independent of GPS. In some cases, purpose-built infrastructure can be built around the area of operation to further enhance the redundancy of the UAV's navigation system [73], [74].

C. Collision Avoidance

As UAVs become more prevalent, the risk of collisions with obstacles such as buildings, trees, and other aircraft also increases. Collision avoidance is therefore a crucial aspect of UAV technology that directly impacts their safety and reliability. In this context, exploring the different categories of collision avoidance and their importance in UAV operations, with a particular focus on the role of LiDAR technology is necessary. Collision avoidance is a critical aspect of safety and reliability in UAV technologies. It involves two main categories: perception and action. Perception, which is the detection of obstacles, can be achieved using sensors, classified into two categories: active and passive sensors. Active sensors emit their own source of light waves and read back the reflections, while passive sensors read only what is reflected from other objects, such as a camera or infrared camera. The next step is action, which is based on the information gathered during the perception stage. The action can be categorized into geometric, force-field, optimized, and sense-and-avoid actions. Geometric action involves using the UAV's location information to avoid obstacles, while force-field action uses attractive and repulsive forces to maneuver around obstacles. Optimized actions are based on known parameters that can be used to avoid obstacles, while sense-and-avoid actions rely on real-time decision making for obstacle avoidance based on data from the sensors. Fig. 6 shows the stages of perception, localization and filtering, motion planning, and obstacle avoidance.

LiDAR technology is one of the most advanced and reliable systems used for collision avoidance in UAVs. It emits laser beams that bounce off objects and surfaces, creating high-resolution 3D maps of the surrounding environment. LiDAR technology provides accuracy and precision in capturing data, which is crucial for safety operations when detecting potential hazards and preventing accidents. This feature greatly improves the ability to navigate complex environments, especially when operating in hazardous or populated areas. In summary, collision avoidance is crucial for safety and reliability in UAV technology. It involves the detection of obstacles through sensors and real-time decision making for obstacle avoidance. LiDAR technology is one of the most advanced systems used for collision avoidance, as it provides high-resolution 3D maps that improve accuracy and precision in navigating complex environments.

D. Operation Time

One way to enhance the safety and reliability of UAVs is by increasing their operational time. Longer flight times

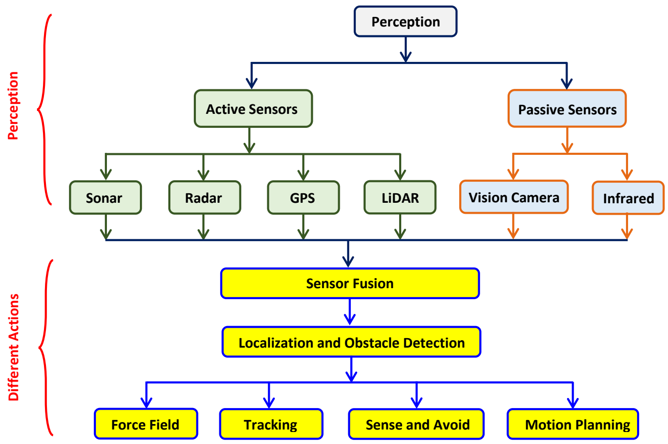

Fig. 6. Stages of perception, localization and filtering, motion planning, and obstacle avoidance.

reduce the number of take-offs and landings, which are the most common causes of accidents. This section focuses on the relationship between the operational time and safety and reliability of UAVs [18]. The operational time of UAVs depends on their power sources. There are several power sources available in the market, including solar power, hydrogen fuel cells, batteries, and traditional combustion engines [18]. Each power source has its advantages and disadvantages, and choosing the appropriate power source for a UAV depends on various factors, including flight time, payload capacity, and environmental impact.

Batteries are commonly used in recreational UAVs due to their portability and rechargeability. However, their low energy density limits the flight time of the UAV. Hydrogen fuel cells have a higher energy density, resulting in longer flight times, but the technology is currently limited to larger UAVs due to its size and weight [18]. Traditional combustion engines provide high operational time, but they are noisy and require regular maintenance, making them unsuitable for recreational UAVs. Solar power is a new technology in the UAV industry that requires more research. Solar panels require a lot of sunlight, and the technology is more expensive than other power sources. LiDAR is a technology that provides several benefits but when used in UAVs it can reduce the operational life of the UAV due to its added weight and power requirements. The choice of power source for a UAV depends on various factors, including the desired flight time, payload capacity, and environmental impact. Increasing the operational time of UAVs can enhance their safety and reliability by reducing the number of take-offs and landings, which are the most common causes of accidents.

