Dynamic Risk Assessment of Unmanned Aerial Vehicles (UAVs)

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in
Engineering Management

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University of Alberta

Abstract:

Unmanned Aerial Vehicle (UAV) systems are increasingly being utilized in public airspaces, necessitating a high level of reliability to minimize risks to the general public. This research focuses on optimizing the probability of mission success by effectively analyzing and managing risks during various operational phases of UAV missions. Given the dearth of established reliability models for UAVs, a systems reliability modeling methodology based on the Structural Analysis and Design Technique (SADT) is employed, along with a conditional risk analysis approach for each mission activity. Through the application of Hazard and Operability (HAZOP) techniques and Failure Modes and Effects Analysis (FMEA), the risks associated with specific mission activities are systematically identified, while incorporating stopping conditions to ensure risks are maintained at an acceptable level. Moreover, the impacts and uncertainties of internal and external failure causes for each activity are described, ranked, and addressed according to their risk priorities.

This research introduces a dynamic risk assessment framework that optimizes mission success probability through comprehensive risk analysis and management across diverse operational phases. Furthermore, this multifaceted risk mitigation approach is applied to enhance the reliability of rotary and fixed-wing UAVs in an industrial setting at a Canadian space data company. The tailored model specifically targets applications such as agricultural farm imagery collection and methane leak detection in pipelines. Identified risks throughout different operational phases are meticulously mitigated through well-defined controls. To ensure the effectiveness of the control measures, a rigorous analysis known as "Minimum Bayes Risk" is employed. This analysis enables the selection of the optimal mitigation strategy from a range of available options by estimating mission reliability through the calculation of posterior probabilities of failure states. By prioritizing failure modes and expertly selecting the most effective

controls for each risk, the proposed strategy is further validated by subject matter experts (SMEs) from the industry. This expert validation instills confidence in the effectiveness of the chosen control strategies, which successfully reduce risk and enhance the probability of mission success. Additionally, a comprehensive checklist is provided to drone operators, outlining the identified risks and their corresponding mitigation strategies.

The outcome of this research is a comprehensive and robust approach that effectively reduces risks and enhances the likelihood of mission success. The application of the "Minimum Bayes Risk" analysis, combined with expert validation, ensures the selection of control strategies that efficiently mitigate risks associated with UAV operations. This approach contributes to the advancement of UAV reliability, particularly in the context of agricultural farm imagery collection and methane leak detection in pipelines. The adaptability and tailored nature of the proposed model facilitates the efficient management of risks across different operational phases, ultimately reducing the potential for failures and enhancing mission success probability. As UAV usage continues to expand, this multifaceted risk mitigation approach holds significant promise for ensuring the reliability and safety of UAV systems in various real-world scenarios.

Preface

This thesis is an original work by Aungshula Chowdhury.

A version of Chapter 4 of this thesis has been published as A. Chowdhury and M. Lipsett, "Modeling Operational Risk to Improve Reliability of Unmanned Aerial Vehicles," 2023 IEEE International Conference on Prognostics and Health Management (ICPHM), Montreal, Quebec, CA. . I was responsible for the data collection and analysis as well as the manuscript composition. M. Lipsett was the supervisory author and was involved with concept formation and manuscript composition.

A version of Chapter 5 of this thesis has been published as A. Chowdhury and M. Lipsett. "Comprehensive Risk Mitigation for Improved UAV Reliability and Performance," The Canadian Society for Mechanical Engineering, and the CFD Society of Canada 2023, Sherbrooke, Quebec, CA. I was responsible for the data collection and analysis as well as the manuscript composition. M. Lipsett was the supervisory author and was involved with concept formation and manuscript composition.

A version of Chapter 2 and 5 of this thesis is under review as A. Chowdhury and M. Lipsett, " Dynamic Risk Assessment for Unmanned Aerial Vehicles (UAVs)," MDPI Drones, 2023. I was responsible for the data collection and analysis as well as the manuscript composition. M. Lipsett was the supervisory author and was involved with concept formation and manuscript composition.

Acknowledgements

I extend my heartfelt appreciation to all the individuals who played a vital role in making this research possible and contributing to its success. Firstly, I am deeply grateful to the Natural Sciences and Engineering Research Council of Canada (NSERC) for their financial support, which allowed me to pursue this academic endeavor.

I would like to express a special thank you to my esteemed supervisor, Dr. Michael Lipsett, whose guidance, and expertise were instrumental in shaping this research. His invaluable technical insights and wisdom extended beyond the scope of this study, and I am truly grateful for the time and effort he invested in my academic and professional growth.

I am indebted to the team at Wyvern INC. for their invaluable support, providing me with access to essential industrial data, which enriched the outcomes of this work.

A special acknowledgment goes to Dr. Zahra Samadikhoshko for her collaborative efforts on various side projects and her assistance in overcoming research challenges. I would like to mention that Mark Sherstan's thesis has been very helpful while structuring mine. I am also thankful to my lab mates, Iraban Turjo and Shayan Meschian, for their technical support and contributions during experiments.

I express my gratitude to previous Engineering Librarian Alison Henry for her meticulous assistance in searching for relevant papers during the literature review phase. Additionally, I extend my thanks to Dr. Martin Barczyk for providing valuable recommendations in the early stages of the experimental system.

Lastly, to my incredible parents and brother, I want to convey my deepest appreciation for their unwavering support and encouragement from the very beginning. Their constant belief in me and words of motivation sustained me during the countless hours of hard work.

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Chapter 1: Introduction

1.1 Background

The history of UAVs began soon after the first manned flight; Elmer Sperry, the inventor of the Sperry Gyroscope, is credited with initiating UAV development in 1916. An automatic control system for Curtiss Flying boat was successfully developed by the company and Peter Hewitt [1]. The development of airborne targets, the current family of UAVs, and cruise missiles like Harpoon and Tomahawk was finally made possible by efforts made during the Interwar Period, World War II, and afterwards [2].

The MQ-1 Predator, a revolutionary long-endurance aerial reconnaissance UAV, was introduced by the US in 1994. The Predator was updated in 2001 to allow it to carry two AGM-114 Hellfire surface-to-air missiles, making it the first "stalk and kill" UAV in history [3]. Aside from what they have done and are still doing for the military, drones have already shown that they can perform surveillance, guarding borders, spraying crops, looking for people who have vanished, taking photographs, and inspecting emergency situations like bushfires, floods, and cyclones. And yes, of course, pizza delivery [4].

Due to their distinctive capabilities like vertical takeoff and landing (VTOL), cost-effectiveness, and hovering, Multirotors are one of the most popular UAV platforms among customers and researchers [5]. The development of the quadcopter can be credited to the Bréguet-Richet Gyroplane in 1907. Gyroplane No. 1 had a human pilot and could lift 0.5 meters off the ground, but it was quite unstable and needed support from a ground crew at all four corners. Under a contract with the US Army Air Service, the de Bothezat helicopter, also known as the Jerome-de Bothezat Flying Octopus, flew for the first time in 1922 [6]. However, the development was scrapped in 1924 due to its complexity. Oehmichen established a world r1ecord in France in 1924 with his quadcopter design flying 360 meters straight [7]. Sikorsky's first practical helicopter, which used a primary rotor for lift and an anti-torque rotor on the tail, flew in 1939. However, the quadcopter trend persisted until 1956, when the Convertawings Model-A Quadrotor prototype was created, which showed how roll, pitch, and yaw could be controlled by changing the propellers' speed [8].

To examine the level of the technology at the time, the Office of the Secretary of Defense (OSD) undertook an evaluation of UAV reliability in 2003. This web-based report provides information on the development histories, operational tempos, and reliability conditions for many DoD models. A second study, published in 2007, included further information on operational tempos as well as investments in the reliability of two UAV types [9].

Increased system reliability has become essential because the worldwide drone market is predicted to reach USD 40.9 billion by 2027. This is true both for mission success and public safety, as well as for demonstrating risk management as part of licensing. UAVs have gained greater scientific attention recently because of their increased accessibility to the general public for a variety of commercial and industrial uses. UAV applications have expanded because of recent growth and development, particularly for multi-rotor UAVs. These scenarios include wildfire monitoring, coastal line assessment, precision agriculture, wetland inspection, surveillance, search and rescue, 3D mapping, and structure inspection.

UAV multirotor research was little in the early years, and it wasn't until 2011 that widespread interest began to emerge [10]. Multirotor UAVs are increasingly being utilized for visual inspections of difficult-to-reach or dangerous regions such as railway infrastructure, bridges, and high-voltage power lines. Bridge, power line, pipeline, and building facade inspection are some of the frequent visual inspection industries where UAVs have already been shown to be helpful instruments. Inspection jobs have traditionally been expensive and may have to be undertaken in difficult-to-access or dangerous regions [11].

UAVs can take over the visual inspection portion of many tasks, decreasing the requirement for human intervention and thereby saving many resources. A flexible UAV-based crack inspection system provides a comprehensive solution for detecting fractures on bridge lateral sides and undersides [12]. This can be used to solve a variety of difficult challenges such as crack detection and mapping, data collection, image stitching, and big-scale image analysis. Additionally, because many oil and gas assets are in harsh environments, there is a constant desire for robots to undertake inspection jobs that are more cost-effective and safer. Autonomous UAVs are cost-effective alternatives to Unmanned Ground Vehicles (UGVs) [13]. Autonomous inspection will also become a reality owing to sophisticated computer vision algorithms, particularly the deep learning method. Researchers have demonstrated multirotor UAV capabilities such as opening drawers, opening doors, unscrewing light bulbs, collecting water samples, having two UAVs work together to overcome payload limits [14]; and collecting volcanic rock samples in Figure 1: Sample-return scenario of volcanic products inside restricted areas [15].[15].

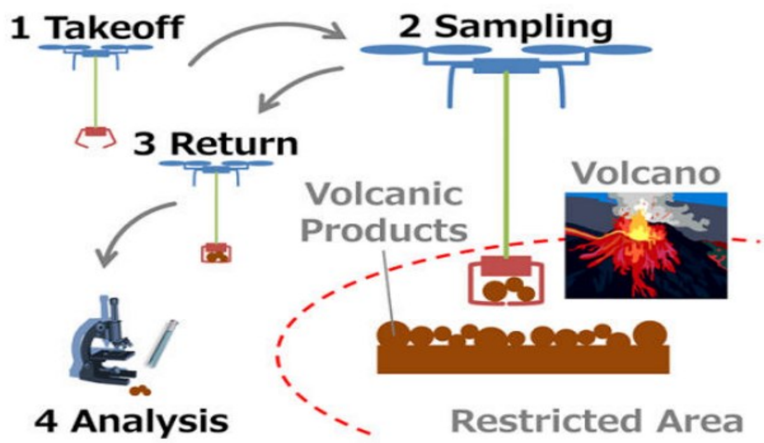

Figure 1: Sample-return scenario of volcanic products inside restricted areas [15].

Using a UAS based on a quadrotor helicopter to inspect power line corridors offers several clear advantages: it is more efficient, less expensive, and safer. The UAV's flight control system and payload are both on board [16]. To inspect the devices and components in power line corridors, the payload for the inspection system employs a color camera and a Thermal Infrared (TIR) camera. This qualitative evaluation is sufficient to identify several typical flaws. A low-altitude UAV remote-sensing platform equipped with an optical digital camera was utilized to monitor power line corridors to make safety inspections more efficient and adaptable. Regular safety checks are required to guarantee that electrical grids operate safely [16]. The main threats to the safe operation of extra high voltage transmission lines within a power line corridor are tall vegetation and buildings.

Previous research has explored using reliability analysis to aid decision making in phased mission systems. Mission reliability was presented as a major decision variable for determining whether a mission should continue in its current structure. A phased mission's reliability is defined as the likelihood that all phases of the mission will be completed without failure [17]. Despite previous studies, more work is needed to attain the speed of quantification required to make real-time judgements when evaluating Prognostic and Health Management System (PMS) with numerous failure mode components. Priced Timed Automata (PTA) models in a few papers simulate factors that may affect communication, such as UAV coordinates to assess reliability. In the paper, the models modify the transmission power, antenna gain, UAV movement speed, transmission delay, receiver, and telemetry device specification parameters [18,19].

During 1986 Sumburgh incident, a commercial Chinook crashed in the North Sea, killing all but one passenger Figure 2. After this accident, these devices were initially implemented by the offshore oil industry [20]. The development of a trustworthy sensor system resulted in, and continues to support, major advancements in both safety and reliability as a response to the relatively poor continuous airworthiness record of rotorcrafts [21,22]. A conventional, reliable system connects a centralized computer unit with a data recording and storage system to sensors placed throughout the airframe and its parts. For system experts to assess if the aircraft has developed (or is likely to develop) defects that need to be fixed, it is especially crucial to monitor patterns in the collected data.

Figure 2: The Chinook responsible for the Sumburgh tragedy

Under the severe environmental circumstances characteristic of such places, a lightweight, vision-aided inertial navigation system such as a UAV delivers trustworthy state estimates. Close hardware integration supports spatial and temporal calibration of the various sensors, resulting in more precise and robust ego-motion estimates [23].

Reliability design is the process of selecting appropriate components, redundancy levels, and schemes, as well as robust system topologies, to ensure that the reliability requirement can be met during the specified mission time under certain operating conditions [24]. Redundancies (in the form of hardware, software, information, and time redundancies) allow a system to endure numerous errors produced by faulty algorithms, component defects or wear out, external disruptions, and so on. Failure diagnosis and analysis are critical for understanding the causes of failures and providing useful information for enhancing the reliability of traditional system designs and reducing the risk of future failures [25,26].

Figure 3: Diana with built-in reliable sensor-based systems

The reliability and effectiveness of UAVs heavily rely on the integration of advanced sensors. Inertial navigation systems, combined with vision-aided systems, provide accurate state estimates, even under severe environmental conditions Figure 3. The close hardware integration of sensors allows for spatial and temporal calibration, resulting in more precise and robust ego-motion estimates [27]. These advancements in sensor technology contribute to the overall reliability and performance of UAVs in various operational scenarios [28].

With the increasing use of UAVs in commercial and industrial applications, regulatory frameworks and safety standards have been developed to ensure responsible and safe operations [29]. Regulatory bodies around the world, such as the Federal Aviation Administration (FAA) in the United States and the European Union Aviation Safety Agency (EASA), have established guidelines and certification processes for UAV operators and manufacturers [30]. Compliance with these regulations and standards further enhances the reliability and safety of UAV operations. The integration of sophisticated computer vision algorithms, particularly deep learning methods, has enabled UAVs to possess autonomous capabilities [31, 32]. These capabilities allow UAVs to perform complex tasks such as opening doors, manipulating objects, collecting samples, and collaborating with other UAVs to overcome payload limitations. Autonomous inspection missions become more feasible, cost-effective, and efficient, reducing the need for human intervention, and improving overall reliability [33].

The applications of UAVs vary across different industries. In addition to visual inspections of infrastructure, UAVs have proven valuable in fields like precision agriculture, wildfire monitoring, coastal line assessment, surveillance, search and rescue, 3D mapping, and structure inspection [34]. These industries benefit from the agility, flexibility, and accessibility of UAVs, which enable them to gather critical data and perform tasks more efficiently and safely. UAVs are equipped with various sensors and cameras, allowing for data collection in diverse environments and scenarios [35, 36]. The collected data, such as images, thermal signatures, or point clouds, can be processed, and analyzed using advanced techniques like image stitching, big-scale image analysis, and data mapping. UAVs facilitate the rapid acquisition of high-quality data, enabling industries to make informed decisions and identify potential issues or anomalies more effectively [37].

The field of UAVs continues to evolve rapidly, with ongoing advancements in technology and capabilities [38]. Future trends include the development of longer endurance UAVs, improved energy efficiency, enhanced autonomy, and increased payload capacities [39,40]. However, challenges remain, such as airspace integration, privacy concerns, cybersecurity threats, and the need for standardized protocols and operating procedures. Overcoming these challenges is essential to ensure the continued reliability, safety, and acceptance of UAVs in various applications [41].

In conclusion, UAVs have come a long way in terms of their development, applications, and reliability. The integration of advanced sensors, autonomous capabilities, and industry-specific applications has expanded their utility in diverse fields. With the establishment of regulatory frameworks and ongoing technological advancements, UAVs are poised to play a significant role in shaping the future of aerial operations, inspection, data collection, and analysis.

1.2 Motivation

UAVs have witnessed a remarkable surge in usage and have become an integral part of various industries. These autonomous machines are controlled through human-operated ground control stations (GCS). Over the years, UAV applications have expanded across diverse fields, including agriculture, entertainment, photography, product transportation, inspection and surveillance, and wireless communication networks [42]. The continuous evolution of UAV technology has propelled it into a prominent area of study.

UAVs possess versatile operational capabilities, such as variable flight speeds, hovering capabilities, stable positioning, and intricate maneuvering to navigate obstacles [43, 44]. However, like any complex system, UAVs are susceptible to reliability issues, including problems with propulsion, power systems, controls, and sensors, among others. The prompt detection and isolation of these problems are crucial for the successful execution of UAV missions. Real-time monitoring of UAV performance allows for the early identification of irregularities, mitigating the potential disastrous effects [45]. Existing research on UAV reliability has primarily focused on fault diagnostics tailored to specific applications. For instance, fault detection systems designed for UAVs used in nighttime fire monitoring may not be applicable to UAVs employed in underground pipe inspections [46, 47]. Recognizing this limitation, the presented research aims to develop a comprehensive reliability model by conducting qualitative analyses of failure categories at each mission stage, as well as activities before and after the mission.

The proposed reliability model offers significant advantages as it is designed with a general UAV mission framework in mind yet remains adaptable to the specific requirements of unique missions. As UAVs are increasingly employed to undertake hazardous and challenging tasks that would otherwise be performed by humans, it becomes crucial to ensure their reliability. The qualitative dynamic risk assessment model for the UAV platform intends to identify critical failure modes and condition indicators for early detection. Additionally, a rugged, lightweight, and easily integrable sensor-based system will be designed to enhance UAV reliability. Incorporating a comprehensive reliability model into UAV operations provides numerous benefits. It allows for proactive maintenance, minimizing downtime and maximizing mission success rates. Early detection of critical failure modes enables timely interventions, reducing the likelihood of catastrophic events. By integrating robust sensors into the UAV system, continuous monitoring and feedback can be obtained, ensuring optimal performance, and mitigating potential risks. Moreover, the proposed reliability model accounts for the dynamic nature of UAV missions, taking into consideration the evolving conditions and environmental factors that influence reliability. This approach allows for adaptive decision-making, enhancing the overall effectiveness of UAV operations.

Furthermore, the reliability model being developed for UAVs considers the entire lifecycle of the mission. It incorporates not only the operational phase but also the pre-mission and post-mission activities. This comprehensive approach ensures that potential failure modes and risks are addressed at every stage, from mission planning and preparation to data analysis and system maintenance.

One of the key advantages of the proposed reliability model is its adaptability to different UAV missions and applications. While there are commonalities in the reliability challenges faced by UAVs, each mission may have unique requirements and constraints. By providing a framework that can be tailored to specific mission objectives, the model enables the identification of mission-critical failure modes and the selection of appropriate condition indicators for early detection.

To support the reliability model, a robust sensor-based system will be designed and integrated into the UAV platform. This system will utilize lightweight and rugged sensors capable of collecting real-time data on various parameters related to UAV performance, environmental conditions, and mission objectives. The collected data will be processed and analyzed to identify deviations from expected performance and potential failure indicators. The integration of the sensor-based system will enable continuous monitoring of the UAV's health and performance, allowing for proactive maintenance and timely intervention. By detecting and addressing potential issues before they escalate, the reliability of the UAV will be significantly enhanced, ensuring the successful completion of missions, and reducing the risk of accidents or system failures.

Additionally, the reliability model and sensor-based system will contribute to the overall safety of UAV operations [48]. As UAVs increasingly undertake tasks in hazardous environments or replace humans in risky operations, ensuring their reliability becomes paramount. By implementing a robust reliability model, the UAV's ability to withstand unexpected events and operate in challenging conditions will be improved, enhancing the safety of both the UAV and the surrounding environment. The continuous monitoring and analysis of UAV performance data will provide valuable insights for system improvement and optimization. By collecting and analyzing data from multiple missions, patterns and trends can be identified, enabling the development of predictive maintenance strategies and the refinement of operational procedures. This iterative process of data-driven improvement will contribute to the overall advancement of UAV technology and the reliability of future UAV platforms.

In conclusion, the development of a comprehensive reliability model and the integration of a sensor-based system offer significant advancements in the field of UAV operations [49]. By addressing the specific challenges associated with UAV reliability and performance, the model and system will enhance the safety, efficiency, and effectiveness of UAV missions across various industries and applications. Through proactive monitoring, early fault detection, and adaptive decision-making, UAVs will become increasingly reliable and dependable tools, revolutionizing the way tasks are performed in numerous fields [50].

1.3 Research Objectives

The rapid growth of UAV usage in commercial applications and scientific research necessitates a comprehensive approach to enhance their reliability and safety. While previous research has demonstrated the benefits of sensor-based systems in improving UAV airworthiness, a comprehensive risk analysis that addresses failures at each stage of a mission and identifies appropriate sensors for mitigation is still lacking. It is crucial to tailor the sensor-based system to the specific requirements of different mission types. For example, a system designed for fire monitoring would not be suitable for pipeline inspection.

The primary objective of our research is to increase the probability of mission success by effectively evaluating and managing UAV risks throughout various operational phases. To accomplish this, we propose a task decomposition model that estimates mission reliability by calculating posterior probabilities of failure states and determining the necessary risk control information. By identifying, describing, and ranking internal and external causes of failure for each mission activity, we can prioritize risks based on their impact and uncertainty. Controls required to reduce these risks are established, and success criteria for each mission activity are defined. The resulting architecture will integrate sensing and actuation capabilities, improving the reliability of different systems, such as rotorcraft, fixed-wing UAVs, and ground robots, for environmental monitoring applications.

The main advantage of our proposed model is its ability to extend the use of sensor-based systems across a wide range of missions, rather than limiting them to specific applications. We will validate this model through conceptual modeling and calculations. Given the complexity of reliability analysis, involving multiple components and academic domains, we have opted for a descriptive thesis for this research. To begin the development process, we will employ the Structural Analysis and Design Technique (SADT) to describe each activity, ranging from mission preparation to demobilization. Failure Modes and Effects Analysis (FMEA) will aid in the identification of risks during mission execution, and appropriate stopping conditions will be established to control the risks of failure within acceptable levels. Controls necessary for risk reduction in each mission activity will be defined, and the most effective mitigation strategy will be chosen using "Minimum Bayes Risk" analysis. SMEs will verify the prioritization of failure modes and the selected controls for each risk.

Furthermore, our research will emphasize the importance of expert validation throughout the development and implementation stages. SMEs from relevant domains, including UAV operations, risk management, and sensor technologies, will contribute their expertise to ensure that the prioritization of failure modes, chosen controls, and risk mitigation strategies align with industry best practices and standards. Their insights will validate the robustness and reliability of the proposed system, providing confidence in its real-world applicability.

By adopting this comprehensive risk analysis model, we aim to enhance the reliability and safety of UAV missions. The incorporation of suitable sensors and controls will mitigate potential failure modes, increase the overall robustness of UAV systems, and contribute to mission success rates. Furthermore, our research will enable researchers and practitioners to harness the full potential of sensor-based systems by providing a framework for their effective utilization across various mission types. Through conceptual modeling, calculations, and expert validation, we will ensure the reliability and applicability of our proposed approach.

In conclusion, the proposed research addresses the need for a comprehensive risk analysis model for UAV missions. By focusing on failure identification, risk control, and the integration of sensor-based systems, we strive to enhance the probability of mission success and improve UAV reliability. The adoption of SADT, FMEA, and "Minimum Bayes Risk" analysis techniques facilitates a systematic approach to risk management. As the complexity and demands of UAV operations continue to grow, our research endeavors to contribute to the advancement of reliable and safe UAV missions.

1.4 Thesis Organization

In this thesis, following the introduction chapter, review of relevant literature about reliability modelling of UAVs and risk assessment is presented in Chapter 2. The methodologies used to perform the risk assessment of UAVs are discussed in Chapter 3. The topics covered in the chapter are Structural Analysis and Design Technique (SADT), Failure Mode and Effect Analysis (FMEA), Minimum Bayes Risk Analysis and Condition Probability estimation of the system, respectively. The complete Risk analysis of a general-purpose mission for a UAV is in Chapter 4. Chapter 5 is devoted to the Industrial Case Study for a Canadian space data company to identify Failures and the consecutive mitigation strategies. The model is specifically tailored to applications such as agricultural farm imagery collection and methane leak detection in pipelines. Finally, Chapter 6 presents the conclusions of the project as well as introducing suggestions for the future work.

Chapter 2: Literature Review

2.1 Importance of Reliability to ensure mission success:

Some failures are more critical than others during a typical mission. Losing longitudinal stability may result in loss of the aircraft and a safety hazard to the public. Losing payload data may mean that a mission needs to be repeated, with time and money lost. Loss of a redundant system element may have no negative effect on the mission at all. These possible failure scenarios are not of the same criticality level, illustrating that an analysis that clarifies the different levels of priority connected with the fault must first be established, such that the designer or mission operator is able to evaluate the effect of a change on mission reliability.

Reliability in the context of UAVs refers to the ability of these aircraft systems to consistently perform their intended functions under a variety of conditions while minimizing the risk of failure or malfunction [51]. Reliability evaluations are conducted to identify the minimum conditions necessary for UAVs to achieve a higher level of dependability. These assessments are pivotal in identifying the least reliable components or elements within specific subsystems, as well as pinpointing the most critical components for overall system functionality. The overarching goal of these evaluations is to ensure the safe operation of UAVs, necessitating their capacity for autonomous situational awareness and the ability to respond safely to events and anomalies that may jeopardize the aircraft, human life, and property.

The primary goal of reliability evaluations is to determine the minimum conditions that allow UAVs to be more reliable. These evaluations also assist us in determining which components or elements of a certain subsystem are the most unreliable, as well as which are the most vital to the system [49]. The safe operation of UAVs is expected to necessitate autonomous situational awareness and safe reaction to events and anomalies that may pose a threat to the aircraft, to human life, and to property [50]. This type of UAV is made up of an unmanned aircraft (UA), one or more payloads (which will vary according to mission objectives), a control element (system to launch, control, and land), a display (how/where sensor payload information is displayed at the operator station or other ground segment location), communications architecture (hardware/software used to send data between the control element, the aircraft, and the display), and life-cycle logistics, according to the requirements for staging, launching, operating, recovering, and maintaining the UAV .

Another critical aspect of UAV missions is Dependability Management. One of the recent approaches to address this issue is the SafeDrones model-based approach which aims to improve reliability and safety of UAVs by enabling runtime reliability and risk assessment of UAVs [50]. SafeDrones builds upon static design-time knowledge in the form of fault trees by combining them with dynamic Markov-based models and real-time monitoring to perform continuous reliability evaluation at runtime [51]. Another approach is the model-driven mission dependability design of unmanned aerial systems which investigates the impacting factors on the system dependability. Various dependability evaluations are performed to comprehend mission reliability decay and mission availability in execution and with regards to different impacting factors. Finally, there is also the model-based dependability assessment of phased-mission UAVs which distinguishes between different mission phases and enables the analysis of phased missions [52].

ISO 31010 is an international standard that offers guidance on the selection and application of techniques for assessing risk across a broad spectrum of situations [53]. It helps organizations address uncertainty and manage risks effectively by providing a toolkit of assessment techniques that can be tailored to suit specific contexts and needs. Key features of this standard include providing a range of risk assessment techniques, supporting decision-making in situations involving uncertainty and summarizing of the techniques, with references to more detailed documents describing each technique. The guidance and techniques, while not UAV-specific, can greatly benefit mission reliability and risk assessment. The standard provides a range of methods for identifying and evaluating risks, which can be adapted to address uncertainties inherent in UAV operations. These techniques aid in scenario analysis, decision-making, and proactive risk mitigation, enhancing the overall reliability and safety of UAV missions. By promoting a holistic approach, compliance with safety standards, and continuous improvement, ISO 31010 supports organizations in effectively managing risks and uncertainties within UAV operations.

2.2 Reliability literature:

Andrews et al. in a 2013 paper discussed how the increasing commercialization of UAVs made ensuring their reliability more important and a method to predict the mission reliability according to varying scenarios through calculations This study investigated ways to speed up the calculation process for phased mission analysis [54]. By considering the specific characteristics of the fault tree structures that offered the causes of phase failure for a UAV mission, the technique enhanced the processing capacity for UAV-phased mission analysis. Additionally, it performed as much quantification as was practical before the mission plan was created. If the chances of mission failure were higher than the acceptable threshold, the mission plan would have needed modifications.

Reimann et al. discussed the importance of UAV reliability in avoiding lethal accidents in a 2014 study [55]. The reliability of the Ultra stick 120 was analyzed in three severity categories, with the catastrophic failure (severity category 1A) having a failure rate of 2.17 failures per 100 hours, the possible landing (1B), and the mission critical (2), having a failure rate of 2.14 failures per 100 hours each. Instead of a complex design, a more feasible design was chosen because the difference in improving reliability between them was not significant. This paper mainly dealt with using quantitative analysis to improve the reliability of the UAV.

In this 2015 study, Cuhadar and Durshan discussed an actual UAV accident, the pilot's experience, dos and don'ts, and challenges. The amount of time left before the crash and the distance to the landing air base were calculated. Additionally, the Return Home route and the landing/crash side were identified and checked [56]. Therefore, in addition to their operating skills, UAV pilots must also possess additional criteria like determination, thorough training, and experience. Within this context, experience sharing, and lessons learned were just as vital as simulators for the training of a UAV pilot. Lessons learned can be used to identify causes, correct errors, and avert future UAV mishaps.