E. Remote Control

Safety and reliability are crucial factors that must be considered when operating UAVs, especially near populated or hazardous environments. Remote control technology plays a critical role in the safe operation of UAVs. In the past, UAVs were operated manually, like conventional aircraft. However, advancements in automation have made it easier for operators to control UAVs remotely. The use of immersive VR displays has further improved the remote-control characteristics of UAVs. Studies have shown that using VR displays during UAV operations has a positive impact on in-depth tasks, which require greater accuracy and precision. Moreover, the combination of automation and VR displays has resulted in better understanding of the operating environment and mechanics of the UAV from a remote setting. NASA has successfully used this technology to improve the usability of UAVs for complex 3D tasks. In disaster emergency response, the use of VR technology in UAVs has been crucial in providing users with a view of the 3D surroundings, which improves the efficiency of rescue operations. The use of automation and immersive VR displays has greatly improved the usability and accuracy of UAVs during complex tasks. The development of more advanced remote-control technology will undoubtedly improve the safety and reliability of UAVs in the future.

VI. Trade off Studies in UAV systems

When comparing UAV technologies, it is important to understand the following factors that will be compared that relate to safety. These factors include reliability, redundancy, robustness, compliance with regulations and human oversight. The system should be reliable and have a low failure rate to minimize risk of accidents. The results of the trade-off study will provide valuable insight into the design and selection of safe and reliable systems for UAVs, helping to mitigate risks associated with UAV operation and ensure their successful deployment during their specific operation. The system should have redundant components to ensure that in that case that one fails. The system should be robust and can withstand environmental disturbances such as wind gusts, turbulence, or electromagnetic interference. It should be able to adapt to changing conditions. The system should comply with relevant regulations such as airspace regulations, altitude limits, and collision avoidance rules. Finally, the system should incorporate a level of human oversight to ensure that the human operator can intervene if necessary. Safe UAVs should incorporate all these safety parameters during operation.

A. Power Supply Trade off Study

Fundamentally in the comparison of power systems utilized in UAVs, the main goal is to identify which power system used in UAV application has the most positive impact on safety and reliability in regular operation. A trade off study will be performed on four different power systems that are commonly used on UAVs. Battery power (Li-Ion and Li-Po), Combustion power (Petrol and Diesel), Hydrogen Fuel Cells (FCs).

Table II compares reliability, redundancy, robustness, compliance with regulations, and human oversight of different energy sources for UAVs. This trade-off study evaluates the performance of electric batteries for powering UAVs. While they are compliant with regulations and have moderate reliability and redundancy, they are not very robust and have limited endurance, reducing their ability to run autonomously. Due to these characteristics it is apparent why batteries are the most utilized power source in non-military applications with a

TABLE II
COMPARISON OF DIFFERENT 5KG PAYLOAD CAPACITY UAV WITH DIFFERENT FUEL SOURCES [18].

	UAV-based Battery Power (Li-Ion and Li-Po)	
	Description	Score
Reliability	Moderate reliability, low power and energy density, prone to power fluctuations and require frequent recharging.	6
Redundancy	Moderate redundancy, multiple batteries instead of one unit, and combined with FCs.	6
Robustness	Less robust (extreme hot or cold conditions may either drain the battery or pose risks).	4
Compliance	Compliant with strict regulations and widely used in nonmilitary applications.	9
Oversight	Limited endurance and range, but monitoring battery levels can enhance efficiency.	7
Total (out of 50)		34
	UAV-based Combustion Power (Petrol and Diesel)	
	Description	Score
Reliability	Engines have a high reliability and require less regular maintenance.	8
Redundancy	Hybrid combustion is comparatively much more complex and environmentally taxing.	2
Robustness	Bulk combustion power is very robust and able to withstand harsh environments.	9
Compliance	Regulated more strictly than other power types due to the dangerous nature. Special authorization is required to be flown.	5
Oversight	High power to weight ratio and long operating time. Complex mechanical nature reduces their ability to be ran autonomously.	3
Total (out of 50)		27
	UAV-based Solar Power	
	Description	Score
Reliability	If sunlight conditions rapidly change, the UAV may be at risk of power loss.	3
Redundancy	Offers low redundancies but can be combined with FCs to improve redundancy.	3
Robustness	Typically operate at high altitudes good fit for extreme weather conditions.	7
Compliance	Comply with strict regulation and can be used in urban areas.	7
Oversight	Require low human oversight due to their simple design.	9
Total (out of 50)		29
	UAV-based Hydrogen FCs Power	
	Description	Score
Reliability	Flow decay, thermodynamic characteristics, and capacitance effect may result in FC systems experiencing fuel starvation.	6
Redundancy	FCs comparatively redundant (multiple cells) and combined with batteries or solar power.	8
Robustness	Require careful handling to prevent accidents. Onboard hydrogen tank is susceptible to leaks and may explode if not handled properly.	3
Compliance	CSA/ANSI Hydrogen Gas Vehicle 2 (HGV 2) standard and the European Union have specifications for the pressure of hydrogen stored however not well defined.	6
Oversight	Long range and endurance compared to batteries. Require high human oversight to ensure proper handling to avoid malfunctions.	6
Total (out of 50)		29

score of 34 out of 50. Combustion power is a moderately safe and effective source of power for UAVs with a score of 27 out of 50 however, they may be dangerous with untrained pilots and urban areas. They have high reliability and robustness, but limited autonomy due to their complex mechanical nature. They are strictly regulated and require special authorization to be flown. Solar power is a very safe and environmentally friendly power source for UAVs with a rating of 29/50. While solar-powered UAVs comply with regulations, operate at high altitudes, and require low human oversight, they have low redundancies, and may be affected by changes in sunlight conditions. FC power achieved a score of 29 out of 50 demonstrating its viability as a UAV power source. FC power offers high redundancy, may require careful handling to prevent accidents and require proper human oversight to ensure their proper functioning. They also face regulatory compliance challenges. FC technology and infrastructure is still in its early stage of development and as technology improves it will prove to be a very safe and effective source of power for UAVs. Through the conducted trade studies above battery powered UAVs received the highest score of 34 out of 50.

While battery powered UAVs lack a long endurance and are particularly vulnerable in unfavorable weather conditions they were demonstrated to excel in every category except for robustness. Due to Electric batteries characteristics, they are the most widely used source of power in nonmilitary UAV application. Gasoline-powered engines offer high reliability and robustness but may not comply with strict regulations, this is demonstrated with their high use in military applications due to operators requiring a higher level of training. Solar cells can be highly robust, compliant with regulations and autonomous, but their safety is compromised with low reliability and redundancies. Hydrogen fuel cells offer moderate reliability and redundancy, but due to their novelty their use may require additional safety measures, and with future development their limitation may be reduced. Ultimately, the decision on which power source to use must consider the specific needs and requirements of the UAV.

B. Navigation System

Table III compares reliability, redundancy, robustness, compliance with regulations, and human oversight of UAV Navigation techniques. When comparing navigation systems, the main goal is to identify which navigation system used in UAV application has the most positive impact on safety and reliability in regular operation. A trade off study will be performed on three different navigation systems that are commonly used on UAVs. A localization navigation system is a system that helps autonomous UAVs to determine their position and orientation in each environment. It typically uses sensors and cameras like LiDAR, radar and GPS to measure the vehicles movement and surroundings and processes this data to determine the UAVs location in real-time. This information is then used by the vehicle's control system to plan and execute movements or tasks. Localization navigation is a moderate source of navigation with a score of 34 out of 50. Localization navigation provides accurate position estimates but suffers from time drift and interference. Different techniques can be combined to create redundancy. Radar-based localization is robust against weather effects, but magnetic-based localization is susceptible to interference. Localization systems are developed in compliance with local aviation regulatory bodies. Magnetic-based localization is easy to set up and deploy and is operational independent of human interaction.

TABLE III
LOCALIZATION NAVIGATION SYSTEM TRADE OFF STUDY [27], [73].