Sundaram et al discussed an online and offline approach to the SHM system that was developed at the Advanced Composites Division of CSIR-NAL of India using fiber optic sensors in 2016 [57]. The scheduled inspection of the structural damages using the Non-Destructive Testing methods decreased the unplanned downtime of a specific UAV mission, thus increasing reliability. The paper argued for a combined online-offline inspection system for UAV maintenance, as the author believed that online FBG-based sensor technology was not on the same Technology Readiness Level (TRL) as traditional Non-Destructive Testing methods.

In this 2016 paper, Shadab et al. talked about the importance of System artefacts of a UAV to make sure that design and requirements were consistent which ensured that the final mission planning design matched with the simulation results which increased the reliability of the mission [58].

In 2017, Wang et al. discussed the use of UAV swarms to increase the reliability of a particular mission but also about the challenges faced due to scarcity of resources, finite energy, and low connectivity [59]. Therefore, to increase the system's flexibility and scalability, a cloud-based UAV system was suggested that integrates cloud computing technology into multi-UAV systems.

In the year 2017, this study by Zhang et al. investigated the variable ordering and quantification efficiency of BDD models, two factors that have an impact on analysis speed. Variable ordering had an impact on BDD size, which in turn had an impact on analysis speed [60]. A brand-new ordering system for usage in the context of decision-making was suggested. Regardless of how the mission configuration changes, variables were already sorted prior to the mission, therefore reordering was not necessary. To address the effectiveness and accuracy of existing models, three BDD models were offered.

In this 2017 paper, Petritoli et al. aimed to analyze the intrinsic reliability during the design stage of the UAV to prevent any catastrophic failure during the actual mission [61]. Predicting the likelihood of failures was necessary to determine how frequently such failures might occur and which was crucial for maximizing system performance. The only way to compare the predictions of the proposed and existing designs was to see how they affect reliability in relation to the proposed design changes. By using Reliability Assessments in predictions, the design's capacity to maintain a desirable degree of reliability in the face of environmental extremes was evaluated. Reliable prediction made it feasible to identify the reliability standpoint's most crucial components and afterward monitor it appropriately.

Petritoli et al. in the 2018 paper discussed the way to determine the ideal maintenance period. The issue of doing preventive and corrective maintenance on UAV systems while taking into consideration their unique needs was looked upon, which are quite different from those of a regular aeroplane [62]. The principles of preventive and corrective maintenance were incorporated, which took system deterioration into the probabilistic computation. The ideal point of maintenance was determined by optimizing the probabilistic functions (under the circumstances of an actual situation).

In 2018, Ruan et al proposed a multi-UAV coverage model for energy-efficient communication by breaking the model into two steps: coverage maximization and power control, which improved the reliability of the system and the overall mission and was demonstrated in the simulation results [63]. This was done by using a common way to gauge a UAV network's capacity for coverage by looking at the ratio of coverage area to specified area.

A fault-tolerant and health-aware control strategy for an octorotor UAV were presented by Salazar et. al in this 2020 study [64], where the control effort was distributed among the available actuators depending on their health information. It was important to note that a reliability enhancement may clash with UAV controllability if an actuator problem occurred. System reliability sensitivity was redefined and changed to avoid uncontrollable circumstances during the UAV's mission. Each actuator was given a priority based on how crucial it is to system dependability. Additionally, the suggested method could modify the controller to adjust for actuator flaws and enhance overall system reliability or postpone maintenance duties.

In this 2020 study, Khayyati compared the reliability across many methods to determine the most effective technique. The system's failure model was created first. After that, three distinct scenarios were considered to investigate the impact of redundancies on the system reliability outcomes [65]. There was no redundancy in the first scenario, one redundant component in the second scenario, and three redundant components in the third situation. Results were achieved by applying static reliability analysis techniques like Fault Tree Analysis (FTA), Reliability Block Diagram (RBD), Markov Chain (MC), and Bayesian Networks (BN) to the situations that were given. Results of applying proposed static and dynamic techniques to a UAV as a case study were discussed. Lastly, to choose the most effective reliability analysis strategy, the characteristics of each methodology and associated criteria were clarified.

The three issues of UAV reliability, flight positioning, and data transmission are the main topics of this 2020 paper by Wu et. al. The UAV used the upgraded Pixhawk flight controller [66]. A combination of FPGA and sensor array was used to address the reliability issue, RTK and 3D positioning were combined to address the positioning issue, and a 4G transmission system was used to address the data transmission issue. The UAV prototype tests demonstrated that the UAV's capabilities and dependability had met its original design goals and had a wide range of practical applications.

In this 2021 paper, Dui et. al discussed how operating the UAVs in swarms increased the reliability of the mission, by ensuring the success rate of the mission. The UAVs needed to be assigned a specific task in a specified task time and environment, and the mission objective was achieved through real-time, data sharing, dynamic networking, and coordination [67]. The only way to increase the reliability of a conventional system was to do subsequent maintenance to return it to a functioning state after a failure. However, a UAV swarm was a collection of several UAVs that work together to complete tasks in a selforganized and adaptable way. Through dynamic adjustment and self-restructuring, the UAV swarm might nevertheless restore its mission reliability to a certain level when certain chosen UAVs fail or crash owing to their own problems, the external environment, or enemy involvement.

In this 2021 paper, Fourlas et al. talked about the latest studies on the importance of fault diagnosis [68]. The UAV operation was tracked by addressing the three main types of subsystems: actuators, main structure, and sensors during fault diagnosis. Regardless of the technological advances, unexpected circumstances and events could occur in their surroundings for operation. Because of this reality, there were additional requirements for developing and using defect diagnosis methods that will aid in the defect identification fast and accurately, both at the sensor and actuation levels of UAVs, as well as isolation.
In this 2021 paper, Raja et al. discussed about how a UAV swarm is effectively built using a Reinforcement Learning technique based on Generation Flight Control for Navigation (FFCN), which reduced networking load by decreasing communication and processing involved in pattern formation [69]. This model made it easier for UAVs to target remote areas. This includes a fault tolerance mechanism which improved the system's reliability. The use of this model decreased the collision rate in successful formation without hitting other UAVs to 3.4%.

In this 2021 paper, Abdelhamid et al. proposed a method called Priced Timed Automata (PTA) models which could alter the receiver sensitivity threshold, telemetry device specification parameters, UAV movement speed, transmission latency, and antenna gain to estimate reliability [70]. These elements rely on the environment that was being addressed and the anticipated power consumption. For fixed-wing UAVs, a fault detection and separation diagnosis system that created a bank of residual generators by utilizing the MAVlink protocol had been developed. This was the first attempt to evaluate the reliability of UAV-UAV communication using formal executable language.

To assess the system's capacity to deliver dependable positioning services, Wang et al. in 2021 suggested a reliability-prediction method and construct the corresponding measure [71]. Because mountainous terrain was more complex and varied than plain or urban terrain, major position mistakes brought on by faults or anomalies might have resulted in monetary losses or even human fatalities. Therefore, in hilly areas, positioning service reliability was of utmost concern.

In this 2022 paper, Gan et. Al constructed a cylinder static protection zone model of UAV to detect the flight conflict trend and near midair collision trend between UAV and intruder, and then a dynamic collision avoidance zone modelling method based on emergency collision avoidance was constructed to improve the safety and reliability of UAV operating in mixed airspace, with reference to flight interval standards [72]. The simulation results demonstrated the method's efficacy.

This 2022 paper by Xing et. al included a critical overview of UAV reliability literature in both theoretical and practical research, highlighting failure causes and UAV system reliability difficulties, classifying, and reflecting on UAV system and key subsystem reliability modeling, analysis, and design methodologies [73]. Some unresolved research issues and opportunities were also highlighted to highlight potential new challenges for creating reliable and resilient UAVs and UAV-assisted IoT systems. Because UAV applications were mission-critical, business-critical, or safety-critical, it was vital that UAVs execute reliably to offer the required service during the intended mission duration. As a result, one of the most important requirements for building and operating UAVs was dependability.

In this 2022 paper, Hannius et. Al outlined a process for determining the specifications for distributed electronic turbofan engine control systems' diagnostic functions' effectiveness [74]. Sensor, actuator, and control unit nodes made up distributed engine control systems, which exchanged data across a communication network. Engine control systems that were somewhat redundant could use this technique. Traditionally, twin-channel solutions with duplicates of all components were used for turbofan engine management systems. The technique was designed to analyze the diagnostic needs of systems with a subset of nonredundant sensors and actuators. To reduce hardware redundancy in engine control systems that rely on analytical redundancy, it was critical to have a mechanism for determining probabilistic requirements on diagnostic functions. By utilizing the suggested method, they could accomplish an existing tool for safety and reliability analysis called FAULTTREE.

2.3 Risk Assessment Literature:

In a 2011 paper, Gebre-Egzibher et al. discussed operational safety risks (including residual risks) and ways of mitigating them [75]. They went into detail about how specific onboard sensors would tackle specific risks of the UAV. Small UAS have many interrelated systems, so understanding each system's internal operation or the risk it poses was necessary. Therefore, tiny UAS solutions based on "turn key" technologies could only be regarded as appropriate after a case-by-case analysis of their deployment in a specific concept of an operation or if they were created to an all-encompassing agreed standard that considered risk.

The risk metric and evaluation approach for UAVs operating in situations usually found in civilian applications were presented in this 2018 study by Rubio-Hervas et al. [76]. This paper presented the risk metric and evaluation methodology for UAVs operating in scenarios typically seen in civilian applications. It was shown that such an approach can be embedded into current standard risk assessment methods which could be easily integrated into UAVs traffic management initiatives. The results through several simulations, including realistic scenarios were analyzed as well. A path-integral formulation was used to explain the proposed mathematical definition of the risk metric, which was based on the probabilistic predictions of such a Gaussian process model.

In this 2018 paper, Bertrand et al. 2018 searched for an accident with damage brought on by a UAV falling on a road, which was the hazardous event considered for risk assessment [77]. It was suggested to use computational models to assess the likelihood of each incident that would eventually result in such an accident. A simple risk index had been proposed to help identify the key risky locations, based on the chance of accident and the period at which the risk was exposed. The computation of all the probabilities involved in the risk evaluation had been demonstrated.

For UAV operation in urban settings, Hu et al. in 2020 offered a thorough risk assessment model [78]. Each risk cost was calculated using the collision probability for each of the three danger categories that were taken into consideration: people, vehicles, and manned aircraft. In order to identify the three risk cost models' ideal coefficients, the risk costs were scaled down from different magnitudes to the same scale. The overall risk was then calculated, and a risk cost map was created for path planning.

In this 2019 paper, Hu offered a probabilistic approach to aid future UAS safety and traffic management. The first proposal was a probabilistic risk-based operational safety bound. This allowed the UAV to keep the deviation from the trajectory plan within a "buffer" zone and avoid obstacles [79]. Techniques such as uncertainty quantification, Monte Carlo simulation, and coordinate transformation were used. In addition, an algorithm for collision avoidance and trajectory planning was created that incorporates reinforcement learning and the suggested operational safety bound. This provided UAVs the ability to learn and modify their behaviour to changing situations. In addition, multi-agent generative adversarial imitation learning was used to investigate large-scale UAV management.

Zhang et al. in 2020 discussed about the risk identification elements, predetermined for the identification subset and set-valued statistics, were used to quantify their qualitative characteristics [80]. It established a generic quantitative approach for identifying the flying danger of UAVs. UAV flight risk was divided into groups based on the many flight risk variables. To support UAV flight risk management, this paper recommended the techno-economic evaluation approach to be applied to the feasibility assessment of the UAV flight risk prevention scheme.

Zheng et al presented a method for selecting a safe landing site for vertical take-off and landing (VTOL) UAV based on the point cloud, which could reduce the cumulative risks posed during touch-down at the chosen landing location in this 2021 paper. The most appropriate landing spot of a landing zone was chosen based on the terrain complexity [81]. Experiments were conducted using terrain point clouds from a simulated scenario and the real world, and the results revealed that the selected landing places may match the safety requirements, demonstrating the usefulness and viability of our suggested method.

In this 2021 study, Bijjahalli et. Al provided a novel risk management paradigm, as well as a methodology for modeling the risk of UAS collisions. In assessing collision risk, the model incorporated the performance of Communication, Navigation, and Surveillance (CNS) systems as well as aircraft vehicle dynamics [82]. The model was applicable to two or more aircraft encounters as well as terrain collision scenarios. The methodology was based on the modeling of CNS error characteristics as well as wind uncertainty, which was then translated to the spatial domain to construct a virtual risk protection volume around each aircraft. After then, the volume was inflated in proportion to a Target Level of Safety (TLS). The methodology was presented in a simulation case study based on aircraft-aircraft collisions.

In this research in 2021, Adam et al. proposed a method for a UAV-based flight mission-definition system, that allowed for the setup and autonomous management of flight trajectories, was presented [83]. The suggested solution was put to the test and verified in a simulated setting using two separate forms of testing, contrasting the UAV's autonomous flying with the user's manual flight. This reduced the risk of damage and cost but requires skilled operators.

2.4 Key Findings

The literature review delved into the multifaceted realm of UAV reliability and risk assessment, unearthing a host of pivotal findings. In the examination of reliability, the surge in commercialization and mission significance emerged as a driving force behind the heightened emphasis on UAV dependability. Techniques like phased mission analysis and fault tree analysis were spotlighted for their ability to dissect the causes of failures, optimizing mission plans, and bolstering overall reliability.

Structural health monitoring systems, both online and offline, demonstrated their capability to curtail unplanned downtime, thereby elevating the reliability of UAV missions. A notable revelation was the significance of maintaining consistency between design and simulation, as this synchronization fortified mission planning and resultant reliability. In the realm of UAV swarms, the potential for enhancing mission reliability was unveiled, albeit the formidable challenges posed by resource scarcity and connectivity constraints. Variable ordering and quantification efficiency garnered attention due to their direct impact on the speed of analysis in BDD models, which in turn influenced reliability assessments. Substantial inquiry was also directed towards intrinsic reliability assessment during design phases and predictive maintenance strategies, both instrumental in fortifying the overall reliability of UAV systems.

Shifting to risk assessment literature, the focus pivoted to addressing operational safety risks through strategic onboard sensor integration. A groundbreaking model emerged, aligning UAV risk assessment with standard methodologies, seamlessly integrating into broader UAV traffic management frameworks. The literature explored computational models, adept at gauging the probability of UAV accidents and furnishing risk indices to identify precarious locations. The paradigm of probabilistic approaches burgeoned, contributing to safety through trajectory deviations and algorithms for collision avoidance. Quantitative methods unfolded, quantifying flight danger for UAVs, in turn providing foundational support for effective risk management and prevention schemes. Innovative methodologies hinged on point cloud data for selecting safe landing sites showcased their ability to mitigate cumulative risks during the UAV touch-down process.

A. Areas of Consensus

The literature review revealed a consensus regarding UAV reliability and risk assessment. Studies unanimously recognized the escalating importance of UAV reliability due to commercialization and critical mission roles. Strategies to ensure dependability in diverse scenarios were seen as imperative. Furthermore, an agreement emerged on the value of advanced techniques like phased mission analysis, fault tree analysis, and structural health monitoring for enhancing reliability. The concept of UAV swarms to bolster mission reliability garnered agreement, despite challenges. Innovations in risk assessment methodologies, such as probabilistic approaches and trajectory deviations, were seen as crucial for UAV safety. Sensor integration's significance for operational safety was a shared viewpoint.

Collectively, the literature highlighted the growing UAV reliability importance, advanced enhancement techniques, UAV swarm potential, innovative risk assessment, and sensors' vital role in operational safety.

B: Areas of Debate

The literature review uncovered areas of debate in UAV reliability and risk assessment. One debated topic revolved around risk quantification in UAV operations. Despite acknowledging the importance of risk assessment, the literature displayed ongoing debates about effective metrics and methodologies. Varied approaches, including probabilistic models and trajectory deviations, sparked discussions about their reliability in real-world scenarios. Moreover, discussions emerged about predictive maintenance's role in boosting UAV reliability. While some emphasized the advantages of preventing failures in advance, others debated the implementation and effectiveness of such strategies. The debate extended to the balance between investing in predictive maintenance versus other reliability-enhancing measures. The incorporation of UAVs into urban settings stirred debates, ranging from risk assessments to the challenges of managing densely populated areas.

Communication strategies within UAV systems also fueled debate. Advocates proposed cloud-based technologies for improved connectivity, but others raised concerns about potential vulnerabilities. Lastly, the literature debated the overall resilience of UAV systems, reflecting the multifaceted nature of decision-making in their design and operation. In summary, the literature review showcased various debates encompassing UAV swarm feasibility, risk quantification, predictive maintenance, urban deployment, communication strategies, and system resilience.

C. Gaps in the reviewed literature to date

One significant gap in the existing literature pertains to long-term studies on UAV reliability. While current research predominantly focuses on immediate improvements, there is a dearth of comprehensive investigations into how UAVs perform over extended operational lifespans and evolving environmental conditions. Bridging this gap would provide valuable insights into the sustained reliability of these systems throughout their service life. Additionally, a noticeable disparity exists between theoretical models and real-world validation. Many studies rely heavily on simulations and controlled scenarios. Addressing this gap by conducting empirical studies in complex operational environments would offer a clearer understanding of the practical applicability of reliability enhancements and risk assessment methodologies.

The literature also lacks an encompassing approach to multi-domain reliability. Given that UAVs are deployed across various domains, including urban environments and adverse weather conditions, research opportunities arise to comprehensively assess reliability across different operational contexts. Integrating factors such as urban challenges and complex airspaces would provide a more holistic understanding of reliability. Another unexplored area is the impact of human factors on UAV reliability. The existing literature focuses predominantly on technical aspects, leaving a gap in understanding how human operators influence UAV mission reliability. Investigating human error, training methodologies, and decision-making processes could shed light on the role of operators in ensuring reliable operations. Moreover, ethical and legal considerations are noticeably absent from the literature. While technical aspects take precedence, the ethical implications of UAV reliability, along with legal issues related to liability in the event of failures or accidents, remain underexplored.

D. Research opportunities

Research opportunities abound in the realm of UAV reliability and risk assessment. Integrated risk assessment frameworks, combining factors like environment, human elements, and system performance, could yield more accurate risk evaluations. Hybrid reliability approaches, integrating traditional methods and newer techniques like probabilistic models and data-driven analytics, offer a comprehensive understanding of UAV dependability.

Exploring resilience engineering for UAV systems, allowing adaptability and recovery from failures, could revolutionize reliability. In urban settings, strategies addressing challenges like collision avoidance and communication resilience could enhance UAV reliability. Human-centric reliability research, delving into operator interactions and human factors, promises insights for safer UAV operations. Lastly, dynamic risk assessment methodologies, enabling real-time adaptability, could ensure UAV operations remain reliable in ever-changing scenarios.

Chapter 3: Methodology

3.1 Structural Analysis and Design Technique (SADT):

This chapter discusses the use of SADT in the context of modeling operational risks for UAVs. While SADT is a valuable approach, there are other modeling frameworks available for system state modeling. Unified Modeling Language (UML) is a widely used modeling language in software engineering. It's versatile and can represent various aspects of a system, including its structure, behavior, and interactions. However, UML might be more oriented toward software-centric systems and may not capture operational risks and dynamic systems as effectively as SADT. Fault Tree Analysis is a technique primarily used to analyze the causes of failures in systems. It works well for identifying potential failure modes and their contributing factors. However, it might not provide a comprehensive view of the system's tasks, processes, and interactions, which is crucial for understanding UAV mission activities. Petri Nets are mathematical models that can represent concurrent and asynchronous systems. They're particularly useful for modeling processes and interactions between different entities. However, they might lack the explicit representation of task decomposition and the structured approach that SADT offers.

SADT's suitability stems from its structured approach and historical success in various sectors. It emphasizes UAV tasks, enhancing clarity for stakeholders. It is difficult to design decision support systems for domains that do not yet exist because approaches such as cognitive task and work analysis are difficult to implement due to a dearth of defined domains or users. Modelling the Operational Risks for UAVs task is an example of such an innovative area. In this paper, we propose the use of SADT to build a pilot area for increasing UAV reliability. SADT was selected because it offers a robust structured method for modelling dynamic systems, as well as the ability to describe and analyze the anticipated mission activities and the associated risk. The individual tasks of the UAV can be described using SADT in terms of input, control, processes, and output.

SADT is a visual modelling language used in systems engineering to define and explain a system's tasks and data flows. Douglas T. Ross and SofTech, Inc. created it in the 1970s [84]. Since its commercial introduction in 1973, SADT has been used in hundreds of initiatives across a wide range of sectors, including the maritime, telecommunications, and aircraft industries [85]. These apps, which describe an instruction system for the US army and simulate a port logistic process in Busan, Korea cover a wide variety of functions [86]. Although none of these examples reflect particularly innovative fields, several themes reoccur in these applications, making SADT particularly useful for the purpose of this thesis. Firstly, SADT concentrates on the tasks that we anticipate an UAV should carry out. The SADT makes those activities clear and will aid all parties in understanding why these activities are necessary. Secondly, SADT structurally accommodates crucial aspects of cognitive work like: - Who or what conducts the activity (referred to as "mechanisms" in SADT terminology); and - What directs or restricts the activity (referred to as "controls").

In conclusion, the model-building process for SADT includes a procedure to engage stakeholders at every level, from Project managers to laypeople, making it useful for enhancing internal communication. The conversation that results clarifies tasks and the responsibilities of SMEs, while also encouraging thought about process duplication and enhancement. Gaining organizational agreement on a method is largely dependent on the model building process.

3.2 Failure Mode and Effect Analysis (FMEA):

With the substantial growth in the use of UAVs in recent years, safety and dependability have taken on a priority status. UAV operations can be complicated, requiring various systems and components, and any failure or malfunction can result in a catastrophic consequence. Therefore, it is crucial to recognize and reduce any dangers related to UAV operations. A useful tool for detecting and controlling possible risks related to UAV operations is Failure Modes and Effects Analysis (FMEA). FMEA is a structured approach that is used to analyze potential failure modes and assess how they might affect the product (design FMEA - DFMEA) and procedure (process FMEA - PFMEA). DFMEA is used to evaluate product ideas before they are put into manufacturing and PFMEA is used to evaluate new or current processes [87]. It concentrates on the possible failure mechanisms connected with both process safety/effectiveness/efficiency and issues with a product's functions induced by process problems. Both approaches are used in this thesis.

A facilitator brings together a group of people with the necessary design and operating knowledge of the subsystem of interest. The process of quantifying Qualitative Assessment (Q) involves converting subjective descriptions, often expressed in Notional Text (NT), into numerical values for Severity (S), Occurrence (O), and Detectability (D). For each element, the group considers and reaches a consensus on three criteria:

- Severity (the consequence of a failure event): We assigned a numerical value to describe the potential impact or consequence of a particular failure mode. This can range from, for example, 1 (negligible impact) to 3 (catastrophic impact) for the scope of this thesis. The higher the number, the more severe the consequence.

- Occurrence (the probability that a failure event will occur within a specified time period without controls in place): We determined the likelihood or frequency of the failure mode occurring. Again, we assigned a numerical value, considering factors such as historical data, expert opinions, or statistical analysis. This scale typically ranges from 1 (highly unlikely) to 3 (highly likely).
- Detection (how a failure event can be detected or prevented): We evaluated the ease or difficulty of detecting the failure mode before it leads to a significant problem. We assigned a numerical value based on factors like the availability of monitoring systems, inspection procedures, or human intervention. The scale usually ranges from 1 (highly detectable) to 3 (difficult to detect).

Risk is conventionally the product of Severity and Occurrence (consequence x probability). Detection allows proactive control or mitigation of the effects of an event. After analyzing, a qualitative analysis is performed where the risks/failures are color-coded based on the value of the RPN. The formula for RPN is:

Risk Priority Number (RPN) = Severity x Occurrence x Detection (1)

The Risk containing the highest RPN value is color-coded in red as it is of the highest priority and the lowest one with the least RPN value is color-coded in green. The failure modes in the middle are color-coded in orange and yellow in ascending order of the RPN value. For the scope of this thesis and to avoid repetition, the FMEA analysis is performed on the actual stages of the mission.

During UAV operations, FMEA is a useful instrument for classifying risks and evaluating their significance. The team can plan for possible failures and take preventative action to mitigate them by recognizing potential failure modes [32]. The drone operating team can target high-risk failure modes and concentrate on mitigating them first with the help of FMEA, which allows them to assess the seriousness of the effects of each possible failure mode. This contributes to improving the safety and reliability of the UAV operation and assuring its effective conclusion without any incidents or accidents by finding and minimizing possible risks [88]. The team can concentrate on the most likely failure modes and take action to avoid them by knowing the probability of failure. FMEA offers a structured approach for creating both corrective and preventive actions to reduce possible failure modes [89].

In conclusion, FMEA is a crucial tool for finding and reducing possible risks connected to UAV missions. FMEA guarantees the secure and dependable completion of UAV operations by providing a structured approach for finding possible failure modes, evaluating their severity and probability, and creating corrective actions to mitigate.

3.3 Minimum Bayes Risk Analysis:

Minimum Bayes Risk (MBR) analysis is a widely used framework in Bayesian statistics for making decisions that minimize expected loss or risk. This analysis is a decision-making framework used in statistical decision theory and machine learning to make optimal decisions under uncertainty. It aims to minimize the expected loss associated with decisions made in situations where outcomes are uncertain and have associated costs or penalties. The basic idea behind MBR analysis is to quantify the risks associated with each potential course of action, estimate the expected loss or utility associated with each option, and then choose the course of action that minimizes the expected loss or maximizes the expected utility.

Conditional risk refers to the probability-weighted cost or loss associated with a specific decision, given that a certain event or condition has occurred. In the context of decision theory and risk analysis, it accounts for the potential consequences of making a particular choice considering the observed circumstances. It takes into consideration both the likelihood of a specific event or condition happening and the associated cost or loss if a particular decision is made under that circumstance. It helps decision-makers evaluate the potential outcomes of their choices while factoring in the uncertainties and variability inherent in real-world scenarios. The formula for each conditional risk is:

$$\boldsymbol{R(\alpha_i|x) = \sum_{j=1}^{C} \lambda(\alpha_i|\omega_j) P(\omega_i|x)} \tag{2}$$

for i = 1,..., a, where

a is the number of possible actions a

c is the number of states in the system

λ(ai|wj) is the loss function for taking an action “ai” when the state of the system is “wj”

P(wj|x) is the posterior probability that the state “wj” given that the feature vector “x” has been measured

We choose the course of action for which the sets of risks are R* (Bayes Risk) minimum:

$$R^* = \min R(a_i | x), \text{ where } i = 1.....a \quad (3)$$

MBR analysis relies on Bayesian probability theory, which provides a systematic way of updating beliefs or prior probabilities based on new evidence. Here, prior probabilities are assigned to different events or outcomes based on available information and expertise. These prior probabilities are then updated based on new information, such as data from sensors or other sources, to calculate the posterior probabilities. This analysis framework allows for the incorporation of uncertainty and ambiguity into decision-making, making it particularly useful in situations where there are multiple potential outcomes, and the risks and benefits of each option are not completely clear. By weighing the expected losses or utilities of different courses of action, it allows decision-makers to make informed choices that minimize risk and maximize utility. The primary objective is to identify the best course of action, i.e., mitigation strategy, that optimizes the expected utility while minimizing the expected cost or loss in the event of a specific failure mode.

In the area of UAVs, where there are numerous dangers and uncertainties related to their activities, Minimum Bayes Risk analysis is especially beneficial. A UAV operation, for instance, might run the chance of colliding with a barrier [89]. Different tactics, like operating the UAV at a lower height or attaching an obstacle recognition and avoidance system, can be used to reduce this danger. The best course of action in this case that reduces the expected chance of accident can be found using MBR analysis. By utilizing probabilistic modeling and prior information, MBR analysis helps to make informed decisions in complex and uncertain environments and supports the safe and efficient operation of UAVs.

In conclusion, MBR analysis is a useful instrument for selecting the optimal risk-mitigation plan for UAV missions. The method uses probabilistic modeling and Bayesian statistics to assess the risks and doubts related to various choices and strategies. MBR analysis can assist in ensuring the secure and effective operation of UAVs by helping to choose the approach with the lowest expected risk.

3.4 Estimating conditional probabilities for this type of system:

Estimating conditional probabilities for a UAV mission requires a thoughtful and data-driven approach. The process involves utilizing historical information to assess risks and failures at different stages of the mission, such as departure, arrival, and landing. By examining past mission outcomes, failure modes, and associated risks, valuable insights can be gained to inform the estimation process.

It is important to recognize that without a substantial amount of data, the analysis may rely more on qualitative assessments and expert judgment. However, by utilizing historical information, employing data-driven techniques, and following a structured approach, the estimation process becomes more robust and informed. This helps to enhance the safety and success of UAV missions while minimizing potential risks. Additionally, the estimation of probabilities from a population of data requires careful statistical analysis. By examining a sufficient sample size of relevant data, trends, patterns, and correlations can be identified. This allows for the calculation of probabilities based on observed frequencies and occurrences of specific events or outcomes. To ensure the accuracy of the estimation, it is crucial to select an appropriate sample that represents the mission characteristics and operational environment. This may involve considering factors such as geographical location, weather conditions, equipment specifications, and mission objectives. By selecting a representative sample, the estimated probabilities can more effectively reflect the actual risks and failure modes encountered during similar UAV missions.

The risk calculation process involves combining the estimated probabilities of various risks and failure modes to determine the overall risk level of the mission. To reduce risk, design and operational changes can be implemented based on the findings from the risk assessment. This may involve enhancing the UAV's sensor capabilities to improve gas leak detection accuracy, implementing collision avoidance systems to mitigate the risk of collisions with objects or humans, and incorporating advanced flight planning algorithms to provides the correct route selection and avoid potential hazards. Furthermore, establishing thorough maintenance protocols, providing comprehensive operator training, and implementing regular system checks and updates can significantly reduce the likelihood of failures and enhance overall mission safety.