	Inertial units-based UAV Localization	
	Description	Score
Reliability	Inertial-based localization suffers from time drift and magnetic-based localization is prone to interference (errors in position estimates).	4
Redundancy	Different localization techniques can be combined via sensor-fusion to improve navigation performance and create redundancy.	7
Robustness	Robust against weather effects (good for outdoor navigation) but is susceptible to magnetic interference.	7
Compliance	Developed in compliance with local aviation regulatory bodies.	10
Oversight	Operational independent of human interaction which are easy to set up and deploy.	6
Total (out of 50)		34
	GNSS-based UAV Navigation	
	Description	Score
Reliability	GNSS/GPS can estimate receiver clock, atmospheric and tropospheric effects, and geographic coordinates, resulting in less error. Not applicable for indoor missions.	9
Redundancy	Multiple satellites used in GPS positioning improve redundancy and time-delay accuracy.	9
Robustness	Widely used and able to provide continuous positioning even during GNSS outages. Spoofing, multipath, and signal-denial are persistent critical challenges in outdoor missions.	8
Compliance	Regulated by ICAO and Transport Canada (see ICAO document 9849 "GNSS Manual").	9
Oversight	Human oversight is involved in interpretation of GNSS data.	8
Total (out of 50)		43

Based on the provided trade off study tables, GNSS navigation has the highest score of 43 out of 50, indicating that it is the most favorable navigation system in terms of the categories of reliability, redundancy, robustness, compliance with regulations and human oversight. GNSS navigation is particularly reliable compared to the UGV navigation and Localization navigation due to its precise positioning capabilities and use of multiple satellites for redundancy. UGV navigation has limitations in the categories of robustness and reliability which comes from its over-dependence on automated technologies. UGV navigation would be a suitable choice for operation in areas which can be seen as harmful for humans, or property. Ultimately the choice on which navigation system is better is based on specific requirements and constraints for a given application.

C. Optical Sensors Trade off Study

In the comparison of optical sensors, the main goal is to identify which optical sensor used in UAV application has the most positive impact on safety and reliability in regular operation (see Table IV). A trade off study will be performed on four different optical sensors that are commonly used on UAVs. The RBG camera, LiDAR sensor, Thermal sensors, and Hyperspectral sensors. Cameras are the most used optical sensors in UAVs. They capture images of the terrain and are used to create maps and 3D models of the environment. Cameras can also be used to detect obstacles, such as trees or buildings, and to track the UAV's position relative to the ground.

TABLE IV
COMPARISON OF DIFFERENT 5KG PAYLOAD CAPACITY UAV WITH DIFFERENT FUEL SOURCES [32], [33], [36], [38].

	RGB Cameras	
	Description	Score
Reliability	Typically dependable and can be impacted by lighting conditions and find difficulties in inclement weather.	7
Robustness	Can be easily damaged by physical impacts or harsh weather conditions, and sensitive to dust which affects image quality.	6
Compliance	Obey majority of UAV laws but subject to privacy and data protection limitations.	9
Oversight	Simple to integrate into autonomous systems, but images require processing and analysis.	7
Total (out of 40)		29
	LiDAR Sensors	
	Description	Score
Reliability	Extremely dependable and can deliver precise 3D mapping data even in bad weather but expensive.	9
Robustness	Withstand physical impacts and harsh weather but prone to vibration and need protection from dust and environmental factors.	8
Compliance	Compliant with most regulations but require additional permits / clearances due to laser interference with other systems.	7
Oversight	Fit for autonomous systems, but processing and analyzing require sophisticated software and hardware.	9
Total (out of 40)		33
	Thermal (Infrared) Sensors	
	Description	Score
Reliability	Reliable and can sense heat even in complete darkness. More expensive than conventional sensors, but require calibration.	8
Robustness	Withstand physical impacts and harsh weather but sensitive to vibration and require protection from environmental factors.	8
Compliance	Compliant with most regulations but may require additional clearances due to radiation emissions and safety.	8
Oversight	Simple to integrate into autonomous systems, but processing and data analysis require additional software and hardware.	8
Total (out of 40)		32
	Hyperspectral Sensors	
	Description	Score
Reliability	More susceptible to variations in lighting, which might impair their accuracy.	5
Robustness	Sensitive to physical impacts or weather conditions and require careful handling and protection to maintain accuracy.	7
Compliance	Require additional permits or clearances (due to data they capture) and privacy and data protection pose concerns.	6
Oversight	The data is more difficult to integrate into autonomous systems.	6
Total (out of 40)		24