Additionally, as the UAV mission progresses and data is collected, the information obtained can be used to refine and update the risk assessment. By analyzing the collected data, patterns and trends can be identified, allowing for a more data-driven approach to estimating conditional probabilities. This iterative process enables the refinement of risk assessments over time, leading to more accurate and reliable predictions of potential risks and failure modes. Furthermore, a robust communication and reporting system should be established to ensure that all stakeholders are aware of the identified risks, mitigation strategies, and any changes made to the mission plan. This promotes transparency, accountability, and effective collaboration among the team members involved in the UAV mission.

In conclusion, while the absence of specific data may present challenges, a combination of qualitative analysis, Bayesian inference, and the utilization of indirect data sources can support the estimation of conditional probabilities and the assessment of risks in the UAV mission of collecting aerial imagery of agricultural farms and methane gas leaks in pipelines. By incorporating design and operational changes based on the identified risks, the mission can be conducted with greater safety and success, while continuously monitoring and adapting to evolving conditions.

CHAPTER 4: Complete Risk Analysis of a General-purpose Mission

The word “mission” refers to the responsibility or assigned task, while “planning” represents a comprehensive and long-term development activity. The main benefit of the modeling approach presented here is that the method is sufficiently flexible to be tailored to the needs of any specific UAV mission. It is challenging to identify and diagnose faults if they resurface mid-flight for which the consequences can be significant, and so detecting an incipient fault before it becomes a functional failure is the preferable approach.

We employed the APEGA Risk Management System, which encompasses the identification, assessment, and mitigation of potential risks associated with engineering and geoscience practices. It employs a structured approach, leveraging industry best practices and regulatory guidelines to ensure the safety and integrity of projects. This system promotes proactive measures to safeguard public welfare and uphold professional standards within the engineering and geoscience community.

In the following diagrams, we show how we created a comprehensive representation of the system being analyzed that can be used to identify and address any issues. Firstly, we identified the system to be analyzed, which in this case was the UAV mission in Figure 4. Secondly, we created a process diagram that shows the inputs, outputs, and processes involved in the component by using flowcharts in Figure 5.

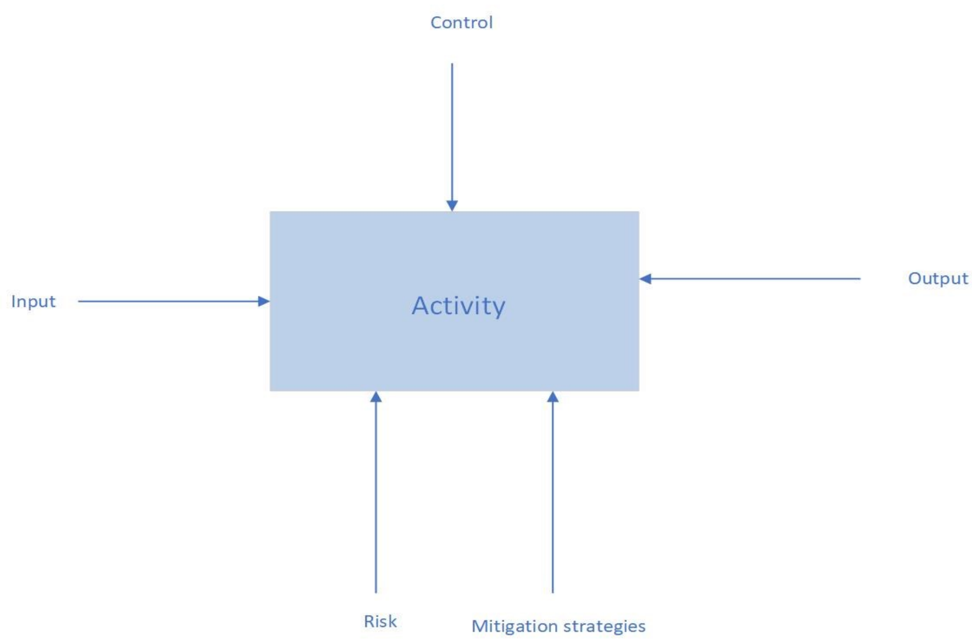

Figure 4: Basis element of the SADT

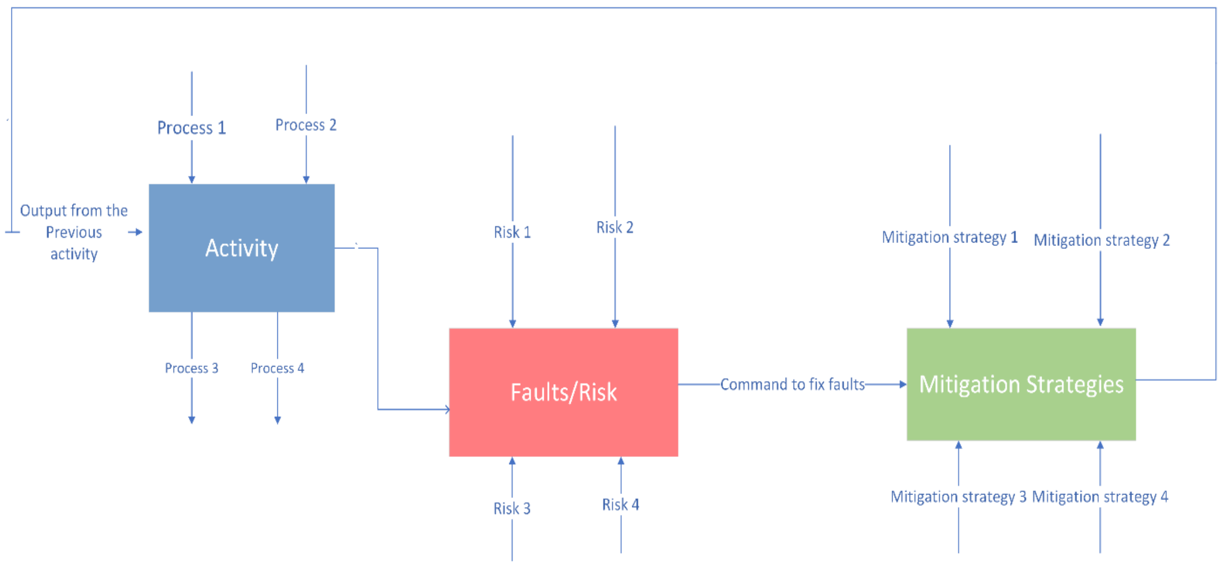

Figure 5: Top-down decomposition structure

We started by defining the key elements of a general-purpose UAV mission, including the objectives, the actual UAV, the operators, the surroundings, and any other elements that are pertinent to the mission. Then, we broke down each essential component into its corresponding functions and sub-functions. The UAV itself, for instance, can be divided into sub-functions for take-off, flying, and landing. We identified the possible risks that might arise for each function and sub-function. Risks in the flight sub-function, for instance, might include losing contact with the UAV or having one of its parts malfunctions. After that, we assigned probabilities and consequences to each of the identified failures. We calculated the RPN value to decide the importance of a specific failure. This made it easier to rank the dangers based on priority by color-coding.

To mitigate the risks, we developed strategies such as implementing redundant systems, increasing operator training, or adjusting the mission parameters. Later, we re-evaluated the probabilities and impact of the risks and calculated the Residual RPN value to determine the effectiveness of the mitigation strategies. The SADT model was documented, along with the risks, probabilities, outcomes, repercussions, and mitigation techniques that had been determined. This will serve as a helpful resource for upcoming operations and can be revised as new risks are found or mitigating measures are put in place based on the type of mission.

Then, we use the process of conducting FMEA for UAV missions as a detailed and structured approach to identify and mitigate potential risks. For the first step, we identified the components of the system and the potential failure modes associated with each component. We then brainstormed and identified all possible failure modes associated with each component, ensuring that no potential failure mode is overlooked [90]. The probability of each possible failure mode occurring was then assessed. This was accomplished using past information from relevant documents, professional judgment, and statistical analysis. Additionally, we assessed the severity of the effect of each potential failure mode on the UAV mission using a severity matrix that assigns a score to each potential effect. The risk priority number (RPN) was subsequently determined for each possible failure scenario. RPN was determined by combining the values for detectability, severity, and probability [91]. For simplicity and as a starting point, Severity was described on a 3-point scale where 3 was highest, Occurrence was described on a 3-point scale where 3 was highest and Detection was described on a 3-point scale where 3 was highest. The maximum value for RPN in this case was 27. Based on the RPN ratings, we prioritized the failure modes and used color coding to prioritize mitigating the high-risk failure modes first [92]. As a result, we created corrective measures to reduce and possibly eradicate the high-risk failure scenarios. This involved redesigning the system or process, improving maintenance procedures, or adding redundancy to critical components in certain cases.

RPNs don't have a cutoff number. In other words, there is no number below which the team is immediately excused from taking a suggested action or above which it must perform the recommended action. The issue was whether corrective action is required, even though the objective of any corrective action is to lower the Severity, Occurrence, and/or Detectability rankings. Based on the findings from the overall risk analysis, we made significant choices about whether to take on the duties at hand or modify them during the risk management process. If a risk level does not exceed an acceptable risk level, which is set at the start of the project, the operation is permissible, and no corrective action is required. In any company field, accepting a "Zero" risk level as the ultimate standard is foolish. Firstly, it is impossible to accomplish, and secondly, even if it were hypothetically feasible, it would not be lucrative.

After that, we used MBR analysis framework that uses probabilistic modeling along with prior information to estimate the risks associated with different options or strategies. The prior probabilities were subjective probabilities assigned based on the available information and expertise of SMEs [93]. These prior probabilities served as the foundation for the analysis, providing an initial assessment of the likelihood of each risk and potential mitigation strategy. Then we estimated the conditional probabilities of the risks and tactics based on the sensor data from the UAV and other external variables. These conditional probabilities helped in refining the prior probabilities and make the estimates more accurate and relevant to the specific mission scenario. Once the conditional probabilities were determined, the expected risks associated with each mitigation plan were calculated. This involved weighing the conditional probabilities of each risk and potential mitigation strategy against the associated costs or losses [88]. The expected risk calculation allowed for a quantitative comparison of the different mitigation strategies and helped to identify the optimal strategy that minimized the overall expected risk. Finally, the best plan or mitigation strategy was determined to be the one with the lowest expected risk. This was the primary goal of the MBR analysis framework – to identify the best course of action that minimizes risk while maximizing utility.

We estimated conditional probability by doing a thorough analysis of available historical data. This data included records from previous UAV missions, incident reports, and any relevant information on similar operations. By carefully studying this data, patterns and trends were identified, allowing for a more accurate estimation of the conditional probabilities associated with different risks and failure modes. Each mission stage was then examined individually to assess the specific risks and failure possibilities. Factors such as equipment malfunction, adverse weather conditions, human error, and technical limitations were considered. By quantitatively analyzing historical data, it became possible to assign probabilities to the occurrence of these risks at each stage of the mission. By taking a data-driven approach, reliance on SME estimates was minimized. Instead, statistical methods and data analysis techniques were employed to derive more objective and reliable estimates. This helped to ensure that the estimation process was grounded in empirical evidence and avoided potential biases or limitations associated with subjective judgments. The calculated conditional probabilities were then combined to calculate the overall Minimum Bayes Risk for the UAV mission. This provided a quantitative measure of the potential risks involved, allowing for a comprehensive understanding of the mission's risk profile. It enabled decision-makers to prioritize and allocate resources effectively, focusing on areas with higher risks and developing mitigation strategies accordingly.

In situations where there was limited or insufficient data available, a qualitative approach, such as a hazard and operability (HAZOP) analysis, was employed. During the HAZOP analysis, a multidisciplinary team of experts, including UAV operators, engineers, agronomists, and pipeline specialists, brainstormed potential hazards and failure scenarios. Each scenario was then evaluated in terms of its likelihood of occurrence and the severity of its impact on the mission objectives and safety. The team drew upon their collective knowledge and experience to estimate the probabilities of these identified risks and failure modes. While these estimates might not be based on quantifiable data, they provided valuable qualitative insights into the risks associated with each mission stage. To reduce risks, design and operational changes were proposed based on the outcomes of the HAZOP analysis. For example, in the departure stage, strict protocols were established to ensure the UAV was properly calibrated, the battery was fully charged, and all required equipment was functioning correctly. During the flight, regular communication between the UAV operator and the ground control station was maintained to address any emerging risks or issues.

The following section outlines the SADT diagram and the Minimum Bayes Risk Analysis as well as going into detailed explanations for the activities. The diagram in Figure 6"mother node" below is divided into three parts: activities preceding the mission, the mission and activities succeeding the mission.

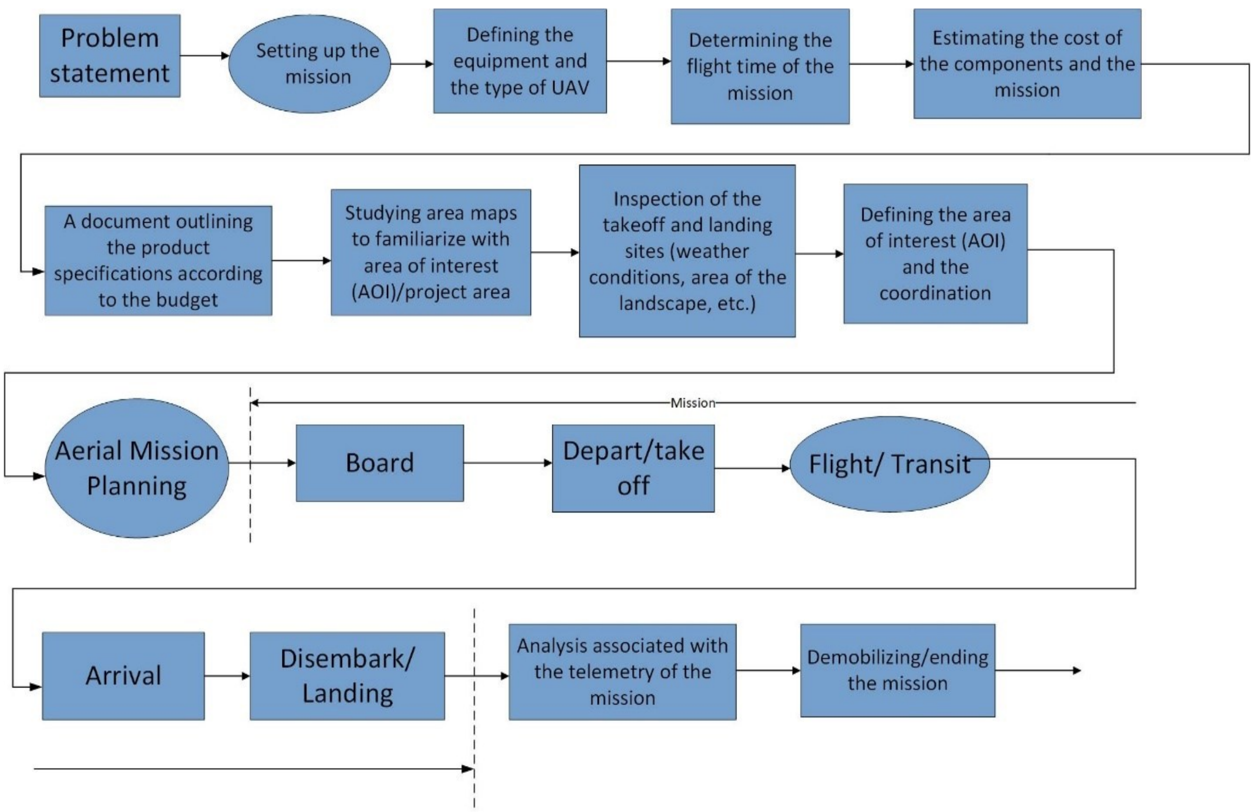

Figure 6: Mother node

4.1 Activities preceding the Mission:

Mission planning includes determining the following requirements for the activities preceding the mission as shown in

Figure 6:

- Determining the objective of a UAV mission (Problem Statement)
- Setting up for the mission
- Defining the equipment
- Determining flight time
- Estimating costs
- Defining product specifications
- Studying area maps
- Selecting take-off and landing sites
- Defining the area of interest and coordination
- Planning the aerial mission
- Tracking/flight
- Landing

4.1.1 Determining the objective of a UAV mission (Problem Statement):

The first and foremost decision that needs to be made before the start of the mission is to determine the objective. Some common objectives for UAV missions include collecting aerial data such as images, videos, or sensor readings, surveying large areas, performing search and rescue operations, monitoring environmental conditions, conducting research, and inspecting infrastructure such as bridges, buildings, and power lines. The goal of the mission may be to gather information, perform a specific task, or support decision-making processes.

The objective of a UAV mission can be influenced by various factors, such as:

- Mission requirements: These requirements can be varied and can include tasks such as surveillance, reconnaissance, search and rescue, delivery, inspection, and mapping. Depending on the mission requirements, the objective of the UAV mission can vary significantly.

- Payload and sensors: The type of payload and sensors installed on the UAV can influence the mission objective. For example, a UAV equipped with a camera might be used for surveillance and reconnaissance, while a UAV equipped with a LIDAR sensor might be used for mapping.

- Environmental conditions: Environmental conditions, such as weather, terrain, and time of day, can also influence the objective of a UAV mission. For example, a UAV mission may need to be rescheduled or modified if weather conditions make it unsafe to fly or if the mission objective cannot be met due to poor visibility.
- Regulatory requirements: UAV missions are often subject to regulatory requirements that can influence the objective of the mission. For example, flight altitude, flight path, and flight duration may be restricted by regulations, which can affect the mission objective.

- Cost and resources: Cost and resource constraints can also influence the objective of a UAV mission. For example, a UAV mission may need to be modified or scaled back if cost or resource constraints make it impractical to achieve the original mission objective.

Determining the objective of the mission is crucial for effective mission planning, resource allocation, mission execution, and performance evaluation as shown in Figure 7. It provides a clear direction for the mission and ensures that the mission objectives are achievable and appropriate. For instance, if the main mission objective of the UAV is to deliver a payload to a ground target, then the UAV needs to be designed with light and durable material to be able to fly at a reasonable pace while carrying a significant weight as a package. The type of mission will determine the selection of the location as well as the required weather conditions on flight day, provide a basis for evaluating the performance of the mission, and aid in allocating the appropriate resources such as personnel, equipment, and budget required for the mission. The output of this stage is a document developed to be signed both by the project managers and stakeholders.

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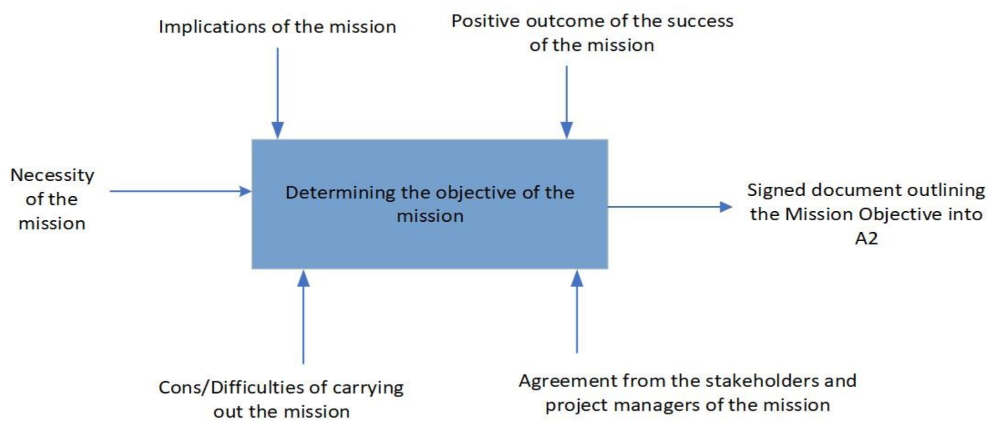

Figure 7: Determining the objective of the mission

In the following Minimum Bayes Risk Analysis tables, the mitigation strategy with the lowest risk value among others is chosen for a specific failure mode. This is highlighted with the color "green". For the scope of this thesis and to avoid repetition, the "Minimum Bayes Risk" analysis is performed on the preceding and succeeding stages of the mission.

Table 1: Failure: Cons/Difficult of carrying out the mission

For this failure, there are two possible risk controls and for 2 possible states there are four consequences conditional risk scenarios.

	Agreement from the stakeholders and project of the mission			DO NOTHING	
c	Reliable	Unreliable		Reliable	Unreliable
P(x|w1)	0.35	0.65	P(x|w2)	0.2	0.8
λ(α1|w1)	0.0025	15	λ(α2|w2)	10	10
	0.000875	9.75		2	8
R1	**9.75**		R2	10	
	Minimum Bayes Risk				

4.1.2 Setting up for the mission:

During setting up for the mission, the UAV needs to undergo a pre-flight check to ensure that it is in good working condition. This check includes verifying that the sensors, batteries, and communication systems are functioning correctly as well as determining the degree of autonomy for the UAV. There are several ways in which UAVs (Unmanned Aerial Vehicles) can be controlled. Some of the most common methods include remote control where a human operator controls the UAV using a remote control device that sends commands to the UAV's on-board flight computer, an autopilot system which is a flight control system that enables a UAV to fly autonomously without the need for direct human input (this system uses sensors and GPS to maintain the UAV's flight path and altitude) and waypoint navigation where the operator pre-programs a series of waypoints that the UAV follows as well as modify the flight plan in real-time if necessary. In short, the UAVs can be directly controlled by an operator, have operational autonomy solely (their operations are planned and overseen by a central station and/or human operators), or have decisional autonomy capabilities, which means they can complete complex missions on their own. However, a central station or a human operator should be able to take control of any of these UAVs depending on the circumstances.

The UAVs need to perform various activities during a mission and so one activity may overlap with another, causing confusion [93]. Therefore, it is important to finalize the order of the activities so that the time frame of an individual activity does not coincide with other activities and/or exceed the scheduled timeline in order to plan and prevent resource conflicts as mentioned in
Figure 8. Additionally, it is necessary to provide a task assignment protocol in the system as well as some metrics to determine whether giving a task to a particular robot is appropriate [94]. Depending on the mission, it may be necessary to obtain permissions or approvals from local authorities or aviation regulators so that UAVs can conduct the mission safely and effectively. This includes obtaining any required flight permits, filing flight plans, and complying with airspace regulations.

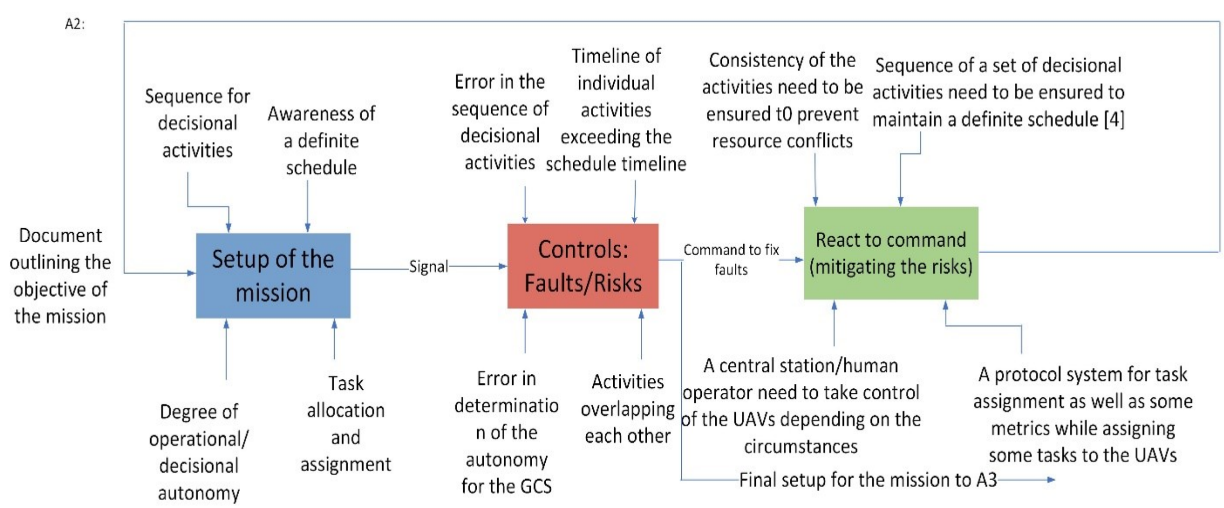

Figure 8: Mission setup

Table 2: Failure: Error in the sequence of decisional activities

For this failure, there are two possible risk controls and for 2 possible states there are four consequences conditional risk scenarios.

	Consistency of activities are ensured to prevent resource conflicts			DO NOTHING	
c	Reliable	Unreliable		Reliable	Unreliable
P(x|w1)	0.45	0.55	P(x|w2)	0.2	0.8
λ(α1|w1)	0.0035	18	λ(α2|w2)	5	5
	0.0001575	9.9		1	4
R1	9.90		R2	5	
				Minimum Bayes Risk	

Table 3: Failure: Timeline of individual activities exceeding the scheduled timeline

For this failure, there are two possible risk controls and for 2 possible states there are four conditional risk scenarios.

	Sequence of a set of decisional activities are ensured to maintain a definite schedule			DO NOTHING	
c	Reliable	Unreliable		Reliable	Unreliable
P(x|w1)	0.65	0.35	P(x|w2)	0.2	0.8
λ(α1|w1)	0.0015	20	λ(α2|w2)	10	10
	0.000975	7		2	8
R1	**7.00**		R2	10	
	Minimum Bayes Risk				

Table 4: Failure: Error in determination of the autonomy of GCS

For this failure, there are two possible risk controls and for 2 possible states there are four conditional risk scenarios.

	A central system/human operator need to take control of the UAVs depending on the circumstances			DO NOTHING	
c	Reliable	Unreliable		Reliable	Unreliable
P(x|w1)	0.75	0.25	P(x|w2)	0.3	0.7
λ(α1|w1)	0.0025	17	λ(α2|w2)	9	9
	0.001875	4.25		2.7	6.3

R1	**4.25**		R2	9	
	Minimum Bayes Risk				

Table 5: Failure: Mission activities overlapping each other

For this failure, there are two possible risk controls and for 2 possible states there are four conditional risk scenarios.

	A protocol system for task assignment as well as some metrics while assigning some tasks to the UAVs			DO NOTHING	
c	Reliable	Unreliable		Reliable	Unreliable
P(x|w1)	0.55	0.45	P(x|w2)	0.5	0.5
λ(α1|w1)	0.0053	15	λ(α2|w2)	9	9
	0.002915	6.75		4.5	4.5
R1	**6.75**		R2	9	
	Minimum Bayes Risk				

4.1.3 Defining the equipment:

When deciding on the best UAV type, we start by defining the mission requirements, including the duration of the mission, the altitude and speed required, the payload requirements, the type of duties the drone will perform need to be considered to determine what characteristics are required: speed and range, or maneuverability and precision, and any other relevant factors.

The flight time, as well as the carrying capacity and take-off weight, should also be considered. The ability to install various payloads and additional equipment is influenced by load capacity. Depending on the tasks and the sort of data required, both the payload and the UAV type need to be chosen. A photo or video camera, a magnetometer, a gas analyzer, or a laser scanner are all possible payloads for the drone involved in specific missions. Precise identification of the data collection method is important. Therefore, the vehicle's weight has an impact on the UAV's stability in the air; the heavier it is, the more stable its trajectory is and the better the image quality as mentioned in Figure 9. For example, Fixed-wing UAVs can stay in the air longer and thus fly longer distances. However, they cannot work in a confined space as it needs to be constantly in motion to fly. Copter-type UAVs are best suited for the examination of objects and confined spaces as they have a simple design and stable flight. But they have a shorter range than fixed-wing UAVs due to comparatively low speed and flight time. In short, different UAVs are suitable for different agendas. To ensure the correct equipment selection, it is essential to conduct test flights and evaluations to ensure the UAV is fully capable of performing the required tasks in the expected environment. So, multiple prototypes can be used at different stages of experimentation to test out the necessary functions which will aid in identifying the components of the UAV(s). It is important to evaluate the performance capabilities of different UAVs, including their range, payload capacity, flight time, maximum altitude, and operating temperature range. The selected UAV should be capable of performing the required tasks, operate in harsh conditions, and be resistant to wear and tear.

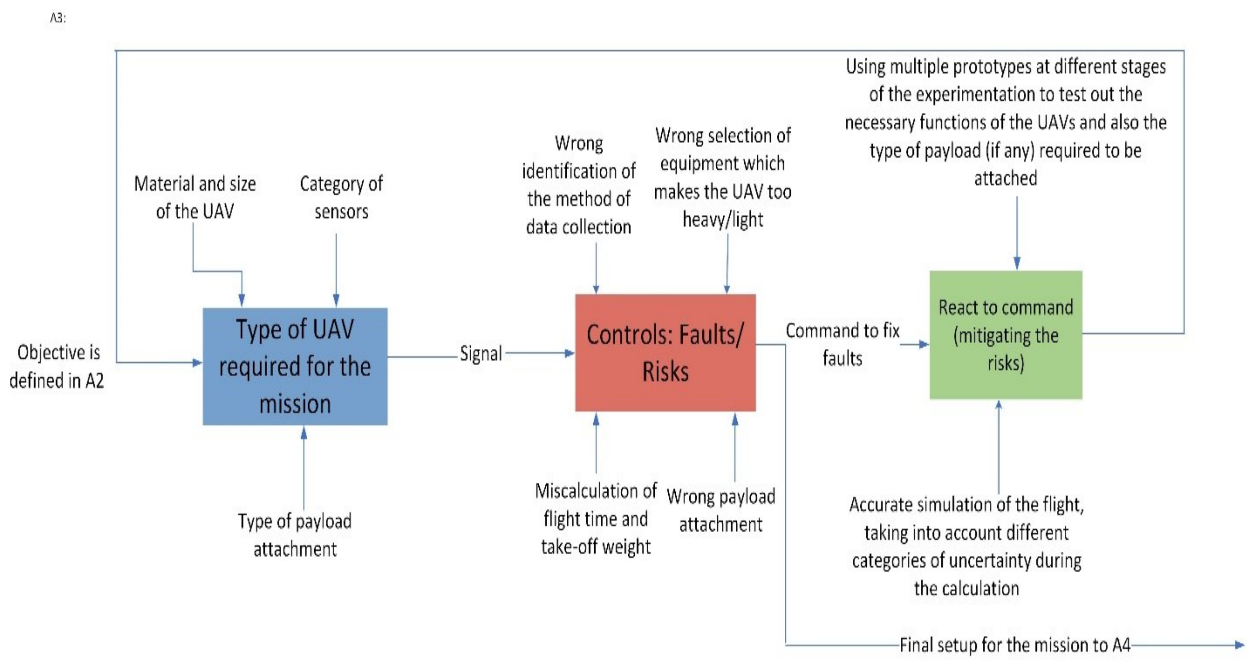

Figure 9: UAV type required for the mission

Table 6: Failure: Wrong identification of method of data collection, miscalculation of flight and take-off time.