According to the study, RGB cameras are a safe and effective sensor to navigate terrain with an overall score of 29 out of 40. RGB cameras are generally dependable but may struggle with low-light or inclement weather conditions. They are not very robust and may be sensitive to environmental factors that can affect image quality. However, they are compliant with UAV laws and can be easily integrated into autonomous systems. With their inexpensive cost it is easily proven how RGB cameras are the most used optical sensors in UAVs, being particularly effective at capturing images of the terrain, creating maps and 3D models of the environment such as obstacles as well as tracking the UAV's position.

Based on our study findings, LiDAR sensors are a safe and effective sensor for UAV use with an overall score of 33 out of 40. Unlike RGB cameras they can deliver precise 3D mapping data even in low light or bad weather. They are generally more robust than RGB cameras but may still require protection from environmental factors. LiDAR sensors are compliant with most regulations but may require additional permits or clearances due to the potential for laser interference with other systems. Although LiDAR sensors require more sophisticated hardware and software for processing and analyzing data, they excel at jobs that require real-time 3D mapping and obstacle recognition. In addition, despite being costly, LiDAR sensors are excellent at navigating terrain and are proven to be highly effective.

Thermal sensors are safe and useful with an overall score of 32 out of 40. Thermal sensors are reliable and can sense heat even in complete darkness but may require further calibration for precise results. They are generally more robust than hyperspectral sensors but may still be sensitive to environmental factors. Thermal sensors are compliant with most regulations but may require additional clearances due to safety concerns. Although thermal sensors are simple to integrate into autonomous systems, processing and data analysis may require additional hardware and software. While thermal sensors may be costly, they are particularly effective in scenarios with temperature differences, which can be used to identify potential obstacles or hazards, such as fires or hot power lines.

While hyperspectral sensors received a lower score than the other sensors with 24 out of 40, they are still considered safe and practical for drone use. They require regular maintenance, may be sensitive to lighting, are not very robust, and require careful handling. They may require additional permits due to the specialized data they collect. They are difficult to integrate into autonomous systems but are appropriate for long-term monitoring initiatives. Although hyperspectral sensors received a low score, they have a niche application in monitoring changes in terrain over time. Overall, the trade-off study shows that LiDAR is the most reliable, robust, and autonomous sensor, but may have more regulatory restrictions. RGB cameras and thermal sensors are both reliable and compliant but may require more external light sources. RGB cameras also tend to be more vulnerable to physical damage compared to the other types of sensors. Hyperspectral sensors are less reliable and may require more human intervention but can provide unique data on the environment. The choice of sensor ultimately depends on the specific use case and the trade-offs between the above-discussed factors.

VII. Future Trends

The Future Trends provides an analysis of the evolving landscape of UAV technology. This section delves into emerging trends in safety and reliability, specifically focusing on flight control technology and automation technology. The analysis focuses on the future of UAV automation technology, with an examination of the regulatory landscape in Europe and its impact on the development of drone automation technology. Furthermore, the potential of regulatory frameworks in Canada to facilitate improvements and enhance accessibility within the rapidly growing UAV industry will be explored. This section uncovers the latest advancements and regulatory shifts moving the future of UAV technology forward and shaping the trajectory of the industry in the years to come both in Canada and worldwide.

A. Emerging Trends in UAV Technology

1) Emerging Trends in UAV Flight Control Technology: The future of flight control systems for UAVs is changing and current regulations need to be changed to meet demand. Safety and reliability are an increasing requirement for the future of FCS due to the growth of UAVs. As a result, stringent space, weight, and power requirements need to be met. The proposal involves the distribution of computing architectures with multiple different entities as it relates to microcontroller units (MCU). An MCU is a small computer that contains a single integrated circuit with a processor core, memory and input and outputs, and are commonly used in-flight control systems. MCU's have been developed in similar cases in the automotive sector. Opening the regulations and promoting collaboration in this technology can help continuing improvement in UAV flight control systems.