For this failure, there are two possible risk controls and for 2 possible states there are four conditional risk scenarios.

	Accurate simulation of flight, considering different categories of uncertainties during the calculation			DO NOTHING	
c	Reliable	Unreliable		Reliable	Unreliable
P(x|w1)	0.75	0.25	P(x|w2)	0.7	0.3
λ(α1|w1)	0.0045	17	λ(α2|w2)	9	9
	0.003375	4.25		6.3	2.7
R1	**4.25**		R2	9	
	Minimum Bayes Risk				

Table 7: Failure: Wrong selection of equipment/payload which makes the UAV too heavy/light for the mission.

For this failure, there are two possible risk controls and for 2 possible states there are four conditional risk scenarios.

	Multiple prototypes are used at different stages of the experimentation to test out the necessary UAV functions			DO NOTHING	
c	Reliable	Unreliable		Reliable	Unreliable
P(x|w1)	0.75	0.25	P(x|w2)	0.7	0.3
λ(α1|w1)	0.0045	17	λ(α2|w2)	9	9
	0.003375	4.25		6.3	2.7
R1	**4.25**		R2	9	
	Minimum Bayes Risk				

4.1.4 Determining flight time:

The flight time of a UAV is influenced by various factors such as the type of UAV, its weight, the environmental conditions, and the mission requirements. Flight testing is one of the most reliable methods to determine a UAV's flight time for a specific mission. It involves flying the unmanned aerial vehicle (UAV) in real-world circumstances, monitoring its performance, and recording flight times, which can then be used to estimate the UAV's flight time under mission circumstances. Additionally, drone flight simulator software can be used by operators to model the UAV and simulate its flight under different environmental and mission conditions to estimate the flight time.

The challenge in mission planning is to identify the routes for a UAV that will save flight time while ensuring recognition of the greatest possible number of stated targets [95]. This is the fundamental mission planning activity, which should be completed at the outset of planning to confirm the mission's viability. Many important factors that will affect how the operation is carried out must be considered in this work, such as the presence of hazards in the area or the necessary window of time for a UAV to arrive at its target as shown in Figure 10. The generic mission plan consists of a particular task being assigned to the UAV according to which a set of waypoints will be assigned to the UAV [96]. GIS software to analyze the location and distribution of targets, as well as the terrain and other environmental factors. This information can be used to plan a route that optimizes flight time while ensuring that the greatest possible number of targets are recognized.

The UAV determines the sequence to visit a collection of waypoints in the smallest amount of time given the waypoints and then autonomously navigates to the waypoints, while avoiding an obstacle, for a particular mission. Miscalculating the flight route will result in failure to cover the necessary waypoints. The objective is to assign jobs so that they are all finished within the minimum amount of time while facing the minimum number of setbacks.

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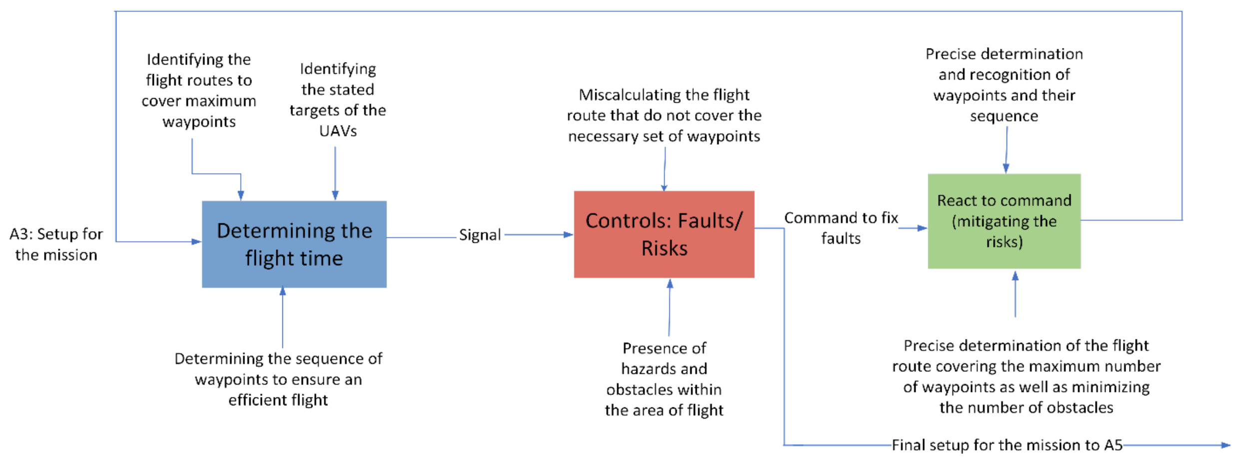

Figure 10: Determining the Flight time

Table 8:Failure: Miscalculating the flight routes that do not cover the necessary waypoints

For this failure, there are two possible risk controls and for 2 possible states there are four conditional risk scenarios.

	Precise determination and recognition of the waypoints and their sequence			DO NOTHING	
c	Reliable	Unreliable		Reliable	Unreliable
P(x|w1)	0.45	0.55	P(x|w2)	0.7	0.3
λ(α1|w1)	0.0015	12	λ(α2|w2)	10	10
	0.000675	6.6		7	3
R1	**6.60**		R2	10	
	Minimum Bayes Risk				

Table 9:Failure: Presence of hazards and obstacles within the area of flight

For this failure, there are two possible risk controls and for 2 possible states there are four conditional risk scenarios.

	Precise determination of the flight route covering maximum number of waypoints as well as minimizing the number of obstacles			DO NOTHING	
c	Reliable	Unreliable		Reliable	Unreliable
P(x|w1)	0.35	0.65	P(x|w2)	0.6	0.4
λ(α1|w1)	0.0025	14	λ(α2|w2)	10	10
	0.000875	9.1		6	4
R1	**9.10**		R2	10	
	Minimum Bayes Risk				

4.1.5 Estimating costs:

The recurring costs per flying hour of an UAVs need to be considered while estimating flight costs. The formulation for recurring costs is the operating and maintenance costs of a fleet divided by the number of flying hours that fleet accumulated during the duration of the mission, acquisition costs and the life-cycle costs per flying hour, which include acquisition costs and costs per flying hour need to be considered as mentioned in
Figure 11 [96].

The following are some of the key factors to consider:

1. UAV hardware expenses: the cost of the components (such as the wings and control surfaces, propulsion systems, control systems, communication elements, and launch and recovery subsystems, data link, sensors) of the air vehicle and the equipment required to attach the payload also needs to be considered.
2. Payload costs: If a payload, such as a sensor or camera, is required for the mission, the expense of the payload must be weighed.
3. Maintenance costs: Regular maintenance is required to keep the UAV in excellent working condition. This covers the expenses of routine maintenance, repairs, and part replacement.
4. Fuel costs: Depending on the type of UAV, the task may necessitate the use of fuel, which can be costly.
5. Personnel costs: These costs include hiring and training personnel to run the UAV and carry out the mission.
6. Insurance costs: Insurance may be needed to protect against damage or loss depending on the nature of the task and the risks involved.
7. Regulatory costs: Depending on the mission's location, regulatory costs associated with getting permits and complying with local regulations may apply.
8. Overhead costs: These are indirect expenses incurred by a business that are not directly tied to a specific product or service, such as rent, utilities, and administrative salaries. They contribute to overall operations but aren't directly attributable to individual production units.
9. Costs of data processing and analysis: If the task necessitates data processing or analysis, these expenses must be considered.

Reviewing the outline of the problem statement and mission setup will aid in accurately estimating each component and/or include the missing ones. There are various cost estimation tools available, such as spreadsheets and specialized software (Costimator) [97], can help in estimating the costs of a UAV mission accurately. Once the initial estimate has been made, the project managers need to evaluate and revise the estimate based on additional information or changes in the mission. Blunders such as wrong selection of equipment can result in a wrong estimation of costs. The cost-benefit analysis needs to be done according to the objective of the mission to optimize the equipment expenses- if accuracy is not of paramount importance, then the quality of the components can be compromised to be cost effective.

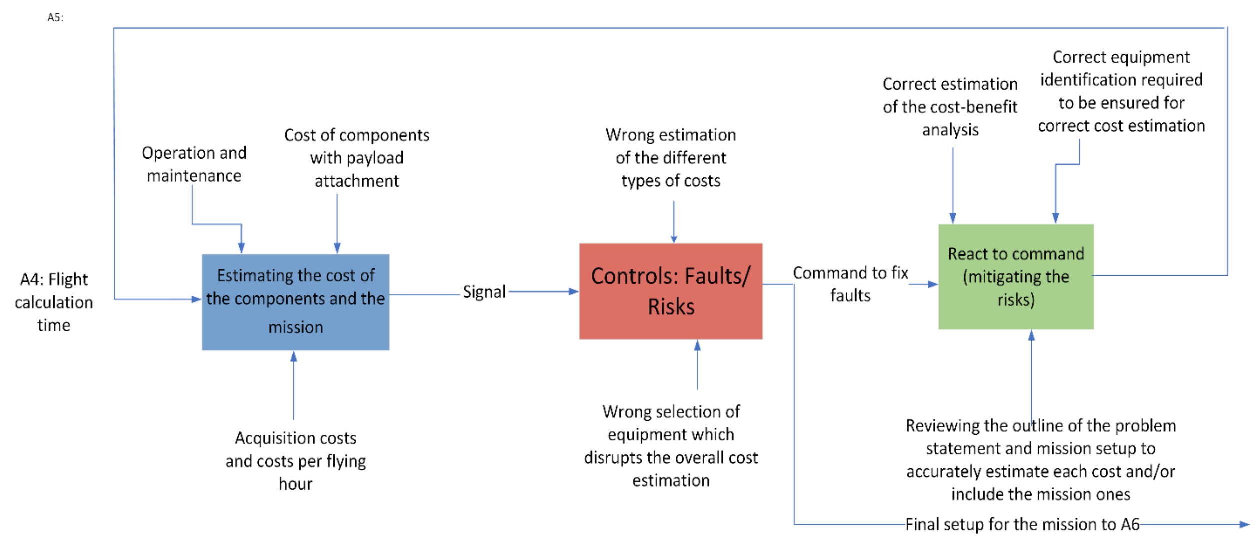

Figure 11: Cost estimation of the mission components

Table 10:Failure: Wrong selection of equipment which disrupts the overall cost estimation

For this failure, there are three possible risk controls and for 2 possible states there are six conditional risk scenarios.

	Reviewing the outline, the problem statement and mission setup to accurately estimate each cost and add/include missing ones			Correct identification of the equipment following the mission objective document			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable		Reliable	Unreliable
P(x|w1)	0.25	0.75	P(x|w2)	0.7	0.3	P(x|w3)	0.7	0.3
λ(α1|w1)	0.0015	12	λ(α2|w2)	15	0.0033	λ(α3|w3)	11	11
	0.000375	9		10.5	0.00099		7.7	3.3
R1	**9.00**			10.50099		R2	11	
	Minimum Bayes Risk							

Table 11:Failure: Incorrect estimation of different recurring costs

For this failure, there are two possible risk controls and for 2 possible states there are four conditional risk scenarios.

	Correct utilization of tools such as cost estimator to perform cost-benefit analysis of the mission			DO NOTHING	
c	Reliable	Unreliable		Reliable	Unreliable
P(x|w1)	0.25	0.75	P(x|w2)	0.5	0.5
λ(α1|w1)	0.0022	12	λ(α2|w2)	12	12
	0.00055	9		6	6
R1	**9.10**		R2	12	
	Minimum Bayes Risk				

4.1.6 Defining product specifications:

Defining product specifications for a UAV mission involves identifying and specifying the performance requirements of the UAV to meet the needs of the mission. The specific mission requirements will help determine the type of UAV and payloads that is best suited for the task. The payload consists of the equipment or instruments that the UAV will transport to complete the mission goals such as aerial photography, mapping, surveying, or surveillance. When developing the UAV's product specifications, the UAV's and payload's weight, size, and power needs should be considered. Thus, this technical document needs to be tailored to that specific objective, mentioning the reason for manufacturing a body part, the final aim of it and the way to measure success.

There are a few major disturbances that might affect the outcome of the mission. For instance, the range, which is the maximum distance that the UAV can travel from the ground station while still maintaining communication and control, will depend on the type of UAV and the communication and control equipment used. This can be different than the values chosen according to UAV mission flight simulation and hence the values provided by the manufacturer. Therefore, the project teams need to create and test prototypes early to verify whether they meet user needs, product specifications and design goals as mentioned in Figure 12. Using a single prototype to test both usability and functionality to save money one time will eventually be more time consuming in the long run [97]. If the prototype is intended to address multiple issues, it may be wiser to divide them into separate prototypes or create more. Making a small number of prototypes will not allow your team to execute tests in parallel as the project moves into the development phase. For instance, a prototype should be used to answer and another to check UAV communication range in the operating environment. This will save time and money and increase the success rate of the project.

Additionally, the cost and time associated with these activities need to be carefully accounted for (by shareholders and project managers) to prevent major schedule delays. The output of this stage is a document that contains a collection of requirements that is used to develop new features or capabilities, expenses of the associated components.

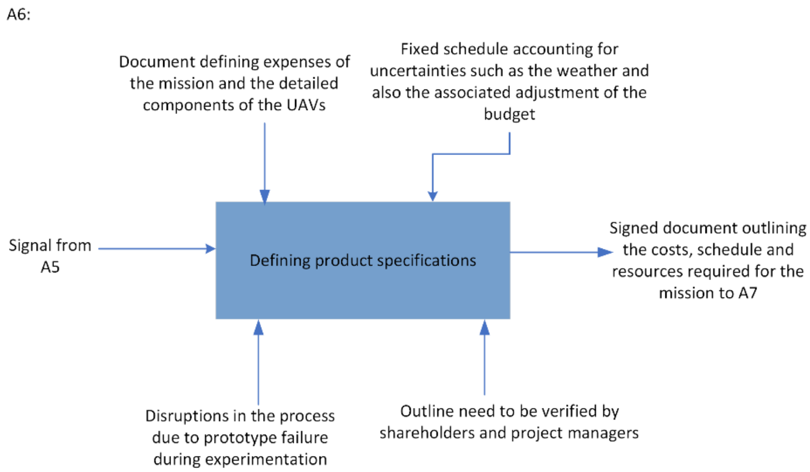

Figure 12: Product specifications

Table 12: Failure: Incorrect Product specifications during flight due to values differing from flight simulation

For this failure, there are two possible risk controls and for 2 possible states there are four conditional risk scenarios.

	Project teams creating and testing multiple prototypes to test and verify user needs, product specifications and design goals simultaneously in the real mission environment			DO NOTHING	
c	Reliable	Unreliable		Reliable	Unreliable
P(x|w1)	0.45	0.55	P(x|w2)	0.5	0.5
λ(α1|w1)	0.0013	8	λ(α2|w2)	12	12
	0.000585	4.4		6	6
R1	**9.10**		R2	12	
	Minimum Bayes Risk				

4.1.7 Studying area maps:

The operators must ensure that they have up-to-date and accurate maps of the region in which they intend to fly. Official sources such as the National Geospatial-Intelligence Agency (NGA), commercial mapping providers, and open-source mapping tools such as OpenStreetMap can provide the maps. Alternatively, flight planners can also familiarize themselves with the project area by looking at several types of maps, specifically U.S. Topo Quadrangle Maps and Sectional Aeronautical Charts. The U.S. Topo Quadrangles Map depicts the outlines of the land in detail. This map provides all the information a planner requires regarding the topography in the project region. Flight plan factors such as flight lines, spacing, and imagery spacing are affected by topography [98].

The Sectional Aeronautical Chart Series is designed for visual navigation of slow to medium speed aircraft at a scale of 1:500,000 [9]. Visual checkpoints, such as populated areas, drainage patterns, roads, railroads, and other unique objects, are included in the topographic data which helps to identify potential hazards, such as power lines, tall structures, and natural obstacles like trees and mountains as mentioned in Figure 13. They are used for flight under visual flight rules. The planner should also check for any airspace restrictions, such as no-fly zones, temporary flight restrictions, and airspace classifications.

Figure 13, the term "Signal from A6" refers to the output generated by the "Defining product specifications" stage, preceding the "Studying area maps" stage in the UAV mission planning process. This output serves as a crucial input signal for the subsequent stage responsible for analyzing area maps and determining safe navigation routes for the UAV. By incorporating the information from the signal, the next stage can make more informed decisions about the drone's navigation, considering factors such as mission requirements, operational constraints, geographical features, and potential hazards [99]. If the flight planners fail to completely understand the flight path of the UAS, it will be difficult to achieve the objective for which it was designed for, resulting in a mission failure. By studying area maps in this way, operators can plan UAV flights that are safe, efficient, and effective in meeting the mission objectives.

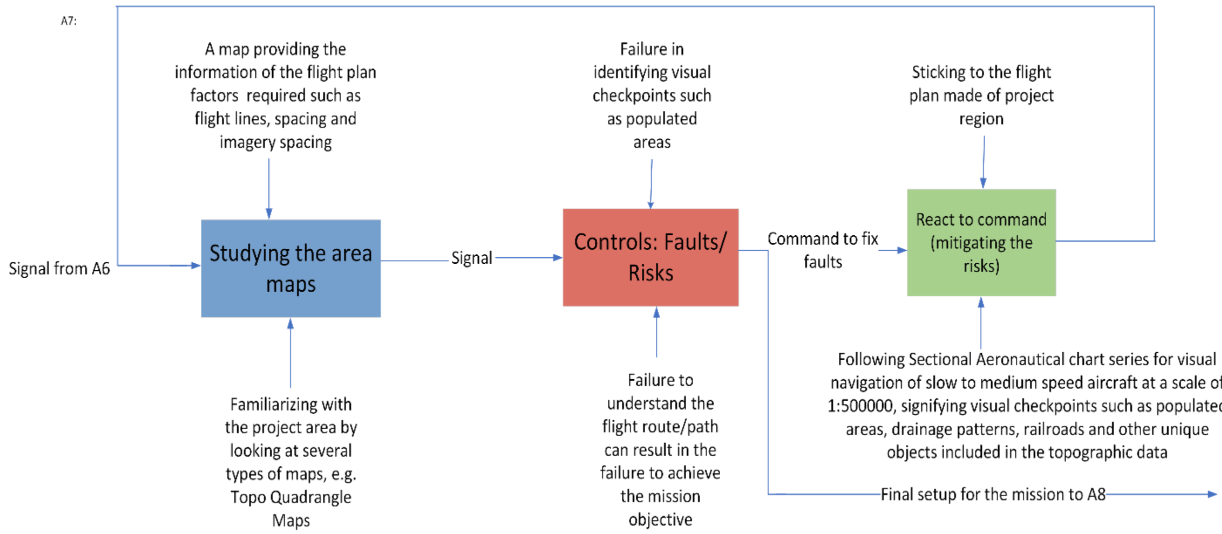

Figure 13: Studying area maps

Table 13 Failure: Unable to identify visual checkpoints such as populated areas and drainage patterns

For this failure, there are two possible risk controls and for 2 possible states there are four conditional risk scenarios.

	The flight planner follows the Sectional Aeronautical Chart Series designed for visual navigation of slow to medium speed aircraft			DO NOTHING	
c	Reliable	Unreliable		Reliable	Unreliable
P(x|w1)	0.15	0.85	P(x|w2)	0.3	0.7
λ(α1|w1)	0.0043	10	λ(α2|w2)	10	10
	0.000645	8.5		3	7
R1	**8.50**		R2	10	
	Minimum Bayes Risk				

Table 14: Failure: Flight planners unable to understand the flight path/route

For this failure, there are three possible risk controls and for 2 possible states there are six conditional risk scenarios.

	Planning using official sources such as the National Geospatial-Intelligence Agency (NGA), commercial mapping providers, and open-source mapping tools such as OpenStreet Map can provide the maps.			Familiarizing with the project area by looking at several types of maps, specifically U.S. Topo Quadrangle Maps, while outlines the area of interest in detail.			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable		Reliable	Unreliable
P(x|w1)	0.45	0.55	P(x|w2)	0.6	0.4	P(x|w3)	0.5	0.5
λ(α1|w1)	0.0005	10	λ(α2|w2)	13	0.0045	λ(α3|w 3)	10	10
	0.000225	5.5		7.8	0.0018		5	5
R1	**5.50**			7.8018		R2	10	
	Minimum Bayes Risk							

4.1.8 Takeoff and Landing sites:

The weather directly impacts small and medium-sized UAVs because they fly at low altitudes as identified in Figure 9. To perform these maneuvers safely, it is critical to understand the direction, wind speed, and air pressure. Operations require fast and accurate weather information for flight preparations, take-offs, and landings. Real-time weather information can be from obtained Local weather stations, which can be installed near the launch and landing sites or along the flight path.

The area/space required for landing procedures is determined by the kind and size of the platform [100]. An open area with a level surface (such as a sports field) is frequently the best option. The following are the factors that need to be considered for choosing an appropriate site:

1. Legal considerations: The site must follow all relevant laws and regulations, including those related to airspace restrictions and safety.
2. Safety: The site must be safe for the UAV to take off and land, with minimal risk of collision with obstacles or other aircraft.
3. Weather conditions: The site should be suitable for the current weather conditions, and ideally,

it should be sheltered from strong winds or other weather hazards that could affect the UAV's performance.

4. Proximity to the mission area: The site should be near the mission area, to minimize the time and energy required for the UAV to reach its destination.
5. Availability: The site should be easily accessible and available for use as needed.
6. Logistics: The site should have enough space for the UAV to safely take off and land, and for the ground, crew to work and prepare the UAV for flight.
7. Cost: The cost of using the site, including any fees or permissions required, should be reasonable and affordable.
8. Support facilities: The site should have all necessary support facilities such as power, communication, and maintenance facilities.

This list is not exhaustive, and it can vary depending on the mission, UAV, and scenario. The route planner determines the “optimal” route in the form of waypoints for the UAV to follow, by receiving start and destination points from the supervisory controller as shown

Figure 14 [101]. A waypoint is a specific point in space that a drone is programmed to fly to or navigate towards.

In

Figure 14, the term "Signal from A7" refers to the output generated by the "Studying area maps" stage that precedes the "Takeoff and landing sites" stage. This output is used as an input signal for the next stage, which is responsible for identifying suitable takeoff and landing sites for the UAV. Essentially, the signal from A7 provides important information to the next stage of the process, enabling it to make more informed decisions about where the drone can safely take off and land. By using this information, the UAV can be deployed more effectively and with greater confidence, ultimately leading to improved performance and safety in drone operations. As mentioned in Figure 8, the risk mitigation strategy would be a desktop assessment utilizing maps and photos that should precede an in-person inspection to ensure that the site is acceptable for takeoff and landing. Proper training of UAV operators is needed to recognize potential hazards and to make safe decisions when choosing takeoff and landing sites. Before selecting a takeoff or landing site, the operator should conduct a thorough assessment of the area to identify potential hazards, such as power lines, buildings, or other obstacles. Although weather-related changes are difficult to predict, planning for extra days might be beneficial.

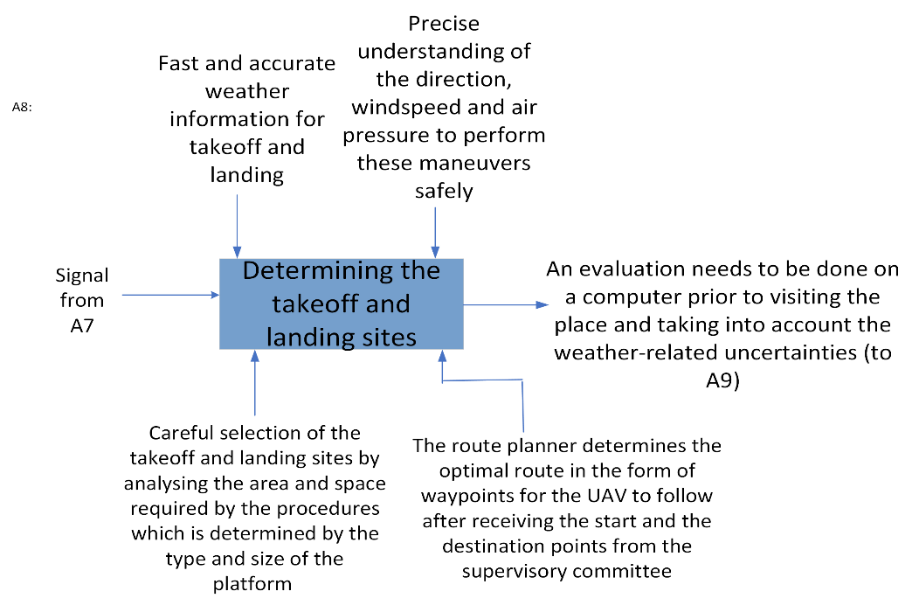

Figure 14: Selection of Takeoff and Landing sites

Table 15: Failure: The operator was unable to maneuver safely at low altitudes due to lack of precise understanding of the weather and wind speed.

For this failure, there are four possible risk controls and for 2 possible states there are eight possible conditional risk scenarios.

	Real-time weather information obtained from Local stations			The route planner determines the optimal route in the form of waypoints, by considering weather uncertainties			A desktop assessment utilizing maps and photos followed by an in-person inspection of the site.			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable	c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.35	0.65	P(x|w2)	0.55	0.45	P(x|w3)	0.25	0.75	P(x|w4)	0.3	0.7
λ(α1|w1)	0.00015	8	λ(α2|w2)	10	0.0055	λ(α3|w3)	0.00022	7.5	λ(α4|w4)	8	8
	0.000525	5.2		5.5	0.002475		0.000055	5.625		2.4	5.6
R1	**5.51**		R2	5.50		R3	5.62		R4	8	
	Minimum Bayes Risk										

4.1.9 Defining the area of interest and coordination:

The selection of the AOI is important as it can impact the safety, efficiency, and effectiveness of the UAV's operation. To minimize risks associated with choosing takeoff and landing sites, it is important to conduct a thorough assessment of the AOI, including evaluating factors such as weather conditions, air traffic, terrain, and potential hazards.

The mapping needs and environmental conditions dictate the area of interest (AOI) where photos will be taken as mentioned in Figure 15 [102]. The area of interest for a UAV mapping mission is determined by a combination of mapping needs and environmental conditions. Mapping needs include factors such as the resolution, accuracy, and coverage required for the final map product. Environmental conditions include factors such as weather, terrain, and land use that may affect the safety and feasibility of the mission as mentioned in Figure 9. For example, if a high-resolution map is required for a densely populated urban area, the AOI will likely be limited to the city limits, whereas if a low-resolution map is sufficient for a rural area, the AOI may be much larger. Additionally, if the mission is to be flown in an area with challenging weather conditions such as high winds or heavy rain, the AOI may need to be adjusted to account for these conditions. Factors such as the availability of take-off and landing sites, and airspace regulations also affect the AOI. It's important to consider all these factors when defining the AOI to ensure a safe, efficient, and effective mission.

In the context of Figure 15, the term "Signal from A8" refers to the output generated by the "Takeoff and landing sites" stage, which occurs prior to the "Defining area of interest and coordination" stage in the UAV mission planning process. This signal represents the information and decisions related to the identification and selection of suitable takeoff and landing sites for the UAV. It provides valuable data and considerations about the chosen takeoff and landing locations, ensuring that the following stage can effectively define the area of interest and coordinate the UAV's mission objectives accordingly. A geographic information system (GIS) is a technology that allows users to collect, store, manage, analyze, and visualize geographic data. This technology can be used as a backdrop to help determine the area of interest (AOI) for UAV operations [101]. GIS can be used to analyze various factors such as terrain, weather patterns, land use, and regulations to identify suitable areas for takeoff and landing sites. Additionally, GIS can be used to create detailed maps that can help UAV operators navigate the AOI and avoid potential hazards. By using GIS as a backdrop, operators can make more informed decisions about the AOI and minimize risks associated with choosing takeoff and landing sites.

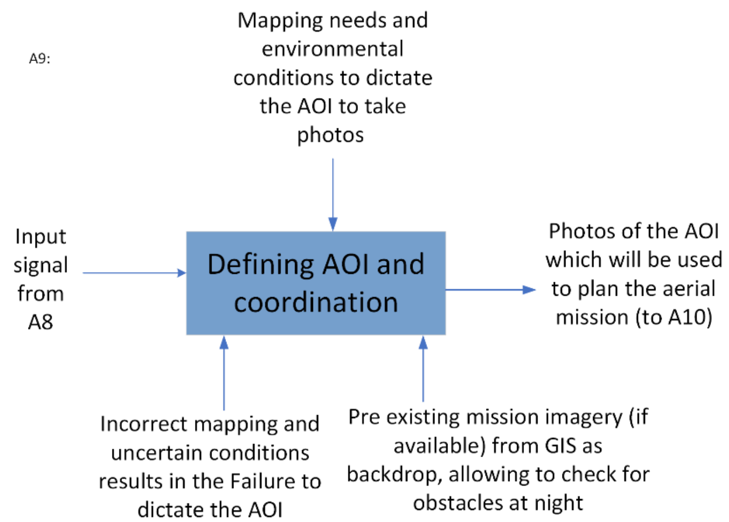

Figure 15: Area of interest definition and coordination

Table 16: Failure: Unable to dictate AOI due to incorrect mapping and uncertain conditions

For this failure, there are three possible risk controls and for 2 possible states there are six conditional risk scenarios.