2) Emerging Trends in UAV Automation Technologies: Current UAVs already have a great variety of hardware and software. However, the success of UAV technology is largely due to the local regulations. As previously mentioned, JARUS initiative has brought together international regulatory bodies around the world to work together to improve oversee UAV development. One of the largest innovation categories in drone development is the rise of autonomy. Autonomous UAVs have many benefits which include not needing a pilot or drone operator, having greater operational efficiency, and reduced costs. UAV traffic and BLOS piloting technology are quickly becoming more popular with the potential to revolutionize the UAV industry. One of the most notable regulatory bodies monitoring the rise of UAVs is the Single European Sky ATM (Air Traffic Monitoring) Research (SESAR). SESAR views itself as the pillar of technology of the EU's single European sky policy. This policy in Europe is a reform in the European air traffic management system which is carried out on four different levels with the goal of improving Europe's airspace in terms of safety, efficiency, capacity, and environmental impact. SESAR defines and develops technology with the aim of transforming the European air traffic sector. Like JARUS, SESAR is a joint undertaking for European entities through a public and private partnership to accelerate research in technologies that can transform air traffic in the continent and make it more environmentally friendly. With this overall goal, SESAR is making itself a notable entity in the development of autonomous drones in Europe and setting the framework.

Enabling the Framework of Drone Automation: SESAR noted the positive effect that artificial intelligence and automation could have on the future of ATC systems and have begun implementing steps in research and development particularly in automation. And within these advancements in automation, one of the main focuses is on the development of this technology in UAVs. The result was the U-Space initiative. Drones are a growing industry in Europe and around the world, they deliver new services both in rural and urban areas and have many applications. Their presence in European airspace means that advancements in safety and reliability are necessary to ensure growth in this sector. Having a clear framework for autonomous drone services is key. U-Space is a set of high-level services that are based on digitalization and automation of functions that are specific to support safe and reliable drone development. U-space has been developed as a framework to support routine missions of drones. The initiative for the U-space blueprint was developed in 2017 with this vision of making autonomous drones more accessible and operationally possible through this framework [75]. The 2017 blueprint covered four sets of services to support the regulatory framework of drone development in the EU. With this U-Space blueprint framework, as the level of UAV automation increases the level of UAV connectivity between UAV and infrastructure also increases. This is necessary to ensure safe implementation of UAV automation in the future. U1 refers to U-space foundation services covering e-registration, e-identification and geofencing. U2 describes a U-space initial services for drone operations management, including flight planning, flight approval, tracking, and interfacing with conventional ATC. U3 refers to U-space advanced services supporting more complex operations in dense areas such as assistance for conflict detection and automated detect and avoid functionalities. Finally, U4 describes U-space full services, offering very high levels of automation, connectivity, and digitalization for both the drone and the U-space system.

The drone system functions are the essential functions that enable the drone to fly safely and reliably [72]. The U-Space framework is a set of guidelines that outlines the development and function of key components necessary for autonomous UAVs. The System Functions component is a critical part of the framework that ensures safe and reliable drone operation. System Functions are composed of several sub-components that work together to enable the drone to perform its core functions. Flight Control is one such sub-component, which includes intelligent mission management and intelligent outer loop control [72]. These capabilities ensure that the drone can fly safely and effectively, even in complex or challenging conditions. Flight Navigation is another important sub-component of System Functions. It includes planning and scheduling, contingency management, deconfliction fail-safe mission, and obstacle detection and avoidance. These features allow the drone to navigate through different environments while avoiding collisions or other hazards [72]. Positioning is also a key part of System Functions, and it includes indoor positioning, georeferencing, geofencing, and simultaneous localization and mapping. These capabilities allow the drone to locate itself accurately and precisely in different environments and navigate through them safely.

System and Environmental Status is yet another important sub-component of System Functions, which includes intelligent vehicle monitoring and intelligent data handling. These features enable the drone to monitor its own performance and environmental conditions and adjust as needed to ensure safe and reliable operation [72]. Coordination is also a critical aspect of System Functions, which includes swarm formation and cooperation, and UAV and UGVs coordination [72]. These features allow multiple drones to work together in a coordinated manner to achieve common objectives. Finally, Communication is a key sub-component of System Functions, which includes network-centric communications and over-the-horizon communications [72]. These capabilities enable the drone to communicate with ground-based operators and other drones, and to receive and transmit data in real-time. Figure below shows the system functions in a tree format for better understanding.