	Geographic Information system (GIS) used as a backdrop to analyze factors such as terrain and weather to create detailed maps which can be used by the operator to avoid hazards and identify suitable sites			Mapping needs such as resolution and environmental needs such as weather, land considered while defining AOI. A contingency plan is implemented to tackle uncertainties		DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable	Reliable	Unreliable
P(x|w1)	0.65	0.35	P(x|w2)	0.55	0.45	0.4	0.6
λ(α1|w1)	0.0085	14	λ(α2|w2)	10	0.0065	12	12
	0.005525	4.9		5.5	0.0065	4.8	7.2
R1	**4.90**			5.50		12	

	Minimum Bayes Risk						

4.1.11 Planning the aerial mission:

Mapping software or a geographic information system (GIS) is used to plan the flight path, including the altitude, speed, and waypoints. Before takeoff, conduct a preflight check of the aircraft, equipment, and flight plan to ensure everything is in order. It is ensured that the aircraft and equipment are in good working condition, charged, and configured correctly before takeoff.

During the mission, the aircraft's performance and the environmental conditions are monitored by a ground-based computer system, which can also control the UAV and its cargo, and adjustments are made as necessary to ensure the mission is completed safely and successfully. If the UAV has payloads, such as a group of sensors, made up of TV cameras, infrared sensors, thermal sensors, etc., to collect data attached to it, the information collected can be processed in part on-board or sent to a base station for more research as identified in Figure 16.

The IMU data in aerial imagery can be used to enhance the accuracy of imagery gathered by the camera or sensor on the UAV. The precise position, attitude, and velocity of the UAV can be calculated using data from the IMU and used to correct for any movement or shake in the imagery caused by the UAV's motion [103]. This is especially essential when capturing high-resolution imagery or data that needs pinpoint accuracy in geolocation. An Inertial Measurement Unit (IMU) is a device that measures and reports a UAV's specific force, angular rate, and sometimes magnetic field. It is an essential component of many aerial platforms used in aerial imagery acquisition. IMUs typically consist of a combination of accelerometers, gyroscopes, and magnetometers that work together to provide accurate data on the UAV's orientation and movement as shown in Figure 10. Furthermore, IMUs can be used to improve the efficiency and safety of UAV flights by giving real-time data on the attitude and stability of the UAV. This data can be used to adjust the UAV's flight path or altitude to avoid obstacles or to keep the UAV within a specified operating area.

Prior to the widespread use of inertial measurement units (IMUs) in aerial imagery, ground control points (GCPs), differential GPS, and photogrammetric tie points were used to acquire navigation and positioning information. GCPs are physical ground markers with known coordinates that serve as reference points for precisely positioning aerial images. Differential GPS uses a network of ground-based GPS receivers to enhance GPS coordinate accuracy. While these techniques are still used today, IMUs have gained popularity due to their ability to provide accurate navigation and positioning information in real time without the need for ground-based reference points.

In the context of Figure 16, "Signal from A9" refers to the output generated by the "Defining area of interest" stage. This stage comes before the "Planning the aerial mission" stage, and its output provides critical information that informs the planning of the mission. A combination of communication methods should keep the base station and UAV in constant contact, such as radio modems, satellite communications, microwave links, etc. for things like wetland ecosystem monitoring, coastal management, damage assessment following a disaster like a major typhoon, and vegetation mapping [104].

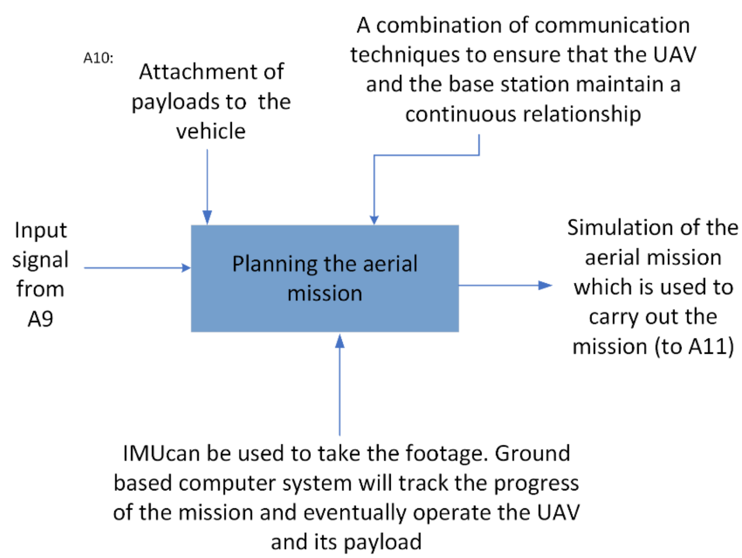

Figure 16: Aerial mission planning

Table 17: Failure: Failing to collect data due to inaccuracy of the software used

For this failure, there are two possible risk controls and for 2 possible states there are four conditional risk scenarios.

	Replacing Ground Control Points (GCPs) with Inertial			DO NOTHING	

	Measurement Unit (IMUs) to collect data				
c	Reliable	Unreliable		Reliable	Unreliable
P(x|w1)	0.25	0.75	P(x|w2)	0.4	0.6
λ(α1|w1)	0.0013	8	λ(α2|w2)	8	8
	0.000325	6		3.2	4.8
R1	**6.000325**		R2	8	
	Minimum Bayes Risk				

4.2 Mission:

The following lists the activities that take place during a general mission:

- Boarding
- Takeoff
- Arrival
- Tracking/flight
- Landing

The following section outlines the SADT diagram and the FMEA Analysis as well as going into detailed explanations for the activities.

4.2.1 Boarding (initialization):

This is the first step of the mission. During boarding, the navigation sensors (GPS+INS) must be tested out. A GPS receiver can be used to provide the UAV with accurate information about its position, velocity, and altitude. This information can be used to control the UAV's flight and ensure that it is following the correct flight path. An Inertial Navigation System (INS) is a navigation aid that uses inertial motion sensors to continuously track position, orientation, and velocity [104]. By using a combination of these different navigation sensors, it is possible to provide the UAV with the accurate and reliable information it needs to navigate safely during the boarding stage.

The Ground operators follow the standard operating procedures which includes running a test of the software and hardware such as vessel inspection. If proper SOP is not followed and/or if the autonomous FCS loses control, the hardware will malfunction, and the results can be catastrophic to human lives in the AOI. Therefore, as a preventive measure correct SOPs should be followed, and faulty sensors should be replaced [105]. Providing operators with proper training on the UAV's systems, controls, and procedures can help to improve their efficiency and reduce the risk of errors or accidents as demonstrated in Figure 18. This can include both classroom instruction and hands-on training with the UAV itself. Automating certain tasks such as takeoff and landing or incorporating an auto-pilot feature can help reduce the operator' and improve efficiency during flight.

The key equation that would be used to analyze the boarding process of a UAV would be Newton's second law of motion, which states that the acceleration of an object is equal to the force acting on it divided by its mass. The thrust equation is important to consider during the boarding process, which relates the thrust produced by the UAV's engines to the velocity of the exhaust gases and the mass flow rate of the fuel being burned. In the case of a UAV, the force acting on it during boarding would be the thrust force minus the drag force, and the mass is the weight of the UAV. The thrust equation is given by:

*T = mdot * ve + (pe - pa) * A_e,* (4)

where *T* is the thrust, *mdot* is the mass flow rate of the fuel, *ve* is the velocity of the exhaust gases, *pe* is the pressure of the exhaust gases, *pa* is the atmospheric pressure, and *A_e* is the area of the exhaust nozzle. The drag equation is given by:

*D = 1/2 * rho * v^2 * S * C_D* (5)

where D is the drag force, ρ is the density of the air, v is the velocity of the UAV, *S* is the wing surface area, and $C_D$is the drag coefficient.

$$Force,\ F = T - D = \dot{m} * v_e + (p_e - p_a) * A_e\} - \{1/2 * \rho * v^2 * S * C_D\} \quad (6)$$

Some systems on a UAV, such as high-resolution cameras, or advanced sensors, may require more power to operate, which can lead to faster battery depletion. Also, UAVs that are flown in harsh environments, such as high temperatures or high altitudes, can experience battery depletion faster, as the battery may have to work harder to power the UAV's systems. The age of the battery can also play a role in battery depletion, as batteries lose capacity over time as shown in Figure 17. This failure can be reduced by carefully planning the flight, such as minimizing the flight time, or selecting the most efficient flight path. Implementing a battery management system can help to monitor the battery's state of charge, temperature, and other parameters, and adjust the UAV's systems accordingly to reduce power consumption and extend the battery's life as shown in Table 18. Regularly replacing the batteries with fresh ones can help to ensure that the UAV has enough power to complete its mission.

In Figure 17, the term "Input from A10" refers to the output generated by the "Aerial mission planning" stage in the UAV mission planning process. The information and decisions derived from the "Aerial mission planning" stage, represented by the Input from A10, play a crucial role in determining the specific requirements, objectives, and parameters of the UAV mission. This input guides the subsequent "Boarding" stage, ensuring that the necessary resources, equipment, and personnel are prepared and ready for the mission.

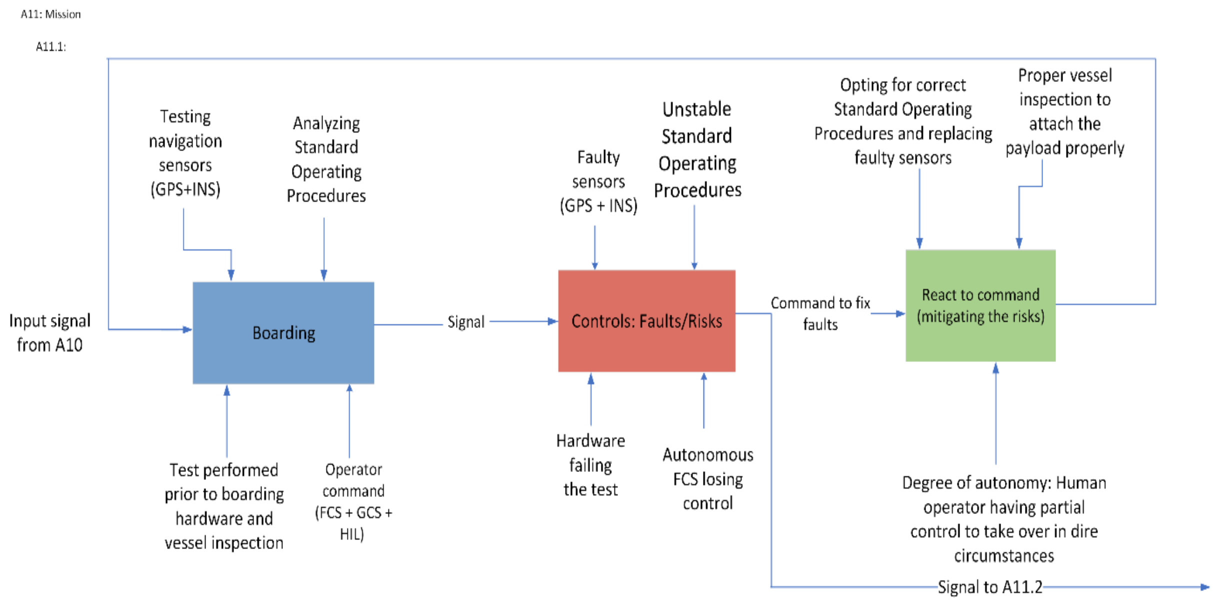

Figure 17: Boarding

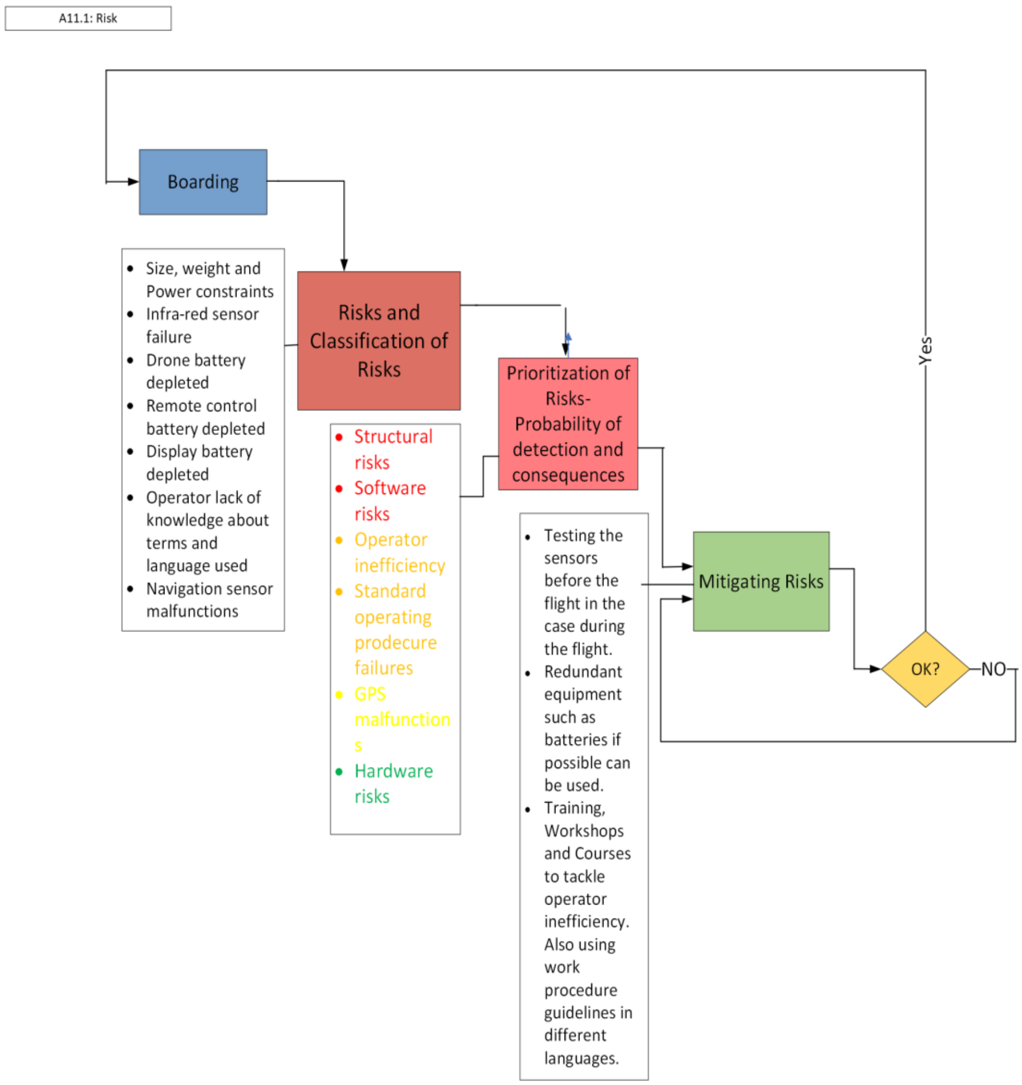

Figure 18: Ranked Risks associated with Boarding

The table below demonstrates a qualitative analysis of the risks associated with the "Boarding" stage of the UAV mission, the RPN values associated with them, the controls implemented to mitigate them, the residual risk after the controls are implemented and the trigger for the failures in the stages:

Table 18: FMEA of the Boarding stage

Faults and related operating conditions	Likelihood	Severity	Detectability	RPN (uncontrolled)	Risk Control	Residual RPN	Trigger
Structural and Software risks: Size, weight, and power constraints	3	3	3	27	The designers who are involved with manufacturing the UAV need to be fully aware of the objective of the mission to appropriately design it	1	Structural risks may be detectable through visual inspections and stress testing of the UAV's components and systems. Software risks can be detected through coding review, testing and quality assurance, penetration testing, and vulnerability scanning.

Operator inefficiency: lack of knowledge about terms and language used	3	2	3	18	Training, workshops, and multilingual work procedure guidelines address operator inefficiency.	2	Questioning the operator about the specific times and procedures, as well as observing their interactions with the UAV. Another approach is to track the UAV's performance and safety during flight operations. If the operator is making errors, it maybe be visible on the flight logs.
GPS malfunctions: Navigation sensor functions	1	3	2	6	Sophisticated navigation algorithms can be set up along with sensors by the design engineers on the control system of the UAV.	2	GPS signals can be blocked by obstructions or jammed, while hardware malfunctions can result from damage or environmental factors.
Hardware risks: Sensor failure, depleted drone, remote control, and display batteries.	2	2	1	4	Operators should check sensors before flight and use redundant equipment if necessary. Routine checks are performed to replace faulty sensors, depleted batteries, and motors.	1	Infrared sensors can fail due to physical damage, extreme temperatures, humidity, or software issues. Drone battery depletion can result from flight duration, energy-intensive features usage, and display battery depletion can occur from prolonged use.

4.2.2 Takeoff/Departure:

The UAV travels until it reaches the target assigned. During this stage, the body rates and the lateral accelerations need to be monitored with low-level control systems [106]. Low-level control systems are divided into Roll Rate Control, Lateral Acceleration Control, Pitch Rate Control, Speed Control, and Yaw Rate Control (ground steering). Loss of guidance due to a failure in any of these control systems, such as sensor fault due to fouling or damage, wiring connection due to corrosion, etc., is a common problem during takeoff/departure. This can result in the lateral acceleration drifting from the inertial output as mentioned in Figure 19. An innovative solution to the gust alleviation issue is Active Spanwise Lift Control. Spanwise control regulates lift and drag with more precision. One way to minimize the risks is to opt for a guidance algorithm to control the rate of acceleration and pitch to a certain extent. An early fault mitigation in this stage is preflight inspection. Preflight inspection involves physical checks of the drone, including the drone's batteries, propellers, and other components; checks of the drone's flight control; checks of the drone's camera and gimbal and document requirements, such as a drone license and insurance.

There are two types of simple aerodynamic flight equations that explain how non-linearities interfere with flight conditions:

Lift equation: This equation relates the lift force exerted on the UAV to the velocity of the air flowing over its wings, the angle of attack of the wings, and the air density. The lift equation is given by:

*L = 1/2 * rho * v^2 * S * C_L,* (7)

where L is the lift force, rho is the density of the air, v is the velocity of the UAV, S is the wing surface area, and C_L is the lift coefficient.

The second equation is the Drag equation L = 1/2 * rho * v^2 * S * C_L,

(7). One way in which the equations can be non-linear is if the lift coefficient or drag coefficient are themselves non-linear functions of the UAV's angle of attack. The lift coefficient and drag coefficient are both aerodynamic coefficients that describe how much lift or drag the UAV's wings produce at a given angle of attack. These coefficients can be highly dependent on the shape and size of the wings, as well as the speed and altitude at which the UAV is flying. If the lift coefficient or drag coefficient are non-linear functions of the angle of attack, the UAV's takeoff performance will also be non-linear as mentioned in Table 19. These factors need to be incorporated in the simulation [107].

The risks associated with the mission as shown in Figure 20. For instance, when the UAV takes off, it might collide with people, man-made structures, and property which might have devastating consequences including loss of lives. The involvement of human lives automatically makes it a high-priority risk. Detect and Avoid (DAA) systems are essential for UAVs to safely navigate in airspace shared with other aircraft. These systems rely on a range of technologies and techniques to detect and mitigate collision risks [108]. One commonly used DAA technology is radar, which uses radio waves to detect the presence and location of other aircraft. Radar sensors provide valuable information on the position, distance, and relative speed of nearby aircraft, enabling the UAV to assess potential collision risks and adjust its flight path accordingly. Another DAA technology is Light Detection and Ranging (Lidar). Lidar sensors emit laser pulses and measure the time it takes for the pulses to return after hitting objects in the surrounding environment. By analyzing the reflected laser light, the sensors can generate detailed 3D maps of the surroundings, including the positions and movements of other aircraft. This information allows the UAV to accurately assess the proximity of nearby aircraft and make evasive maneuvers if necessary.

Cameras are also commonly used in DAA systems. They capture visual images of the surrounding airspace and feed them into computer vision algorithms that can detect and track other aircraft. These vision-based systems use advanced image processing techniques to identify and analyze the position, size, and trajectory of nearby aircraft. By continuously monitoring the camera feed, the UAV can detect potential collision risks and take appropriate avoidance actions. Furthermore, some DAA systems utilize Automatic Dependent Surveillance-Broadcast (ADS-B), a technology that allows aircraft to broadcast their identification, position, altitude, and other information. UAVs equipped with ADS-B receivers can receive this broadcasted data from other aircraft, enabling them to maintain situational awareness and avoid potential conflicts. Additional examples of DAA technologies include acoustic sensors that detect the sound signatures of other aircraft, as well as electronic scanning phased array radars that provide enhanced coverage and detection capabilities.

While transponders on other aircraft can provide valuable information, relying solely on estimating distances from transponders may not be sufficient for safe UAV operation. Transponders provide limited data and may not always accurately represent the actual position and proximity of other aircraft. Therefore, UAVs typically utilize multiple detection and tracking systems, including radar and sensors, to enhance situational awareness and ensure reliable collision avoidance.

Rules and regulations for UAV (unmanned aerial vehicle) flight vary depending on the country or region where the UAV is being flown as mentioned in Figure 20. In general, there are several key rules and regulations that are commonly enforced to ensure the safe operation of UAVs. Flight Restrictions: UAVs are generally not allowed to fly in restricted airspace, such as near airports, military bases, and other sensitive areas. They are also typically restricted from flying above certain altitudes, such as higher than 122 meters above ground level in many countries. Visual Line-of-Sight (VLOS) requirements: Many regulations require that the pilot or operator of a UAV must always maintain visual line-of-sight (VLOS) with the UAV [109]. This means that the pilot or operator must be able to see the UAV with the naked eye, without the use of binoculars or other visual aids. Remote Pilot Certification: Depending on the country and type of flight, an operator may be required to obtain a remote pilot certification, which typically involves passing an aeronautical knowledge test and undergoing a flight review. Aircraft registration: Some countries may require UAVs to be registered before they can be flown [110]. This can help to ensure that the UAVs are operated safely and in compliance with the rules and regulations. Insurance: Many countries require UAV operators to have liability insurance to cover any damage or injury that may occur because of a UAV flight. Flight Planning: Before each flight, a flight plan should be created, and safety precautions need to be taken. This includes identifying the location of the take-off and landing sites, the flight path, the weather conditions, and any potential obstacles or hazards in the area [111]. Educating the employees about rules and regulations through training, workshops, and courses can mitigate the failures that result from deviating from the Standard Operating Procedures (SOP). It is important to be familiar with the specific rules and regulations for UAV flights in your area, as they can vary widely from country to country, and even from one region to another. Many countries are also updating their regulations as UAV technology is evolving quickly, so it's a good idea to stay informed about any changes.

In Figure 19, the term "Input from A11.1" refers to the output generated by the "Boarding" stage in the UAV mission planning process. The information and decisions made during the "Boarding" stage, represented by the Input from A11.1, play a vital role in preparing the UAV for departure and take-off. It includes factors such as crew and equipment readiness, payload integration, safety checks, and any necessary final adjustments before the UAV initiates its mission. The Input from A11.1 ensures a smooth transition from the boarding phase to the actual departure and take-off of the UAV, facilitating a well-prepared and efficient start to the mission.

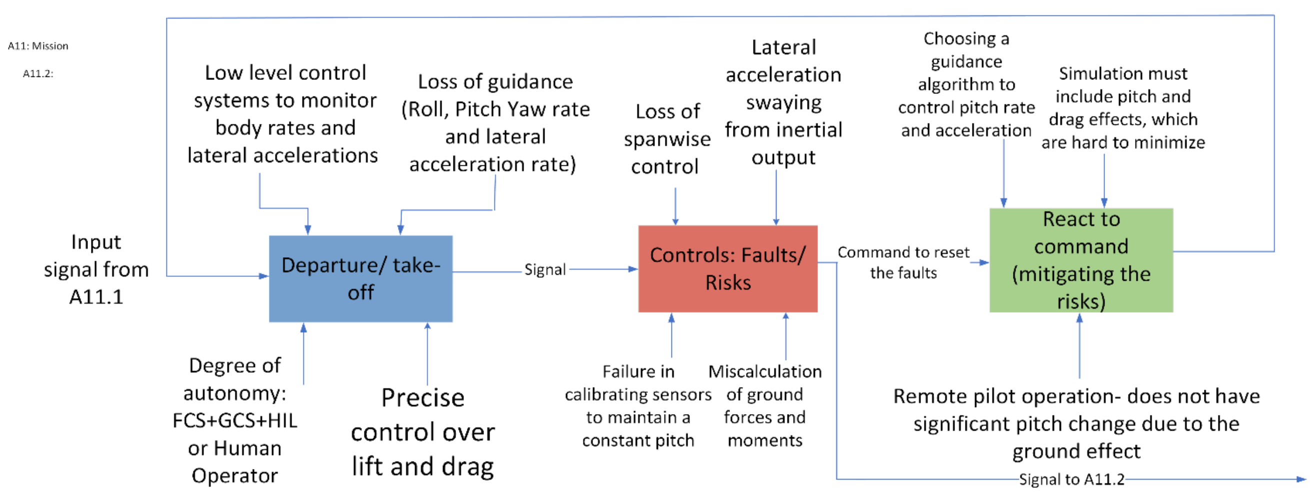

Figure 19:Departure/ take-off

A11.2: Risk

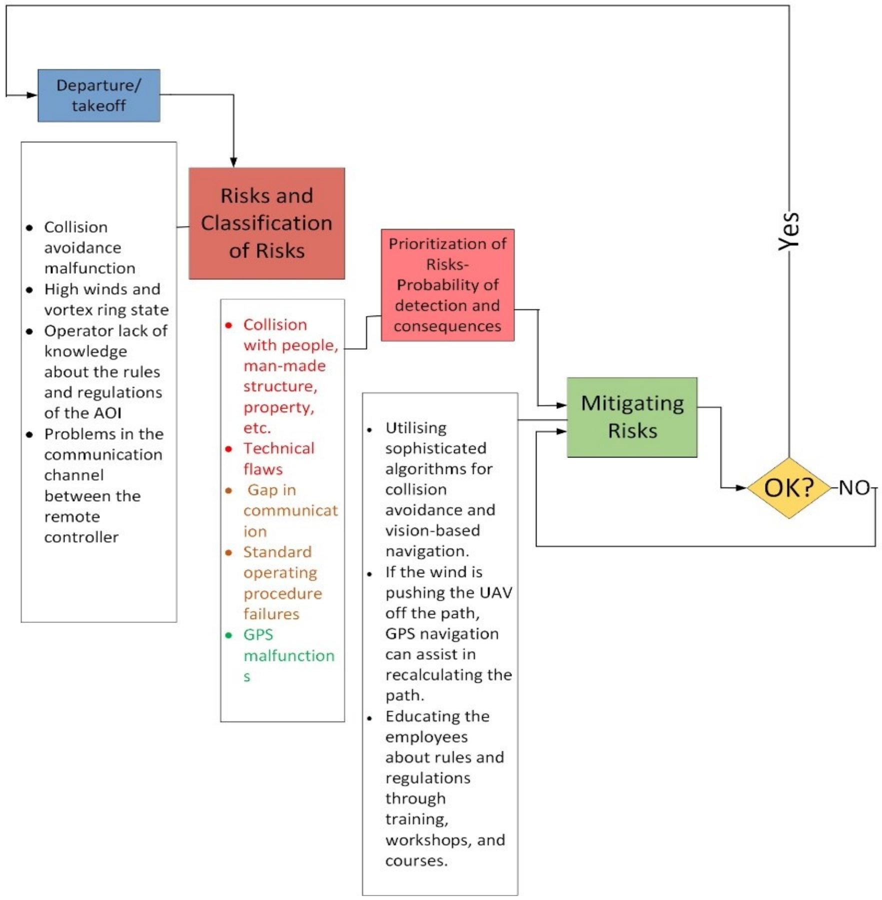

Figure 20:Ranked Risks associated with Departure

The table below demonstrates a qualitative analysis of the risks associated with the "Departure" stage of the UAV mission, the RPN values associated with them, the controls implemented to mitigate them, the residual risk after the controls are implemented and the trigger for the failures in the stages:

Table 19: FMEA of Departure/Take-off

Faults and related operating conditions	Likelihood	Severity	Detectability	RPN (uncontrolled)	Risk Control	Residual RPN	Trigger
Collision with people, man-made structure, property, etc.	3	3	3	27	Software engineers can utilize sophisticated algorithms, DAA systems within close vicinity of flight for collision avoidance and vision-based navigation.	4	FBG strain sensors placed on the airframe can detect unusual stress with a high degree of accuracy.
Inherent technical flaws: failure to take-off due to any faults in the hardware and software	2	3	3	18	Routine check-ups before take-off of the architecture of the drones by the Operators and design engineers will help to find out faulty parts and connections, helping to reduce the risk incidence.	3	Sensors placed close to the applicable faults such as battery depletion, loose wiring, etc. will separate the cause of the risks and identify faults.

system of the drone							
Wind gusts: High winds and vortex ring state during drone flight	2	3	2	12	If the wind is pushing the UAV off the path, the operators can set up a GPS navigation which can assist in recalculating the path.	2	Wind speed sensors attached to the drone will detect unusual flight speed which is an indicator of wind gusts.
Gap in communication : Problems in the communication channel between the remote controller and the drone	2	2	2	8	The operators can set up data communication link which gives performance and failure data in real time which can aid in adjusting the operation of the drone in emergencies by the GCS.	4	The operator unable to receive real-time data because of loss in connection
Standard Operating Procedures: Operator lack of knowledge about the rules and regulations of the AOI	2	1	2	4	Training, workshops, and courses organized by the project manager to tackle operator inefficiency. Also using work procedure guidelines in different language.	2	The UAV flying off track because the drone operator failed to control and monitor the flight path of the UAV, abiding by the regulations of the AOI.
GPS malfunctions	1	2	1	2	Sophisticated navigation algorithms can be set up along with sensors by the design engineers.	1	If the level of Signal to Noise Ratio (SNR) is higher than the threshold level, that navigation function needs to be healed

4.2.3 Flight/Transit:

The flight or transit of a UAV refers to the movement of the drone from one location to another, either for a specific mission or as a means of transportation. During the flight, the UAV must follow the planned flight path and navigate any obstacles that may be present in the airspace. The flight must also be monitored and controlled by a ground control station, which receives real-time data from the UAV's sensors and sends commands to the drone's flight control system. The goal of the flight is to ensure that the UAV arrives at its destination safely and successfully completes its mission.

The UAV is assigned to perform a specific mission during the transit stage. For instance, UAVs collect imagery with cameras and sensors mounted on the drone. These cameras and sensors can range from simple cameras for capturing still images to more advanced cameras that can capture high-resolution video and thermal images. The cameras are typically controlled by the UAV's flight control system, which is programmed to capture images at specific locations and altitudes as shown in Figure 21. The images are then processed and analyzed to obtain the desired information or data. To generate seamless mosaics that indicate the location of the features in the image, forward and side overlap must be properly managed [112].

AGL stands for Above Ground Level, which refers to the height of an object, such as a drone, above the ground. In UAV imaging, AGL distances are used to determine the altitude at which a drone is flying and collecting data. Distortions in AGL distances can occur due to factors such as inaccuracies in GPS readings, atmospheric conditions, and instrument error, which can affect the quality of the imagery captured by the drone as demonstrated in Figure 21. To mitigate these distortions, UAV operators may use additional sensors and equipment, such as barometers and other altimeters, to improve the accuracy of their AGL readings [113].

Extreme weather conditions such as high winds, thunderstorms, and turbulence can impact the stability and control of UAVs, hindering the flight of the UAV. Physical obstacles such as trees, buildings, and power lines can obstruct the flight path of UAVs and cause deviations from the intended trajectory. Also, electromagnetic interference from sources such as radio towers or other UAVs can disrupt the communication and navigation systems of UAVs, causing inaccuracies in the flight trajectory as shown in Figure 22. This failure mode is of high priority because if the UAV went off track it might cause damage to the people and property. To mitigate these risks, UAVs typically have safety features such as obstacle avoidance systems and redundant communication and navigation systems. Operators can also minimize the risk of hazards by performing pre-flight checks, monitoring weather conditions, and maintaining awareness of the flight environment as written in Table 20. Despite taking measures, it is sometimes difficult to completely eradicate hazards and so it is necessary to keep a buffer aid in accommodating unavoidable circumstances.

There might be a breach of communication between the UAV and the GCS and/or hardware malfunctions in the hardware (e.g.: depletion of the remote-control battery) which might result in the UAV stopping flying midair. However, hardware and software faults are frequently detectable in the experimentation stages and thus it is of lower priority than external factors which are normally very difficult to control and detect as demonstrated in Figure 22. The fault can be minimized by regularly inspecting and maintaining the hardware and software of the UAV can help identify and fix faults before they occur during flight; installing redundant systems such as backup power systems, GPS, and flight control systems can help ensure the UAV can continue its mission even if one system fails, conducting thorough pre-flight checks can help identify potential faults and address them before takeoff, incorporating on-board diagnostics into the UAV software can help identify and report faults during flight, allowing the operator to take appropriate action, and developing and practicing emergency procedures can help the operator respond quickly and effectively if a fault occurs during flight.

In Figure 21, the term "Input from A11.2" refers to the information and decisions generated during the "Departure/Take-off" stage in the UAV mission planning process. This input plays a critical role in the subsequent stage, known as the "Flight/Transit" stage. The output from the Departure/Take-off stage, represented by the Input from A11.2, encompasses important factors such as successful take-off, confirmation of flight parameters, activation of communication systems, and the establishment of navigation plans.

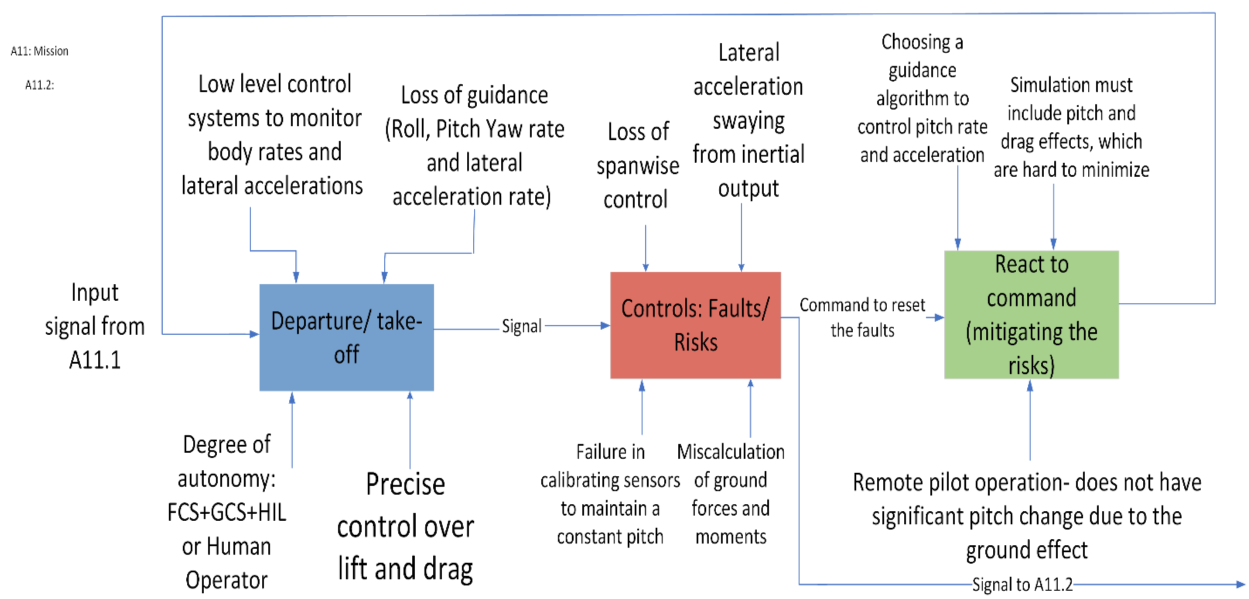

Figure 21:Flight/ Transit

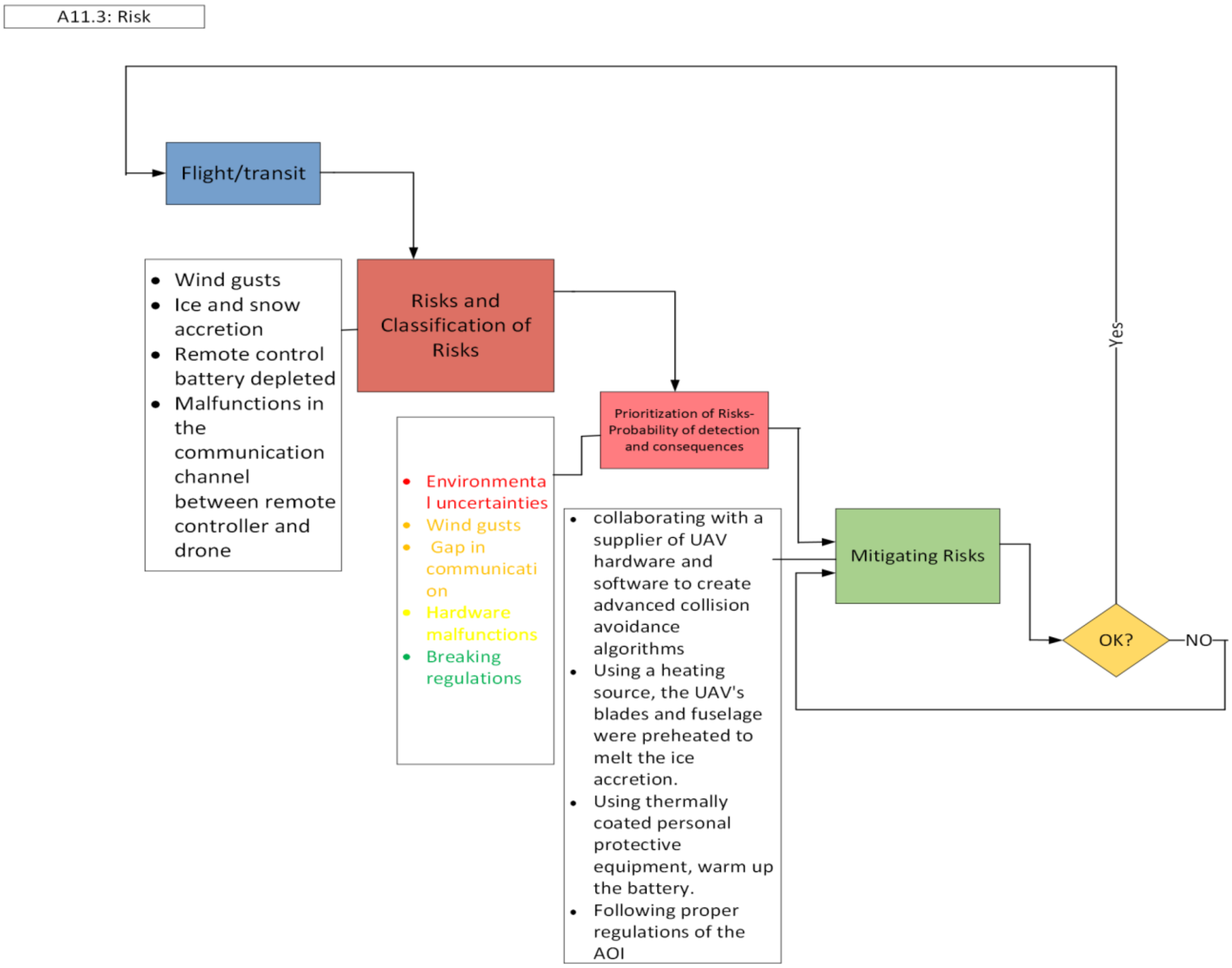

Figure 22:Ranked Risks associated with Flight/Transit

The table below demonstrates a qualitative analysis of the risks associated with the "Flight" stage of the UAV mission, the RPN values associated with them, the controls implemented to mitigate them, the residual risk after the controls are implemented and the trigger for the failures in the stages:

Table 20: FMEA of Flight stage

Faults and related operating conditions	Likelihood	Severity	Detectability	RPN (uncontrolled)	Risk Control	Residual RPN	Trigger
Environmental uncertainties: Wind gusts and snow accretion	3	3	3	27	Collaborating with a UAV hardware supplier to create advanced collision avoidance algorithms and DAA systems. If the engineers use a heating source to preheat the UAV's blades and fuselage to melt the ice accretion.	3	Windspeed sensors attached to the wings of the drone will detect unusual flight speed which is an indicator of wind gusts. Moisture sensors detect snow accretion effectively if placed on the outer extremities. Wind gusts can affect UAV stability and performance. Ice and snow accretion can affect UAV's aerodynamics, weight, and power consumption.
Gap in communication	3	2	3	18	The operators can set up a data communication link	4	The operator is unable to receive real-time data regarding the flight

: Malfunctions in the communication channel between the remote controller and drone					which gives performance and failure data in real time which can aid in adjusting the flight oath of the drone during emergencies by using GCS.		which can be caused by radio frequency interference, limitations in range, power supply disruptions, hardware failures, software bugs, lack of proper testing and incorrect settings. These can cause the drone to malfunction or shut down.
Hardware malfunctions: battery malfunction due to subzero temperatures	2	3	2	12	The design engineers can use athermally coated personal protective equipment to warm up the battery.	2	Sensors will be required to detect the voltage flow in the voltage sensors for any sort of battery depletion. The remote control's battery can be depleted due to improper charging. Also, normal use and age can cause the remote control's hardware to wear out. Exposure to extreme temperatures and humidity, physical damage and lack of maintenance can cause the remote control to lose power.
Breaking regulations	2	3	1	6	Operators must follow proper regulations of the area of interest will prevent from any legal lawsuits and accidents.	1	Inexperience or unfamiliarity with UAV regulations on the part of the operator may lead to unintentional violations. Inadequate flight planning and poor communication can also contribute to regulatory breaches, as can technical problems with the UAV, pressure to complete a task, misinterpretation of rules and regulations, lack of oversight and reinforcements. This can result in warning and lawsuit cases from the are officials.

4.2.4 Arrival:

The arrival of a UAV refers to the time when the drone reaches its destination. This can be a landing site or a specific location in the air where the drone is meant to perform its mission. The arrival of a UAV is typically controlled by its onboard navigation system, which guides the drone to its destination using GPS, computer vision, or other technologies. It is important to carefully plan the flight path of a UAV and monitor its progress to ensure a safe and successful arrival.

Path planning of the UAVs is dependent on the path coordination and path following of the UAVs. If there is a time constraint, then the UAVs can be assigned multiple overlapping tasks, only if there is no presence of resource constraints as demonstrated in

Figure 23. Continuous communication between the controller office and the drone needs to be maintained otherwise the drone will sway away from its path and collide with other UAVs and/or environmental obstacles/hazards. Assigning targets to UAVs may aid in obtaining maximum system utility

(the highest value of a particular performance metric that a system can achieve under a set of constraints or conditions) [114].

There might be interruption in data collection due to one or multiple sensors being inaccessible. This risk can be mitigated by establishing a localization network to locate un-known nodes/sensors by a beacon node. A localization network is a system used to determine the position of unknown nodes or sensors in a network. One way to do this is by using a beacon node, which is a known node with a known location. The beacon node transmits signals to the unknown nodes, which use the received signals to calculate their own position relative to the beacon node. This process is known as ranging, and it can be done using various technologies such as Bluetooth, Wi-Fi, or ultrasound. The localization network can also use additional information, such as the time of flight of the signals or the angle of arrival, to improve the accuracy of the position calculations as shown in
Figure 23. The goal of the localization network is to provide information about the location of the unknown nodes in real-time, which can be used for various applications such as asset tracking, environmental monitoring, or autonomous navigation [115].

Data collection of any sort is of top priority during this stage and a drone might fail to perform this function due to limited visibility if the camera malfunctions and/or there might be a problem in the communication channel between the drone and display. If the UAV is equipped with a backup camera, it can be switched to the backup camera to continue the mission or if the camera is not essential for the mission, the UAV can fly without the camera and complete the mission with other sensors or instruments as written in Table 21. Alternatively, the mission can be re-programmed to eliminate tasks that require the camera, allowing the UAV to complete the mission with the remaining sensors or instruments. If any of these salvation methods are not possible, the sole safety in this situation is to save the UAV by using GPS navigation to fly it back to the base because the mission is unsuccessful in the event of the camera malfunctioning [116].

External environmental factors such as rain, fog and moisture can delay or hamper the process of data collection. This risk can be mitigated to a certain extent by mounting an illumination gadget to light the way of the UAV and using GPS navigation as demonstrated in Figure 24. Weather forecasts can help in avoiding unfavorable conditions if we carry out the mission on clear days and stop the UAV-assisted inspection in the event of severe rain. If it is necessary to fly during that period, the operator should plan alternative routes and backup plans in case the conditions are too poor to fly and/or consider using a backup data collection method, such as ground-based surveys or satellite imagery, to compensate for any data that is not collected due to weather conditions as shown in Figure 19. A low-impact failure is if the workload of the human operator might exceed his/her cognitive and physiological capacity. This can be easily controlled by assigning multiple people to analyze and collect the data which also helps in case the individual needs to be replaced.

In Figure 24, the term "Input from A11.3" refers to the output generated by the "Flight/Transit" stage in the UAV mission planning process. This output serves as a crucial input for the subsequent stage, which is the "Arrival" stage. The information and decisions made during the "Flight/Transit" stage, represented by the Input from A11.3, play a significant role in guiding the UAV towards its intended destination. This input includes factors such as navigation updates, flight progress monitoring, communication status, and any necessary adjustments during transit. The Input from A11.3 ensures a smooth and successful transition from the flight and transit phase to the subsequent stage of arrival, facilitating a well-coordinated and efficient conclusion to the UAV mission.

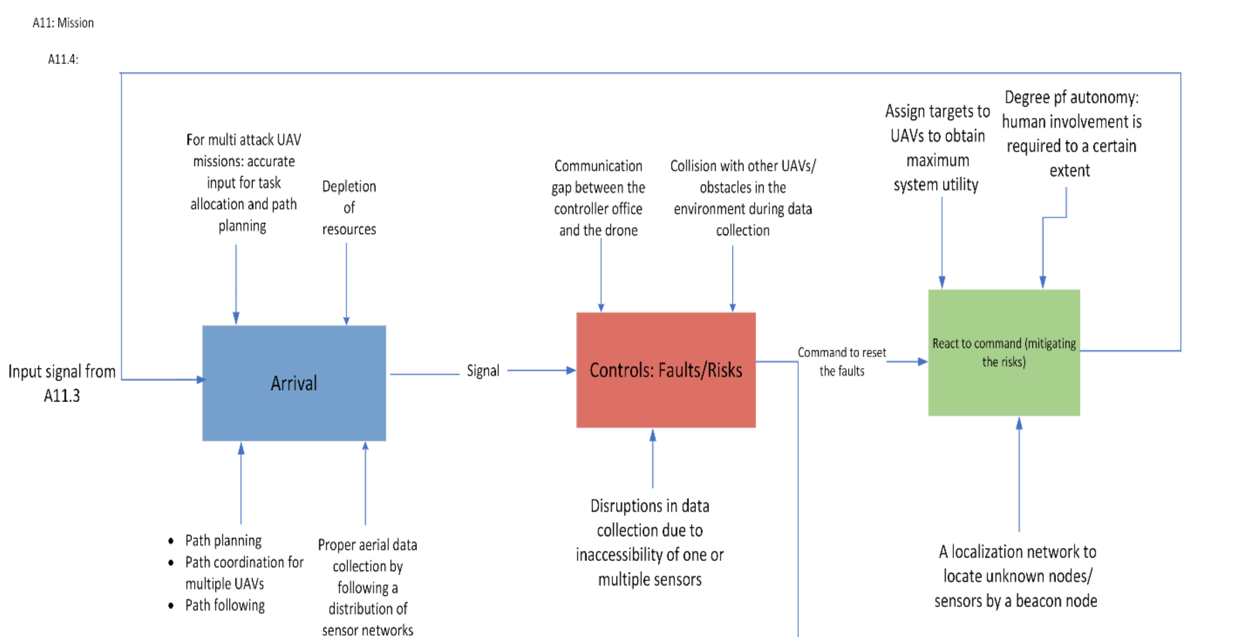

Figure 23:Arrival

A11.4: Risk

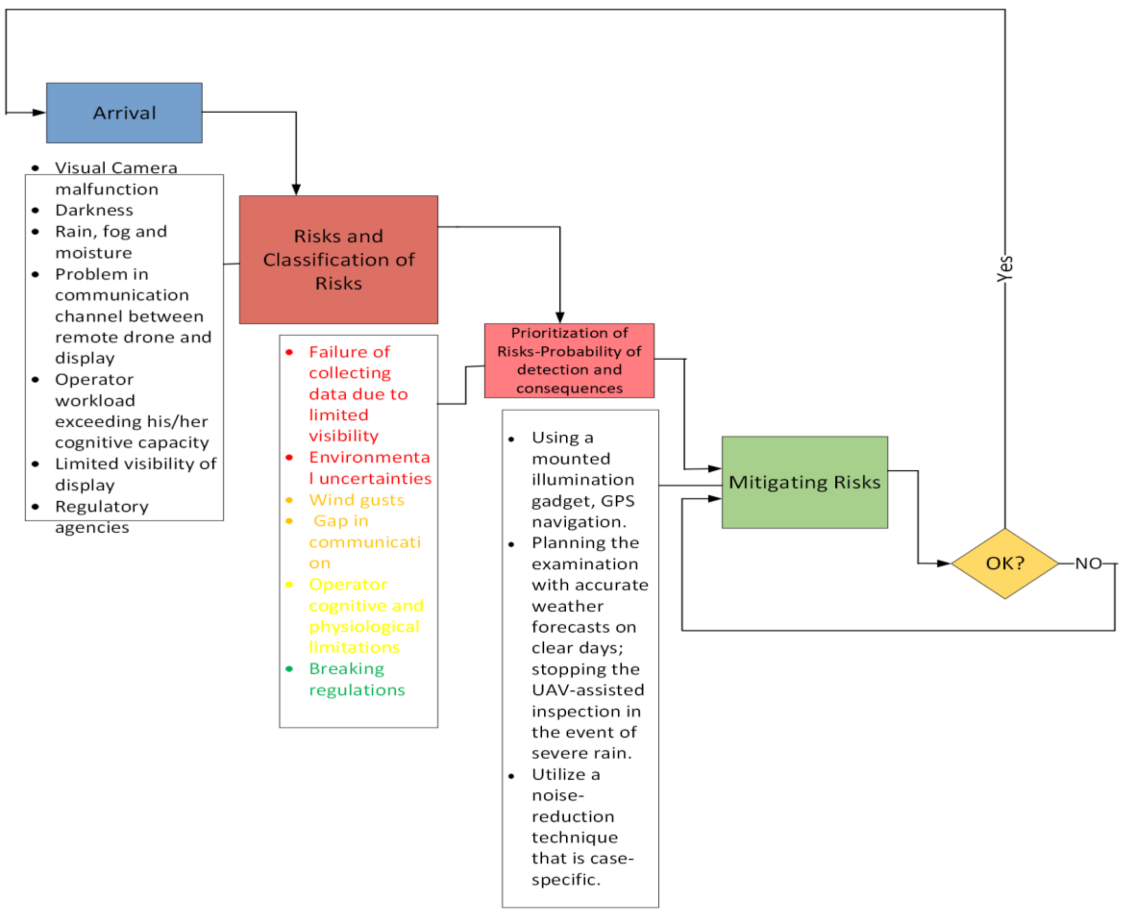

Figure 24: Ranked Risks association with Arrival stage

The table below demonstrates a qualitative analysis of the risks associated with the "Arrival" stage of the UAV mission, the RPN values associated with them, the controls implemented to mitigate them, the residual risk after the controls are implemented and the trigger for the failures in the stages:

Table 21: FMEA of the Arrival Stage

Faults and related operating conditions	Likelihood	Severity	Detectability	RPN (uncontrolled)	Risk Control	Residual RPN	Trigger
Failure of collecting data due to limited visibility: Visual camera malfunction during darkness	3	3	3	27	The sole safety of the situation is to save the UAV if the operators use GPS navigation to fly it back to base if the mission is unsuccessful if the camera malfunctions. The engineers can mount illumination gadget and GPS navigation. It is important to test the camera and ensure that the camera is properly set up to minimize visibility issues during data collection.	4	Limited visibility can cause the failure of data collection due to various factors, such as malfunction of visual camera (hardware or software issues), darkness, poor weather conditions, and operator error. Inaccuracies of practical real time data when compared with the simulated data of the prototype.

Environmental uncertainties: Rain, fog, wind gusts	3	2	3	18	The operator in charge should plan the mission according to the clear weather forecasts, stopping the UAV-assisted inspection in the event of rain. To operate safely in these conditions, it is important to be aware of weather patterns and plan accordingly as well to have proper equipment and safety measures.	3	Windspeed sensors attached to the drones will detect unusual flight speed which is an indicator of wind gusts. Weather patterns, such as thunderstorms and high humidity, can lead to rain and moisture. Sudden temperature changes cause fog or mist. Certain topological features, such as mountains and valleys, can cause wind gusts and turbulence. These conditions are more likely to occur during certain seasons, such as the monsoon season.
Gap in communication : Malfunctions in the communication channel between the remote controller and the drone	2	3	2	12	The operators can set up communication which gives performance and failure data in real-time which can lead in adjusting the drone in emergencies by the GCS.	2	Interference from other RF devices can disrupt communication between the remote controller and the drone. Limited range of radio frequency can cause communication loss if the drone is flown too far from the controller. Power supply issues, hardware issues such as wear and tear, software failures, and vulnerabilities can cause loss in communication which results in the operator not receiving data.
Operator cognitive and physiological limitations	1	3	3	9	The operator can utilize a noise-reduction technique that is case specific. It is important to ensure that the operator is well-trained and well-rested. They should have adequate technology to operate the drone. It is also important to monitor the workload and other factors.	2	When the operator is multitasking, this cam exceeds one's cognitive capacity and leads to mistakes. Limited visibility of the display can also affect an operator's decision to ensure safety of the drone. Fatigue, stress, and medical conditions can lead to mistakes.
Breaking regulations	2	1	2	4	Operators must follow proper regulations of the area of interest will prevent from any legal lawsuits and accidents.	1	Inexperience or unfamiliarity with UAV regulations on the part of the operator may lead to unintentional violations. Inadequate flight planning and poor communication can also contribute to regulatory breaches, as can technical problems with the UAV, pressure to complete a task, misinterpretation of rules and regulations, lack of oversight and reinforcements. This can result in warning and lawsuit cases from the area officials.

4.2.5 Disembark/Landing:

After completing the aerial mission at a specific time, the UAV will start the landing stage and will finish the landing at t=T interval. Then the vehicle will continue its pre-planned path again until it comes to a complete stop. The GCS operator manually initiates the landing. A passing waypoint of the landing stage

refers to a specific location on the flight path where the drone is programmed to fly through before reaching the destination or landing site. It is a pre-determined point that the drone will pass through to reach the landing site as demonstrated in
Figure 25[117].

Developing the threshold for altitude by estimating the navigation errors (position error which happens when the drone's navigation system reports an incorrect position and heading error which occurs when the drone's navigation system reports an incorrect heading) causes the drone to fly in the wrong direction. If the height is too low, the touchdown (this is the point at which the UAV's wheels or landing gear contact the ground during the landing stage of flight) will be out of the limit which can result in damage to the UAV [118].

A crab angle at touchdown is when the UAV is not aligned with the runway or landing surface. This can happen if the UAV is experiencing crosswinds or if the operator is attempting to land in an area where the surface is not flat or level. Error in these angles might cause a large transient weight transfer, preventing a smooth landing. To mitigate these risks, the descent rate and the crab angle are decreased during the flare maneuver to lower the undercarriage side loads and yaw transients at touchdown as shown in Figure 26 [119].

The lift equation in L = 1/2 * rho * v^2 * S * C_L,

(7)*,* describes the upward force on an aircraft's wing that opposes the weight of the aircraft. The drag equation in *(5)* describes the opposing force to the motion of the aircraft. The thrust equation describes the force that propels the aircraft forward. This equation relates the thrust produced by the UAV's engines to the velocity of the exhaust gases and the mass flow rate of the fuel being burned. The pilot must carefully balance the lift, drag, and thrust of the aircraft. If there is too much drag, the aircraft may not be able to slow down enough to land safely. If there is too little thrust, the aircraft may not be able to maintain altitude and control while slowing down. If there is too much lift, the aircraft may float above the runway and risk overshooting it.

To mitigate these risks, pilots use a variety of techniques. One common technique is to use flaps and slats on the wing, which change the shape of the wing and increase lift and drag to help slow down the aircraft. Pilots may also use thrust reversers on the engines to increase drag and help slow the aircraft down.

Additionally, pilots carefully manage the thrust of the aircraft during landing to maintain control and to touch down at the correct speed.

Careful tuning should be done to ensure that there is no coupling between the rolling mode and the natural frequency of the yaw controller. This mode is typically used to control the heading of the UAV and is often implemented in the form of a control algorithm that uses feedback from the UAV's onboard sensors to adjust the yaw angle of the UAV to match a desired setpoint as shown in Figure 21 [120]. During the descent, the highest priority risk is the UAV colliding with humans, animals, man-made objects, and environmental uncertainties such as wind gusts. Therefore, if the wind is pushing the UAV off the path, GPS navigation can assist in re-calculating the path. A collision with a ground vehicle can have devastating consequences as mentioned in Table 22. Therefore, notifying and removing any equipment used by third parties that are using the same frequency and bandwidth from the operation site can prevent collision malfunctions [121]. Hardware malfunctions and system recovery failure can result in the UAV crashing during landing, so it is recommended to undertake a procedure to check recovery failure as mentioned in Figure 26.

In Figure 26, the term "Input from A11.4" refers to the output generated by the "Arrival" stage in the UAV mission planning process. This output serves as a critical input for the subsequent stage, which is the "Disembark/Landing" stage. The information and decisions made during the "Arrival" stage, represented by the Input from A11.4, play a pivotal role in ensuring a safe and successful conclusion to the UAV mission. This input includes factors such as navigation updates, situational awareness, communication with ground control, and any necessary preparations for landing or disembarking.