The Payload Technology aspect of the U-Space framework refers to the various types of sensors that are used in autonomous UAVs. These sensors are categorized into four groups: optical sensors, microwave sensors, initial sensors, and external sensors. Optical sensors can be further divided into two subcategories: active optical LiDAR and passive optical sensors. Active optical LiDAR sensors use lasers to create detailed 3D maps of the drone's surroundings, while passive optical sensors use visible light to detect objects. Microwave sensors are also divided into two subcategories: active microwave and passive microwave. Active microwave sensors emit microwave radiation and measure the time it takes for the signal to bounce back from surrounding objects, while passive microwave sensors detect naturally occurring microwave radiation. Initial sensors include various types of sensors, such as microsystems-based chemical sensor arrays, chemical detection sensors, meteorological data sensors, and CO_2 detection sensors. These sensors are used to measure environmental factors such as air quality, temperature, and humidity. Finally, external sensors are used to detect environmental factors outside of the drone's immediate surroundings. This includes geophysical sensors, weather stations, and perimeter sensors that are used to detect objects and obstacles in the drone's flight path. Overall, the Payload Technology aspect of the U-Space framework provides the necessary sensors and tools for autonomous UAVs to effectively sense and navigate their environment.

The U-Space framework includes a set of tools that are intended to support the development of autonomous UAVs. The first tool in this category is the Service Specification, which includes several subcategories. The User Requirements subcategory outlines the needs of the drone's user, such as payload requirements, flight duration, and data collection. The Acceptance Testing subcategory involves testing the drone to ensure that it meets the user requirements and that it can operate safely and effectively. The Data Analytics subcategory involves analyzing the data collected during drone flights to provide insights that can improve future drone development. Finally, the Mission Planning subcategory involves planning the drone's flight path and setting waypoints to ensure that the drone can navigate to its destination safely and efficiently [72]. The second tool in the "Tools" category is System Development, which also includes several subcategories. The System Requirements subcategory involves outlining the technical requirements for the drone's hardware and software, such as processing speed and storage capacity. The Design subcategory involves creating a detailed design plan for the drone, including its physical structure and its software architecture. The Implementation subcategory involves building the drone's hardware and software components, while the Integration subcategory involves bringing these components together to create a working drone system. Finally, the Validation and Verification subcategory involves testing the drone system to ensure that it meets the requirements outlined in the Service Specification and that it can operate safely and reliably [72].

B. Future of Regulatory Framework in Canada

The use of UAVs, commonly known as drones, has grown exponentially in recent years. As UAV technology continues to advance, regulations governing their operation and use are evolving as well. In Canada, UAVs are subject to strict regulatory frameworks aimed at ensuring safety and promoting responsible use. However, there is an increasing need for a more flexible and risk-based approach to UAV regulations that considers different parameters such as area, purpose, and visibility. In this section, we will explore the future regulatory framework for UAVs in Canada. We will discuss the current regulatory landscape, the challenges faced by various stakeholders, and the proposed changes and priorities outlined by TC for the future. The goal is to provide insights into the direction of UAV regulations in Canada and how they may impact the UAV industry, innovation, and consumers.

Canada is known to have one of the most stringent regulatory frameworks for UAVs in the world. Current regulations require all UAVs weighing between 250g and 25 kg to be registered with TC, and pilots of these vehicles must be certified. Additionally, operations involving UAVs over 25 kg require a SFOC, and only operations under the SFOC are allowed. These regulations pose significant administrative burdens and paperwork for both public consumers and commercial users of UAVs, which may deter their use for hobby or commercial purposes. In contrast, the European Union Aviation Safety Agency (EASA) follows a risk-based approach, where operations assessed to have low risk to the public and/or infrastructure are subject to less regulation, and some operations may not be regulated at all. Stocker et al. (2017) [76] identified various stakeholders who play roles and are affected by changes in the regulatory framework for UAVs. Government institutions and regulatory bodies have political mandates to ensure safety in the UAV space while promoting innovation. UAV researchers and manufacturers aim for technical advancements and seek to lower barriers to access the technology. End users have their own needs and market interests. The key challenge is to strike an optimal balance between the demands of these various stakeholders. The authors concluded that a risk-based approach to regulating UAVs seems to be the preferred approach for many NAAs. It is evident from research and discussions among various international regulating bodies that assessments and requirements are largely based on UAV weight. However, considering the diverse applications of UAVs, future UAV regulations will need to take into account other parameters such as area, purpose, and visibility (VLOS or BVLS).