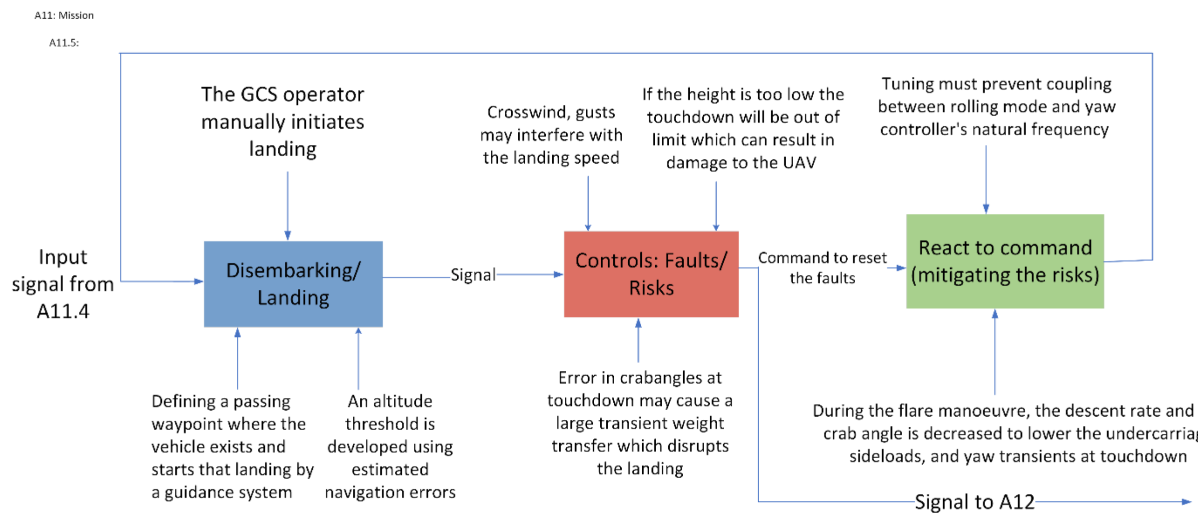

Figure 25;Disembarking/Landing

A11.5: Risk

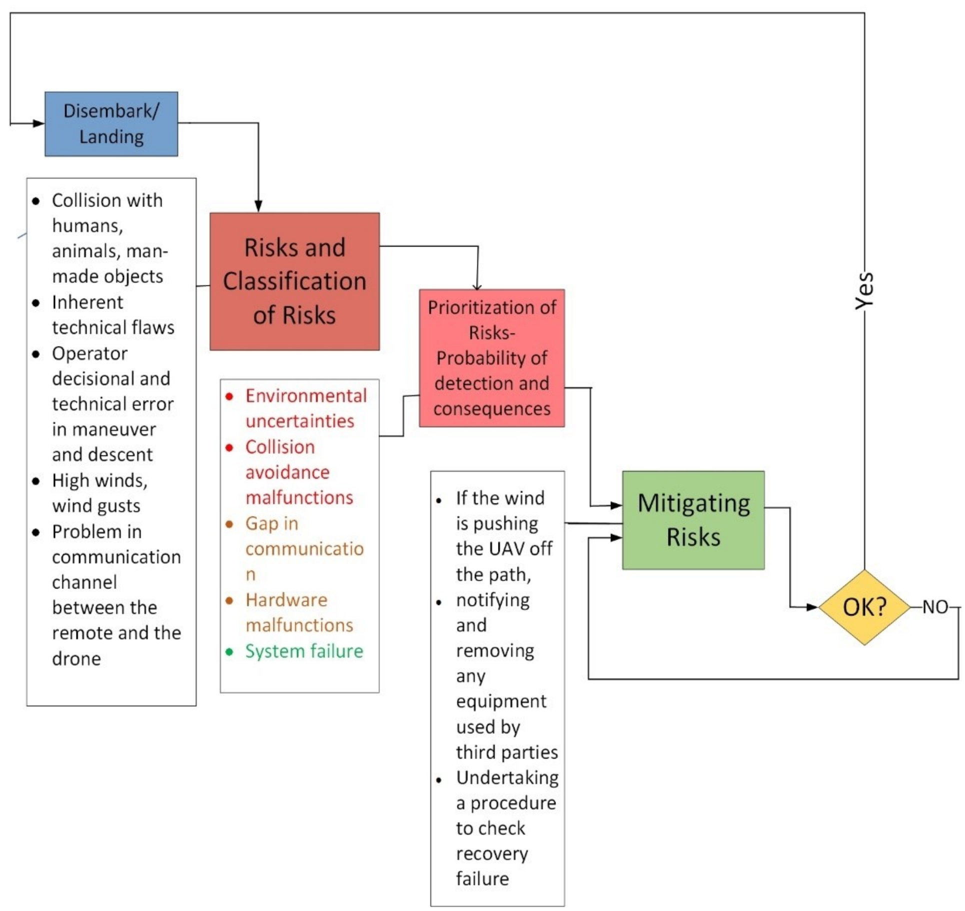

Figure 26: Ranked Risks associated with Disembarking/Landing

The table below demonstrates a qualitative analysis of the risks associated with the "Landing" stage of the UAV mission, the RPN values associated with them, the controls implemented to mitigate them, the residual risk after the controls are implemented and the trigger for the failures in the stages:

Table 22: FMEA of the Disembarking/Landing Stage

Faults and related operating conditions	Likelihood	Severity	Detectability	RPN (uncontrolled)	Risk Control	Residual RPN	Trigger
Environmental uncertainties: High wind, wind gusts	3	3	3	27	The operator in charge should plan the mission according to examination of the weather, stopping the UAV assisted inspection on severe rainy days.	4	Windspeed sensors attached to the drones will detect unusual flight speed which is an indicator of wind gusts. Weather patterns, such as thunderstorms and high humidity, can lead to rain and moisture. Sudden temperature changes cause fog or mist. Certain topological features, such as mountains and valleys, can cause wind gusts and turbulence. These conditions are more likely to occur during certain seasons, such as the monsoon season.
Collision with people, man-made structure, property, etc.	2	3	3	18	Software engineers can utilize sophisticated algorithms, DAA systems within close vicinity of flight for collision avoidance and vision-based navigation.	4	FBG strain sensors placed on the airframe can detect unusual stress with a high degree of accuracy.
Operator decisional and technical error during maneuver and descent	1	3	3	9	Operator must be well-trained by the management to be well acquainted with the descent process.	3	Delay in mission completion time and failure to follow predetermined flight path.
Gap in communication : Malfunctions in the communication channel between the remote controller and the drone	2	3	2	12	The operators can set up communication which gives performance and failure data in real-time which can lead in adjusting the drone in emergencies by the GCS.	2	Interference from other RF devices can disrupt communication between the remote controller and the drone. Limited range of radio frequency can cause communication loss if the drone is flown too far from the controller. Power supply issues, hardware issues such as wear and tear, software failures, and vulnerabilities can cause loss in communication which results in the operator not receiving data.
Hardware malfunctions: Inherent technical flaws and battery depletion	1	3	2	6	The design engineers can use athermally coated personal protective equipment to warm up the battery.	2	Sensors will be required to detect the voltage flow in the voltage sensors for any sort of battery depletion. The remote control's battery can be depleted due to improper charging. Also, normal use and age can cause the remote control's hardware to wear out. Exposure to extreme temperatures and humidity, physical damage and lack of maintenance can cause the remote control to lose power.

4.3 Activities Succeeding a Mission:

The following lists the activities that take place after a mission has been completed:

- Analysis associated with the Telemetry of the mission
- Demobilizing and ending a mission Tracking/flight
- Limitations and lessons learned

The following section outlines the SADT diagram and the Minimum Bayes Risk Analysis as well as going into detailed explanations for the activities.

4.3.1 Analysis associated with the Telemetry that comes from the Mission:

The telemetry system is designed to transmit essential technical information from the board in real time, as well as to record this information in the log for later analysis [122]. The information's content is determined by the system's purpose and the operator's requirements. The telemetry data can include information such as the UAV's altitude, speed, heading, battery life, GPS location, and other parameters related to the mission objectives. Analyzing this data can provide valuable insights into the UAV's performance, as well as identify potential issues or areas for improvement.

When the flight is over a small distance and the copter is visually observed, it is sufficient to accurately monitor the voltage of the power batteries [123]. It is required to regulate the range of flight and the level of the radio signal during a flight controlled by the camcorder to avoid losing connection, as well as monitor the voltage of the video channel's battery. Most modern telemetry systems can manage current sensor indicators, voltage, and temperature, as well as GPS data flow, independently. is both more convenient and safer.

The use of telemetry allows for the determination of the UAV's distance from the take-off location, speed, flight mode, and the number of GPS transmitters in the unmanned aerial field of view, among other things [122]. The execution of the path is examined and compared with the planned path of the UAV [117]. There might be disruptions in the communication data link, loss of connection with the GCS. Therefore, the data delivery should be completed on site with one individual dedicated to post processing [123] to minimize errors in data processing and distribution. Due to communications failure or range restriction, the air to ground data link is temporarily broken. Different ground stations operate the air vehicle’s control and monitoring systems.

Telemetry data can be gathered in raw or semi-processed form. The information needs to be made more understandable and usable by processing it. Filtering, smoothing, or changing the data may be involved. To obtain insights into the performance of the UAV, employ appropriate data analysis techniques. Calculating summary statistics, creating plots or charts, or using machine learning algorithms to spot patterns or anomalies are all examples of this. The places where the UAV's performance could be improved based on the analysis need to be identified. This could include changing operational processes or optimizing flight paths.

Semi-automatic directives issued by the ground station need to be carried out by the air vehicle. The entire collection of straightforward mission simulations is run to provide telemetry. Decision trees are created that link this information to the mission model and enable real-time determination of the mission condition. The effectiveness of decision trees is next tested using a second set of intricate simulations [124].

In Figure 27, the term "Input from A11.5" refers to the output generated by the "Disembark/Landing of the UAV" stage in the UAV mission planning process. The information and data obtained during the disembarkation and landing of the UAV, represented by the Input from A11.5, provide crucial insights for analyzing the mission's performance and overall UAV operation. This input includes factors such as landing conditions, sensor readings during the landing phase, and any observed events or anomalies during the UAV's touchdown. The Input from A11.5 guides the subsequent stage, allowing for the thorough analysis of telemetry data collected during the mission. It contributes to assessing the UAV's performance, evaluating the mission objectives, and identifying any potential issues or areas for improvement.

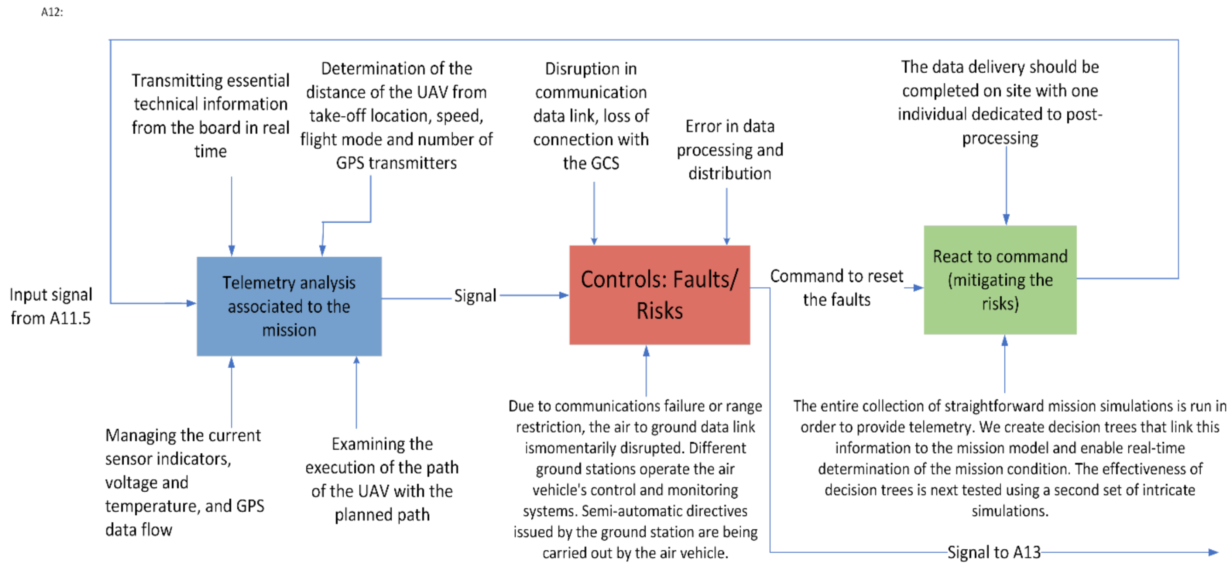

Figure 27: Telemetry analysis associated with the mission

Table 23: Failure: Disruption of communication data link, loss of connection with the Ground Control System

For this failure, there are three possible risk controls and for 2 possible states there are six conditional risk scenarios.

	Current sensor indicators, voltage, and temperature , as well as GPS data flow are connected directly to the telemetry module			The data delivery should be completed on site with an individual dedicated to post processing			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable		Reliable	Unreliable
P(x|w1)	0.25	0.75	P(x|w2)	0.65	0.35	P(x|w3)	0.3	0.7
λ(α1|w1)	0.0055	10	λ(α2|w2)	12	0.0055	λ(α3|w 3)	8	8
	0.001375	7.5		7.8	0.001925		2.4	5.6
R1	**7.50**			7.80		R2	8	
	Minimum Bayes Risk							

4.3.2 Demobilizing and ending a mission:

Once the UAV has completed the mission it needs to be demobilized. Demobilizing a UAV mission requires careful planning and execution to ensure that the UAV and associated equipment are safely returned, and the site is properly restored. The operator is responsible for safely returning the UAV to its assigned landing site and ensuring that all required safety protocols are followed during the landing.

The method of demobilization depends on the objective of the mission. For instance, if the drone is used for delivering a package, it is required to program the drone to drop the package in the designated location and return it to the storage facility. If the aim of the drone is to defuse a bomb, it will disintegrate afterwards. Some of the demobilization techniques includes:

1. Manual landing: This entails manually lowering the UAV to the ground using a remote control or piloting it back to a designated landing location. It necessitates skilled pilots who can fly the drone in a safe and controlled way.
2. Autonomous landing: Some UAVs have the capacity to land on their own. Typically, this is accomplished by programming the landing site and enabling the drone to navigate and land on its own. It requires precise GPS and other navigation instruments.
3. Return to home: Some UAVs have a "return to home" feature that allows the drone to automatically fly back to its initial take-off position and land. This is helpful in the event of a loss of communication or other emergencies.
4. Parachute landing: Some larger UAVs or those carrying valuable payloads may have a parachute system that can be released in an emergency to securely land the drone.

Whatever method is used, it is critical that the project manager and the operator plan the demobilization process ahead of time, ensure that the landing area is clear and secure, and have qualified personnel on hand to handle the UAV. The UAV should be correctly stored, maintained, and prepared for the next mission after landing.

The ground control equipment, telemetry systems, or sensor equipment can malfunction during the demobilization process. This can cause delays and potentially impact on the safety of the operators or those around the equipment as shown in Figure 28. As a result, a data link for effective communication is required to ensure the successful completion of a mission as well as the demobilization of the drone safely, minimizing damage to people and property [125]. A signal is needed to indicate the end of the completion of the objective of the UAV as well as to initiate demobilization. So, a strong communication data link needs to be set up between the drone and the GCS to avoid loss of communication between the ground control and the drone during demobilization.

Before inactivation can begin, a new team must be formed. Division of labor according to expertise in the field is essential to avoid ineffective demobilization of the mission due to lack of expertise. This begins with task organization and placing the appropriate people in the appropriate locations [124]. Therefore, the personnel are required to be trained according to the type of drone mission otherwise it can be catastrophic when human lives are involved.

In Figure 28, the term "Input from A12" refers to the output generated by the "Telemetry analysis" stage in the UAV mission planning process. This output serves as a crucial input for the subsequent stage, which is the "Demobilizing and ending the mission" stage. The information and insights derived from the telemetry analysis stage, represented by the Input from A12, play a vital role in assessing the performance, health, and operational data collected during the mission. This input includes factors such as flight data, sensor readings, system diagnostics, and any anomalies or events detected during the UAV's operation. The Input from A12 guides the subsequent stage, enabling effective demobilization and the proper conclusion of the mission. It assists in identifying any necessary post-mission actions, such as maintenance, data analysis, or further investigations based on the telemetry data.

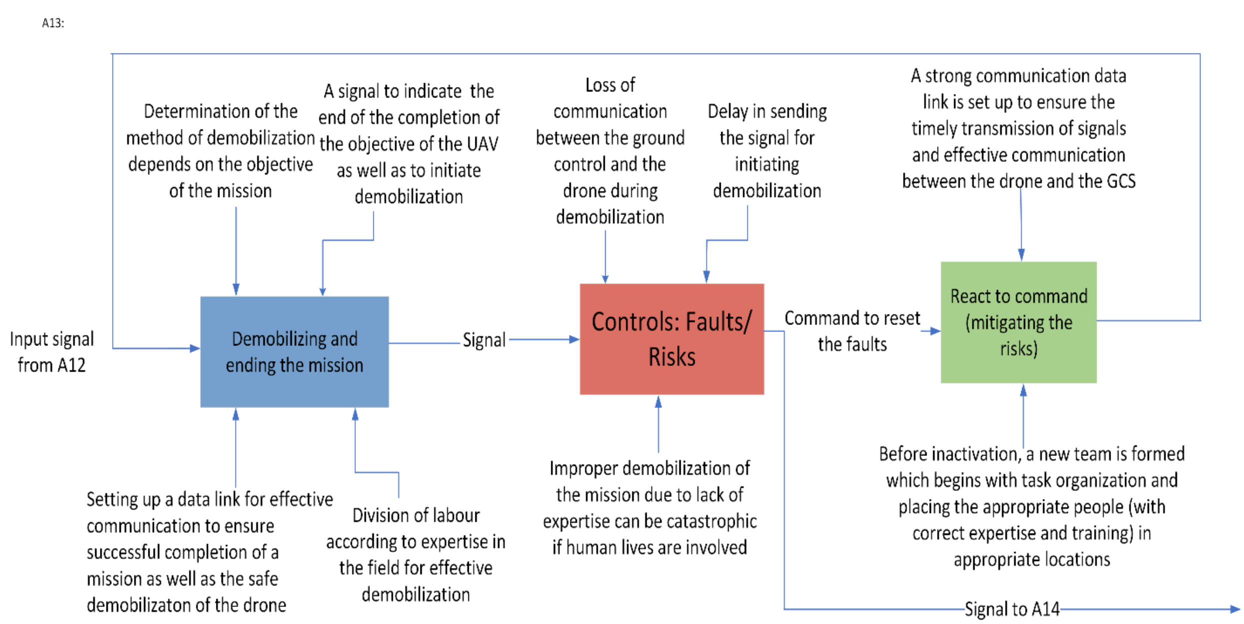

Figure 28: Demobilizing and ending the mission

Table 24: Failure: Loss of communication and delay in sending signal between the ground control and the drone during demobilization

For this failure, there are two possible risk controls and for 2 possible states there are four conditional risk scenarios.

	Strong communication link between the drone and the GCS to ensure timely transmissions			DO NOTHING	
c	Reliable	Unreliable		Reliable	Unreliable
P(x|w1)	0.15	0.85	P(x|w2)	0.3	0.7
λ(α1|w1)	0.0012	10	λ(α2|w2)	9	9
	0.00018	8.5		2.7	6.3
R1	**8.50**		R2	9	
	Minimum Bayes Risk				

Table 25:Failure: Improper demobilization of mission due to lack of expertise among the team

For this failure, there are two possible risk controls and for 2 possible states there are four conditional risk scenarios.

	Division of labor is ensured and the personnel with appropriate expertise are involved after training them			DO NOTHING	
c	Reliable	Unreliable		Reliable	Unreliable
P(x|w1)	0.55	0.45	P(x|w2)	0.7	0.3
λ(α1|w1)	0.0062	15	λ(α2|w2)	8	8
	0.00341	6.75		5.6	2.4
R1	**6.75**		R2	8	
	Minimum Bayes Risk				

4.3.3 Limitations and Lessons Learned:

After the end of every mission, the project team should evaluate the difficulties they faced while undertaking the specific mission and the ways they overcame it. For example, when planning a mission, it is critical to consider weather conditions and have contingency plans in place in case weather conditions shift. Also, prior to a mission, it is critical to have redundancy in communication devices and to test communication links. Furthermore, missions must be carefully planned to ensure that the UAV has enough battery life to finish the mission and that contingency plans are in place in case of unexpected battery depletion. It is important to inspect and maintain equipment on a frequent basis, as well as have backup plans in place in the event of equipment failure. Lastly, it is critical to comprehend and follow all applicable regulations, as well as to have a compliance plan in place. In short, to ensure the safe demobilization of a UAV and the successful completion of a mission, it is critical to meticulously plan the mission, test equipment and systems before the mission, and have contingency plans in place in case of unexpected issues.

Regular training and drills can help operators better plan for potential issues and react to unexpected events. It is equally important to keep a record of the perspectives of the mission that went smoothly because of the steps undertaken to ensure this and ways in which the individual mission activities along with the overall mission procedure can be improved as mentioned in Figure 29. Each mission activity needs to be evaluated to look for ways in which the performance of the UAV during the mission can be improved, if possible, at a lower cost, while at the same time not compromising the reliability of the drone. This can be done by finding low-cost alternatives in which the above-mentioned risks of the mission activities can be mitigated.

In Figure 29, the data obtained from the telemetry analysis of the mission, referred to as "input from A13," can provide valuable insights for analyzing the challenges and limitations encountered during the mission, as well as identifying the key lessons learned. By examining this data, mission planners and analysts can gain a better understanding of the factors that may have impacted the success of the mission and use this knowledge to inform future missions and improve overall performance.

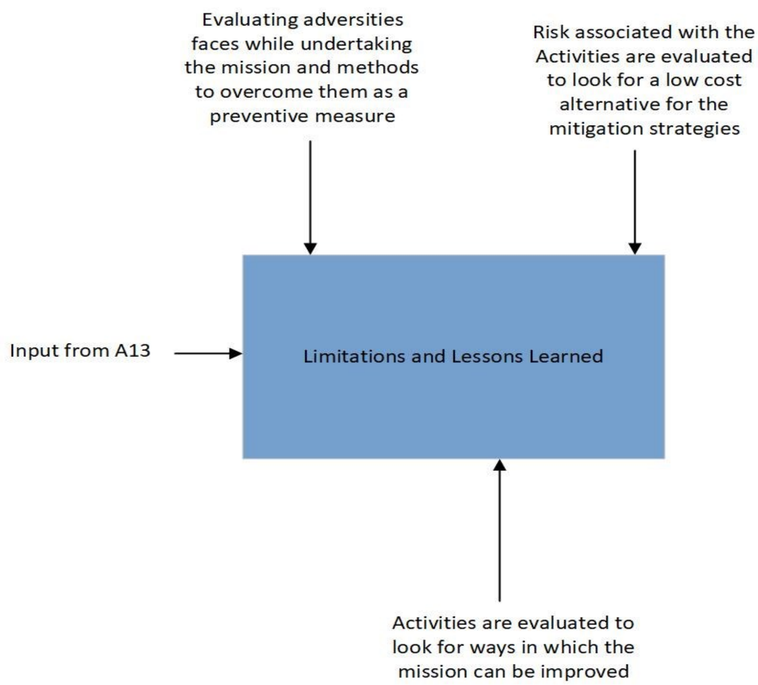

Figure 29: Limitations and Lessons Learnt

4.5 Concluding remarks on the reliability model for general-purpose mission

This chapter presents an overview of the mission activities of a UAV from a general perspective. Due to their effectiveness and increased accuracy, UAVs are being employed more frequently for surveillance operations. By modeling mission risks effectively, one can come up with a system for risk controls that addresses a majority of commercial and military UAV mission risks. The proposed reliability model, incorporating qualitative and quantitative analysis, thus has the potential to make drones more reliable and cost-effective.

The analysis of fault modes involved verifying and validating the mission reliability model by calculating the Posterior Probabilities of each failure state of the mission, the collection of data, and the appropriateness of the data for a particular style of mission. We analyzed the most appropriate mitigation strategies by calculating the Minimum Bayes Risk for a specific risk of the mission, under the evaluation of SMEs.

In the next chapter, a detailed study will be done of the mission risk profile and proposed controls of a commercial fixed-wing VTOL UAV platform used for land survey and imaging. Conditional risk assessment and improved observability will enable early detection of faults and operational controls to prevent UAV incidents.

Chapter 5: Industrial Case Study for a Canadian aerospace data company

In this chapter, we apply this multifaceted risk mitigation approach to enhance the reliability of rotary and fixed-wing UAVs at a Canadian aerospace data company, showcasing its effectiveness in an industrial setting. The model is specifically tailored to applications such as agricultural farm imagery collection and methane leak detection in pipelines. Risks identified during different operational phases were meticulously addressed through defined controls. Here, we have proposed the failures that mission applications like this are prone to facing and ranked the failure according to their frequency of occurrence and stated the optimum mitigation strategy to reduce the effect.

The company encountered several challenges in the past. These included the failure to lay out the calibration tarp on approximately a dozen occasions, resulting in potential issues with data accuracy. IMU/GPS calibration problems occurred during one flight, leading to potential inaccuracies in positioning data. The company experienced processing software and hardware issues during almost every flight, estimated to be around 30 instances, due to computer hardware and software does not correct for the size of the fields being worked on. Flying too fast was a concern to maintain consistent lighting conditions, which affected data quality once. Changing cloud cover throughout the afternoon resulted in lighting conditions fluctuating, exacerbated by the absence of a light sensor on the drone. As a result, there were two crashes, leading to the implementation of new operating procedures. Weather issues led to the cancellation of one flight after takeoff. The company also encountered wind-related problems that created gaps in imaging during one flight, prompting an increase in imagery overlap. Additionally, there were a few instances (estimated 3-4) where the sensor malfunctioned and stopped capturing images. It was noted that tracking these issues in more detail should have been a priority.

This chapter provides an industrial perspective on the mission activities of the company's UAVs in collecting aerial imagery for agricultural farms and detecting methane leaks in pipelines. UAVs are increasingly utilized in surveillance operations due to their effectiveness and enhanced accuracy. We propose a reliability model that integrates qualitative and quantitative analysis, prioritizing failures and determining optimal mitigation strategies using Minimum Bayes Risk calculation. This model has the potential to enhance the reliability and cost-effectiveness of drones in these applications.

5.1 Boarding (Initialization):

The boarding process for UAVs used in collecting aerial imagery of large agricultural farms and for small flights of detecting methane leaks in mining/oil sites involves a similar mission planning process.

To ensure comprehensive risk management, the risks and mitigation strategies identified during the boarding stage of a general UAV mission should also be applicable and considered for agricultural surveys and methane leak detection. When collecting aerial imagery of large agricultural farms and detecting methane leaks in mining/oil sites, the UAV's mission involves a series of steps to ensure accurate and reliable data collection. This includes properly testing and calibrating the UAV's navigation sensors, such as GPS and INS, to provide accurate information for safe flight control as mentioned in Figure 30. Additionally, proper SOPs should be followed by the ground operators to minimize the risk of hardware malfunction and ensure the safe and efficient operation of the UAV. Regular maintenance and replacement of faulty sensors and components can also help prevent failures and improve the overall performance of the UAV.

There are some key differences in the way the boarding process is carried out for these two applications. For collecting aerial imagery of large agricultural farms, the mission planning process starts with selecting the area to be covered and creating a flight plan that considers the size and shape of the area, any obstacles that may need to be navigated, and the UAV's capabilities. Additionally, the altitude and camera settings need to be set to ensure that the imagery captured is of high quality and useful for agricultural purposes. It is also important to consider factors such as weather conditions, terrain, and potential hazards that may pose a risk to the UAV as mentioned in Figure 30. To ensure that the mission planning process is carried out effectively for this application, it is important to conduct research on the area to be covered, assess the weather conditions and other environmental factors that may affect the flight, identify potential hazards, and establish safety protocols before launching the UAV as described in Table 26.

On the other hand, the boarding process for small flights of detecting methane leaks in mining/oil sites involves a similar mission planning process. However, the focus is on selecting the areas where methane leaks are likely to occur and creating a flight plan that considers the UAV's capabilities to detect methane concentrations. In this case, the altitude and camera settings need to be set to ensure that the UAV can detect methane concentrations effectively [125]. It is also essential to consider factors such as weather conditions, terrain, and potential hazards that may pose a risk to the UAV as mentioned in Figure 31. To ensure that the mission planning process is carried out effectively for this application, it is important to conduct research on the areas where methane leaks are likely to occur, assess the weather conditions and other environmental factors that may affect the flight, identify potential hazards, and establish safety protocols before launching the UAV [126].

Physics concepts are also important in determining the altitude and camera settings for the UAVs. The altitude at which the UAV operates is influenced by the laws of gravity and the density of the atmosphere, which impact its ability to generate lift and maintain altitude. Camera settings, such as focal length and shutter speed, are determined by the physics of light and optics, which determine how light is refracted and focused through lenses. Also, the detection of methane leaks requires gas sensors that operate on the principles of physics [126]. Sensor characteristics are important, for instance, integration time necessary for a sensor to collect a sufficiently large signal may affect image quality depending on UAV speed and orientation changes that may cause smear in images. These sensors detect the concentration of methane in the air based on gas diffusion and the interaction between light and matter.

In summary, the boarding process for UAVs used in collecting aerial imagery of large agricultural farms and small flights of detecting methane leaks in mining/oil sites involves a similar mission planning process. However, the focus is on selecting the areas where the UAV will operate, creating a flight plan that considers the UAV's capabilities, setting the altitude and camera settings to ensure effective data collection, and establishing safety protocols to ensure the safe operation of the UAV [127].