Canada is currently a global leader in UAV regulations, having introduced comprehensive regulations for VLOS UAV operations in 2019 through CAR Part IX. This includes the launch of the Drone Management Portal to centralize pilot examinations and drone certification, as well as the establishment of the Safety Assurance Program to evaluate manufacturer compliance with technical standards for advanced operations. In a 2021 report by TC, the government outlined its vision for the future of the UAV space in Canada over the next 4 years. In this report, TC states that they are adopting a "safe innovation" approach to UAV regulation, which promotes progress and integration by providing a clear and predictable regulatory framework [75]. Their priorities include developing lower-risk BVLOS rules for operations in rural and remote areas, issuing medium-risk BVLOS SFOCs to test new technologies, and supporting projects and trials that inform the development of BVLOS rules. This safe innovation approach closely aligns with the risk-based approach, as TC demonstrates a commitment to reevaluating the "one-size-fits-all" approach of current regulations by taking into account the area, purpose, and visibility aspects of UAV flights as investigated by [76]. TC also aims to promote innovation by lowering the SFOC threshold to allow for experimentation by Canadian UAV innovators, taking into consideration the different actors in the UAV space. Furthermore, TC is dedicated to crafting harmonized UAV certification requirements by collaborating with the International Civil Aviation Organization (ICAO) and the JARUS, which would enable Canada to easily integrate into the international UAV market, both as innovators and consumers. Additionally, Canada has proposed amendments to CAR Part IX that would expand the existing VLOS regulations to incorporate heavier UAVs into the framework, likely requiring changes to the current operational levels (basic, advanced, special), but would still require pilots to demonstrate understanding and aptitude for the regulations and technical aspects of UAV operations.

The future regulatory framework for UAVs in Canada is expected to be more flexible and risk-based, considering different parameters such as area, purpose, and visibility. The "safe innovation" approach outlined by TC aims to promote progress and integration while ensuring safety. Lower-risk BVLOS rules, reduced SFOC thresholds, and harmonized certification requirements are among the proposed changes and priorities for the future. These changes are expected to have a significant impact on the UAV industry, innovation, and consumers in Canada. Stakeholders will need to stay informed and adapt to the evolving regulatory landscape to ensure responsible and compliant use of UAVs.

VIII. Conclusion

Safety and reliability are crucial aspects of UAV technologies, and regulations play a vital role in ensuring their safe and responsible use. The importance of regulations and certifications in the UAV industry, as well as the associated risks of UAV technologies, such as collision incidents have been highlighted. Safety occurrences and incidents in Canada and internationally have been analyzed, and a decline in incidents in Canada have been observed, which can be attributed to increased safety regulations. Global data provided by IATA also supports this trend of decreasing UAV incidents worldwide, indicating the positive impact of regulations on safety. A comparative analysis of different UAV technologies, including power supply, navigation, and optical sensors have been conducted. Batteries were found to be the most reliable power supply technology, while GNSS was identified as the most effective navigation technology. LiDAR was determined to be the best optical sensor due to its compliance with regulations and redundancies with other systems. The regulatory framework in Canada have been examined, comparing it with the risk-based approach followed by EASA. We found that current regulations in Canada are relatively strict, but the future trends indicate a shift towards adopting regulations similar to EASA's approach in conjunction with JARUS, an international organization working towards streamlining UAV regulations worldwide. Additionally, we highlighted emerging trends in technology, particularly automation and flight control technologies, with a focus on European regulations that are shaping the future of UAV trends in automation. By following the best practices of other regulatory bodies, embracing emerging trends, and adopting a risk-based approach, Canada can further promote the growth of the UAV industry while ensuring safety and reliability in UAV technologies.

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IX. Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

X. Data Availability

No data for this work.

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