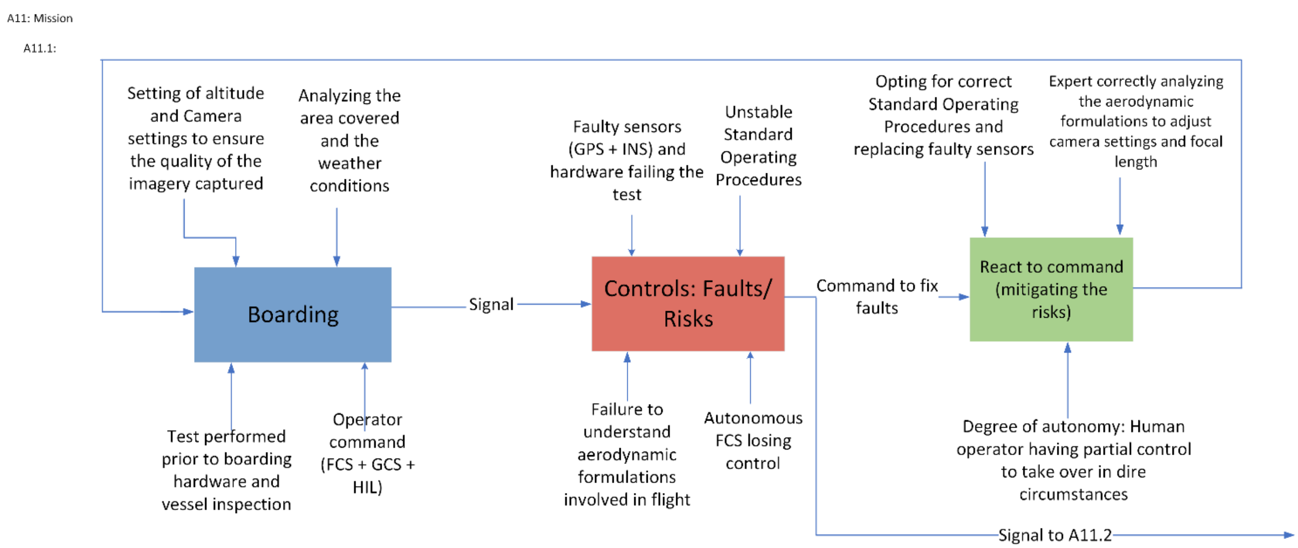

Figure 30: Boarding stage of the company

A11.1: Risk

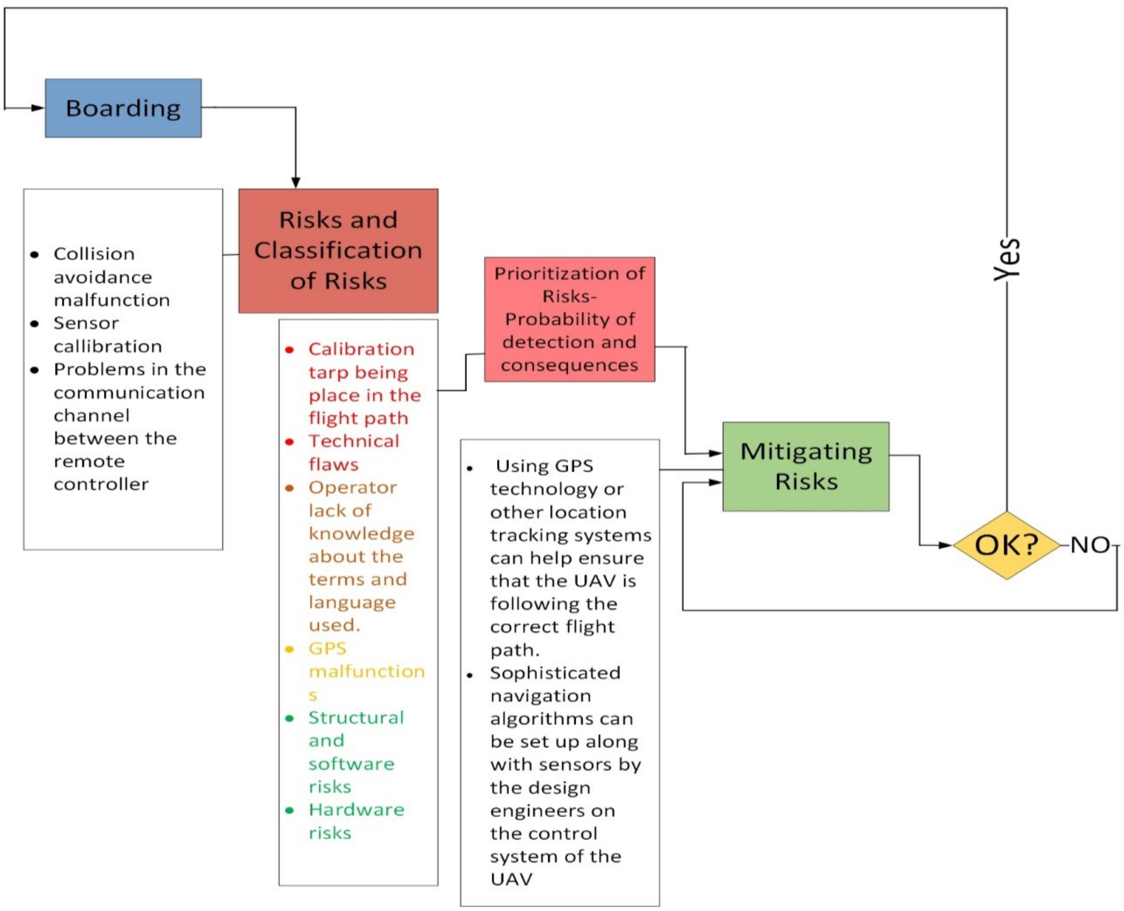

Figure 31: Ranked Risks associated with the Boarding stage of the company

The table below demonstrates a qualitative analysis of the risks associated with the "Boarding" stage of the UAV mission, the RPN values associated with them, the controls implemented to mitigate them, the residual risk after the controls are implemented and the trigger for the failures in the stages:

Table 26: FMEA of the Boarding Stage

Faults and related operating conditions	Likelihood	Severity	Detectability	RPN (uncontrolled)	Risk Control	Residual RPN	Trigger
Calibration tarp not being placed in the flight path	3	3	3	27	Strict procedures, including a dedicated team member for tarp setup and using GPS technology, ensure UAV adherence to the designated flight path. Training, regular checks,	1	The absence of a calibration tarp during a UAV mission can cause inaccurate mapping or data collection as it serves as a crucial reference point for the UAV's sensors.

					and refresher courses for operators and staff.		
Operator inefficiency: lack of knowledge about terms and language used	2	2	3	1	Training, workshops, and multilingual work procedure guidelines address operator inefficiency.	2	One approach is to monitor UAV performance and safety during flight operations, which can reveal operator errors through flight data logs or observations.
GPS malfunctions: Navigation sensor functions	1	3	2	6	Sophisticated navigation algorithms can be set up along with sensors by the design engineers on the control system of the UAV	2	GPS signals can be blocked by obstructions or jammed, while hardware malfunctions can result from damage or environmental factors.
Structural and Software risks: Size, weight and Power constraint	2	1	2	4	The designers involved with manufacturing the UAV need to be aware of the objective of the mission to appropriately design the drone.	1	Structural risks can be detected through visual inspections and stress testing, while software risks can be identified through coding review, testing, and vulnerability scanning.
Hardware risks: Sensor failure, depleted drone, remote control, and display batteries.	2	2	1	4	Operators should check sensors before flight and use redundant equipment if necessary. Routine checks are performed to replace faulty sensors, depleted batteries, and motors.	1	Infrared sensors can fail due to physical damage, extreme temperatures, humidity, or software issues. Drone battery depletion can result from flight duration, energy-intensive features usage, and display battery depletion can occur from prolonged use.

In the following Minimum Bayes Risk Analysis tables, the mitigation strategy with the lowest risk value among others is chosen for a specific failure mode. This is highlighted with the color "green".

Table 27:Failure: Calibration tarp not being placed in the flight path

For this failure, there are three possible risk controls and for 2 possible states, there are six possible conditional risk scenarios. The "Do Nothing" represents the situation in which the mission may continue with degraded performance if there is a minor functional failure.

	Assigning a team member for tarp setup and ensure UAV follows designated flight path.			Using GPS or tracking systems to verify UAV's route adherence.			DO NOTHING	

c	Reliable	Unreliable	c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.65	0.35	P(x|w2)	0.5	0.5	P(x|w3)	0.35	0.65
λ(α1|w1)	8	0.0055	λ(α2|w2)	16	0.0075	λ(α3|w3)	10	10
	5.2	0.001925		8	0.00375		3.5	6.5
R1	**5.20**		R2	8.00		R3	10	
	Minimum Bayes Risk							

Table 28: Failure: Operator lack of knowledge about terms and language used

For this failure, there are two possible risk controls and for 2 possible states there are four possible conditional risk scenarios.

	Training, workshops, and multilingual work procedure guidelines address operator inefficiency.			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.25	0.75	P(x|w2)	0.55	0.45
λ(α1|w1)	16	0.004	λ(α2|w2)	8	8
	4	0.003		4.4	3.6
R1	**4.00**		R2	8	
	Minimum Bayes Risk				

Table 29: Failure: GPS navigation malfunctions

For this failure, there are three possible risk controls and for 2 possible states, there are six possible conditional risk scenarios.

	Setting up of sensors by the design engineers on the control systems of the UAV			Work procedure guidelines in different languages			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.25	0.75	P(x|w2)	0.25	0.75	P(x|w3)	0.55	0.45
λ(α1|w1)	0.0031	12	λ(α2|w2)	10	8	λ(α3|w3)	6	6
	0.002325	3		2.5	6		3.3	2.7
R1	3.00		R2	**8.5**		R3	6	
				Minimum Bayes Risk				

Table 30: Failure: Structural and Software risks: Size, weight, and Power constraints

For this failure, there are two possible risk controls and for 2 possible states, there are four possible conditional risk scenarios.

	SMEs aware of the mission objective and design the			DO NOTHING	

	UAV accordingly				
c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.3	0.7	P(x|w2)	0.55	0.45
λ(α1|w1)	0.001	18	λ(α2|w2)	8	8
	0.0003	12.6		8.5	1.5
R1	12.60		R2	**10**	
				Minimum Bayes Risk	

Table 31:Failure: Hardware Risks: Infra-red sensor failure, drone battery depletion, remote control battery depletion, display battery depletion

For this failure, there are three possible risk controls and for 2 possible states, there are six possible conditional risk scenarios.

	Routine checks performed by the SMEs			Setting up of sensors by the design engineers on the control systems of the UAV			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.25	0.75	P(x|w2)	0.65	0.35	P(x|w3)	0.55	0.45
λ(α1|w1)	0.0033	12	λ(α2|w2)	10	8	λ(α3|w3)	6	7
	0.002326	3		6.5	2.8		3.3	3.15
R1	9.00		R2	9.3		R3	**6.45**	
							Minimum Bayes Risk	

5.2 Takeoff/Departure:

The takeoff process of UAVs used for collecting aerial imagery of large agricultural farms and detecting methane leaks in mining/oil sites is crucial to ensure safe and effective operations.

The risks and mitigation strategies identified in the takeoff/departure stage of a general UAV mission should be extended to include agricultural surveys and methane leak detection. To ensure the UAV reaches its target, low-level control systems monitor body rates and lateral accelerations, including Roll Rate Control, Lateral Acceleration Control, Pitch Rate Control, Speed Control, and Yaw Rate Control as shown in Figure 32. However, sensor fouling or damage, wiring connection corrosion, or other issues can cause system failures and lateral acceleration drift. To address this, Active Spanwise Lift Control can precisely regulate lift and drag, mitigating gust issues. Additionally, a guidance algorithm can control the rate of acceleration and pitch, while preflight inspections can identify faults and ensure document requirements such as a drone license and insurance are met. Human control can also be incorporated to further decrease risks of failure as demonstrated in Figure 32.

When it comes to simulating the takeoff performance of an unmanned aerial vehicle (UAV), it's important to consider the non-linear relationships that may exist between the lift coefficient and drag coefficient and the UAV's angle of attack. This can affect the UAV's ability to take off in certain conditions, such as turbulent air or when there are wind gusts. Additionally, collision avoidance and vision-based navigation algorithms are crucial to minimize the risk of injury or damage to people, structures, and property during takeoff and flight [128]. To ensure safe operation, there are several rules and regulations enforced for UAV flight, including flight restrictions, visual line-of-sight requirements, remote pilot certification, aircraft registration, insurance, and flight planning as shown in Figure 33. It's important to educate employees on these regulations through training and workshops to minimize the risk of deviation from standard operating procedures and potential failures.

For agricultural surveys, the UAV is usually launched from a designated takeoff and landing site, which could be an open field or a flat area near the farm. For methane leak detection, the UAV can be launched from a mobile unit or a designated launch site near the target area [129]. Before takeoff, the UAV operator should also conduct a pre-flight inspection of the UAV to ensure that there are no visible signs of damage or malfunction which includes checking the battery level, verifying the GPS signal, and testing the camera and sensor systems as well whether the area is clear of any obstacles, such as trees or buildings, that could interfere with the flight.

Once the pre-flight inspection is complete, the UAV can be launched. The launch process involves powering on the UAV, starting the propellers, and initiating the takeoff sequence. During the flight, the UAV will follow the pre-planned flight path and capture aerial imagery of the agricultural farm using its onboard camera as mentioned in Figure 4. The UAV will also transmit telemetry data back to the ground station to ensure that everything is working correctly.

Next, the UAV is placed on the ground, and the operator activates the motors. The UAV will begin to lift off the ground, and the operator will need to adjust the throttle to control the ascent [130]. It is important to maintain a steady climb rate and to avoid sudden changes in altitude or direction. As the UAV gains altitude, the operator will need to adjust the yaw, pitch, and roll of the aircraft to ensure stable flight. This is accomplished using the remote control, which communicates with the onboard flight controller as mentioned in Table 32. The operator should also monitor the UAV's position and altitude using the telemetry data provided by the UAV's sensors [130]. Once the UAV reaches the desired altitude and position, the operator can begin the survey or detection mission.

The UAV must generate enough lift to overcome the force of gravity and gain altitude. The lift generated by the UAV's rotors is a function of the thrust produced by the rotors and the UAV's weight. The thrust is a function of the speed at which the rotors spin and the pitch of the rotor blades. The pitch of the rotor blades determines the angle at which they slice through the air, and the angle of attack determines the amount of lift generated. The takeoff process is initiated by the operator accelerating the UAV to a sufficient speed to generate enough lift to overcome the force of gravity. This speed is dependent on the size and weight of the UAV, as well as the aerodynamic properties of its design. The lift generated by the rotors is given by the equation:

$$\text{Lift} = 0.5 \times \rho \times A \times \omega^2 \times C_L \qquad (8)$$

where:

Lift represents the force exerted by the rotors to lift the UAV off the ground

ρ (rho) represents the air density

A represents the rotor area

ω (omega) represents the rotor speed

C_L represents the lift coefficient where the lift coefficient is a function of the angle of attack of the rotor blades and other factors affecting rotor performance.

As the UAV gains altitude, the operator must adjust the yaw, pitch, and roll of the aircraft to ensure stable flight. The UAV's attitude is controlled by varying the speed and pitch of the rotor blades. The UAV's orientation in space is determined by the Euler angles of roll, pitch, and yaw. Euler angles are a set of three angles that define the orientation of a rigid body in three-dimensional space. The most common convention for defining Euler angles is the Tait–Bryan convention, which uses three angles to define the rotation of three distinct axes. The three angles are usually denoted as roll (ϕ), pitch (θ), and yaw (ψ). The rotation is performed in a specific order, which is usually represented by a sequence of three letters, such as XYZ or YZX, with each letter indicating the axis of rotation.

The equations for converting between Euler angles and rotation matrices are:

$$R = Rz(\psi)Ry(\theta)Rx(\varphi) \tag{9}$$

where R is the rotation matrix, and Rx(ϕ), Ry(θ), and Rz(ψ) are the rotation matrices corresponding to rotations about the x, y, and z-axes, respectively:

$$Rx(\varphi)= \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(\varphi) & -sin(\varphi \\ 0 & sin(\varphi & cos(\varphi) \end{bmatrix}; \quad Ry(\theta) = \begin{bmatrix} cos(\theta) & 0 & sin(\theta) \\ 0 & 1 & 0 \\ -sin(\theta) & 0 & cos(\theta) \end{bmatrix}; \quad Rz(\psi)= \begin{bmatrix} \cos(\psi) & -sin(\psi & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix};$$

The operator adjusts these angles using the remote control, which communicates with the onboard flight controller. The operator should also monitor the UAV's position and altitude using the telemetry data provided by the UAV's sensors. Once the UAV reaches the desired altitude and position, the operator can begin the survey or detection mission. For agricultural surveys, the UAV will follow a pre-determined flight plan, taking images and videos of the farm at regular intervals. The flight plan should consider the terrain, obstacles, and wind conditions. For methane leak detection, the UAV will fly over the target area, using gas sensors to detect any leaks. The gas sensors operate based on the principles of gas diffusion and the interaction between light and matter. The concentration of methane in the air is detected by measuring the absorption of light by methane molecules. The gas sensors provide real-time data to the UAV's flight controller, which can adjust the flight path based on the detected methane concentration.

In conclusion, the takeoff process for UAVs used for agricultural surveys and methane leak detection involves several important steps, including checking the systems, conducting a pre-flight inspection, and controlling the ascent and flight direction. Careful attention to these steps is crucial for safe and effective UAV operations.

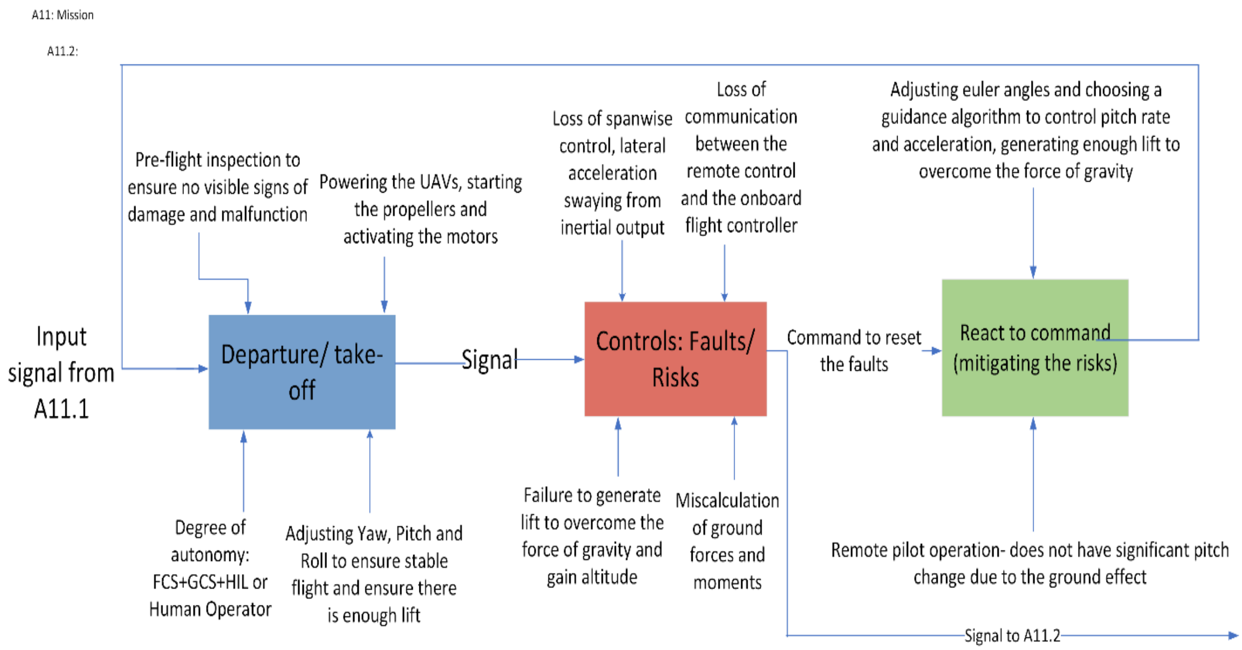

Figure 32: Take-off/Departure stage of the company

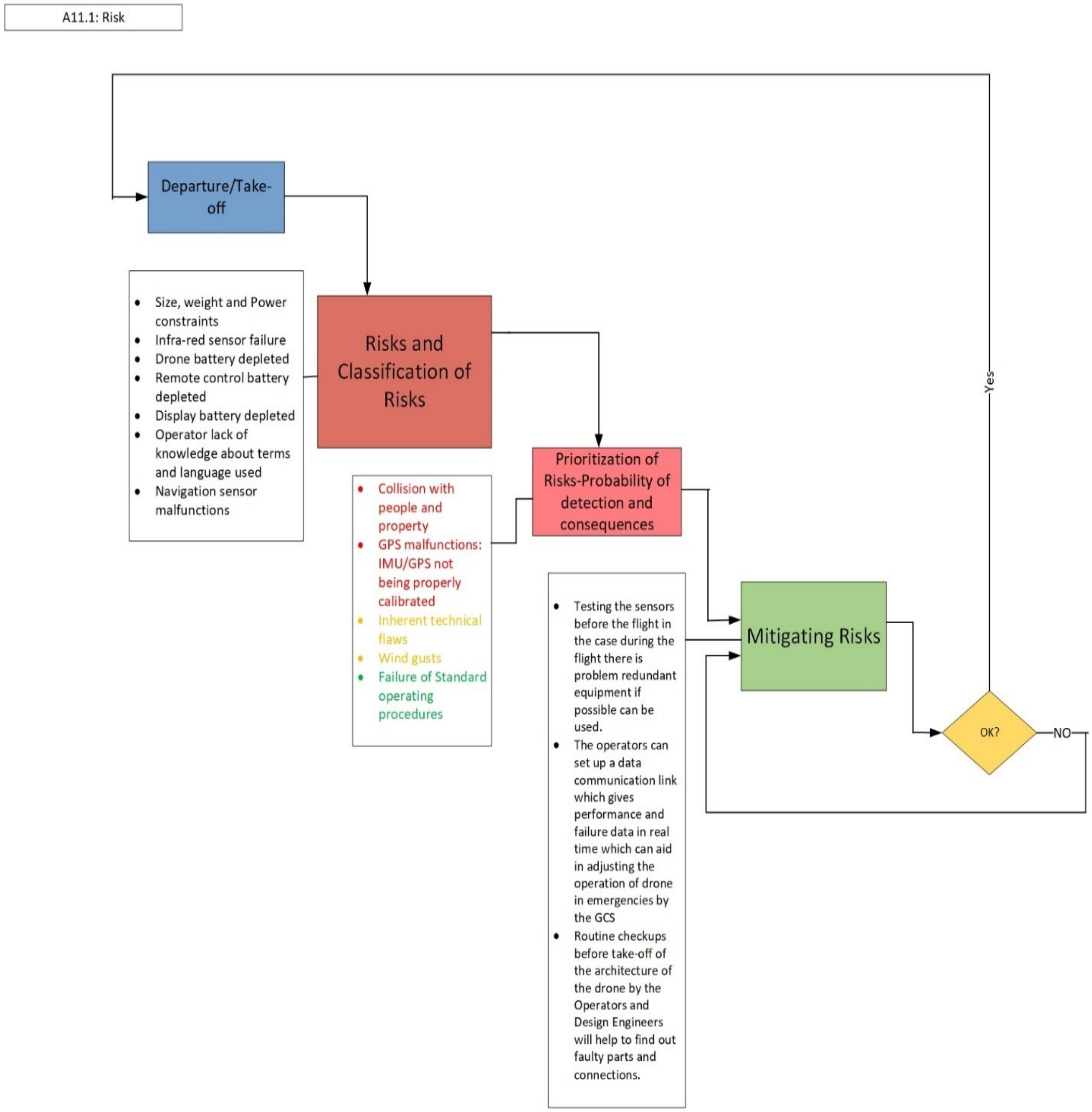

Figure 33: Ranked Risks associated with the Take-off/Departure stage of the company

The table below demonstrates a qualitative analysis of the risks associated with the “Departure” stage of the UAV mission, the RPN values associated with them, the controls implemented to mitigate them, the residual risk after the controls are implemented and the trigger for the failures in the stages:

Table 32: FMEA sequence of the Take-off/Departure stage

Faults and related operating conditions	Likelihood	Severity	Detectability	RPN (uncontrolled)	Risk Control	Residual RPN	Trigger
Collision risks include malfunctions and collisions with people, birds, structures, and property.	3	3	3	27	Software engineers use advanced algorithms and short-range sensors like proximity sensors, cameras, and microphones to enable collision avoidance and vision-based navigation on UAVs.	9	UAVs rely on sensor systems to detect and avoid collisions, but malfunctions or adverse weather conditions can hinder their effectiveness. Collisions with obstacles like birds, buildings, or undetected structures are possible risks.
GPS malfunctions: IMU/GPS not being properly calibrated	3	3	3	27	Regular maintenance, testing, and calibration are essential to detect and prevent malfunctions. Double-checking calibration and data during flight helps identify errors or deviations from the planned path.	2	Stable power supply is crucial for GPS/IMU navigation systems to function correctly. Checking data quality helps detect calibration issues. Signal jamming can lead to navigation errors or security breaches.
Technical flaws can prevent take-off due to hardware and software faults.	2	3	2	12	Routine checkups by operators and design engineers can identify faulty parts and connections, reducing the risk of incidents.	4	UAVs may experience design flaws, physical damage, software bugs, or power supply disruptions, leading to malfunctions or failures. Proper testing and validation can help mitigate technical flaws.
Wind gusts: High winds and vortex ring state during drone flight	2	3	2	12	Operators can use GPS navigation to recalculate the path if the wind pushes the UAV off course. Flying in high winds requires caution, and a reliable flight management system and proper planning can help mitigate risks associated with wind gusts and turbulence.	4	High winds, particularly during thunderstorms, can generate strong and unpredictable gusts that impact the UAV's stability and performance. UAVs with inadequate aerodynamics or lightweight designs are particularly susceptible to wind gusts, compromising their stability in strong winds.
Problems in the communication channel between the remote controller and the drone when the drone is taking off	2	2	2	8	Operators can establish a real-time data communication link that provides performance and failure information, enabling prompt adjustments by the GCS during emergencies. Identifying the cause of communication gaps is crucial to prevent future occurrences.	4	Operators may not be aware of airspace restrictions such as flight altitude limits, restricted areas, which can lead to the UAV being flown in dangerous proximity to other aircrafts. Operators may not be aware of the legal requirements and regulations that apply to UAV operations in the AOI, which can result in non-compliance and legal or safety issues.

The following tables demonstrate the Risk calculation for each of the mitigation strategies for a specific failure which might occur during the take-off of the UAV:

Table 33: Failure: Collision avoidance malfunction, collision with humans, birds, man-made structures,

property, etc.

For this failure, there are two possible risk controls and for 2 possible states, there are four possible conditional risk scenarios:

	Software engineers use advanced algorithms and short-range sensors			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.75	0.25	P(x|w2)	0.2	0.8
λ(α1|w1)	0.003	18	λ(α2|w2)	10	10
	0.00225	4.5		2	8
R1	**4.50**		R2	10	
	Minimum Bayes Risk				

Table 34:Failure: GPS navigation malfunctions

For this failure, there are three possible risk controls and for 2 possible states, there are six possible conditional risk scenarios.

	Regular maintenance, testing, and calibration			Double-checking calibration and data			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.25	0.75	P(x|w2)	0.25	0.75	P(x|w3)	0.55	0.45
λ(α1|w1)	0.0031	12	λ(α2|w2)	10	8	λ(α3|w3)	6	6
	0.002325	3		2.5	6		3.3	2.7
R1	3.00		R2	**8.5**		R3	6	
				Minimum Bayes Risk				

Table 35:Failure: Inherent technical flaws- Failure to take off due to any faults in the hardware and software systems of the drone.

For this failure, there are two possible risk controls and for 2 possible states, there are four possible conditional risk scenarios:

	Routine checkups by operators and design engineers can identify faulty parts and connections			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.65	0.35	P(x|w2)	0.2	0.8
λ(α1|w1)	0.002	15	λ(α2|w2)	9	9
	0.0013	5.25		1.8	7.2
R1	**5.25**		R2	9	
	Minimum Bayes Risk				

Table 36:Failure: Wind gusts- High winds and vortex ring state during drone flight.

For this failure, there are two possible risk controls and for 2 possible states, there are four possible conditional risk scenarios.

	If the wind is pushing the UAV off the path, the operators set up a GPS navigation to recalculate the path			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.55	0.45	P(x|w2)	0.4	0.6
λ(α1|w1)	0.0025	17	λ(α2|w2)	9	9
	0.001375	7.65		3.6	5.4
R1	**7.65**		R2	9	
	Minimum Bayes Risk				

Table 37:Failure- Problems in the communication channel between the remote controller and the drone when the drone is taking off.

For this failure, there are two possible risk controls and for 2 possible states, there are four possible conditional risk scenarios.

	If the wind is pushing the UAV off the path, the operators set up a GPS navigation to recalculate the path			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.55	0.45	P(x|w2)	0.4	0.6
λ(α1|w1)	0.0025	17	λ(α2|w2)	9	9
	0.001375	7.65		3.6	5.4
R1	**7.65**		R2	9	
	Minimum Bayes Risk				

5.3 Flight/Tracking:

The flight and tracking process for these applications is critical and requires careful planning and execution to ensure safe and reliable operation. Mission planning is the first step in the flight and tracking process for UAVs. This involves selecting an appropriate UAV platform based on the mission requirements, including the payload capacity, endurance, and range. The mission plan should also include the identification of the target area, the required imaging resolution and accuracy, and the flight parameters such as altitude, speed, and flight path [131].

To cover agricultural surveys and methane leak detection, the risks and mitigation strategies noted during the flight/tracking phase of a typical UAV mission should be broadened. UAVs use cameras and sensors to collect imagery, ranging from simple cameras to advanced ones for high-resolution video and thermal images. The UAV's flight control system controls the cameras, capturing images at specific locations and altitudes. These images are then processed and analyzed to obtain desired data. Properly managing forward and side overlap is necessary to generate seamless mosaics that indicate the location of features as mentioned in Figure 34. AGL refers to the height of an object above the ground, which in UAV imaging, is used to determine the altitude at which a drone is flying and collecting data. However, factors such as GPS inaccuracies, atmospheric conditions, and instrument error can affect the quality of the imagery [132]. To mitigate these issues, UAV operators may use additional sensors and equipment, such as barometer and altimeter.

For collecting aerial imagery of large agricultural farms or detecting methane leaks in mining/oil sites, the UAV flight process involves pre-flight checks and mission planning, followed by launching the UAV and flying it along the predetermined flight path while using onboard sensors to maintain position and altitude. The UAV operator may also make manual adjustments to the flight path as needed to avoid obstacles or ensure important areas are covered as shown in Figure 34.

To collect aerial imagery of large agricultural farms, the UAV's flight path is usually planned in parallel lines to ensure seamless coverage of the entire area. After the flight, the images captured by the UAV's sensors are stitched together to create a mosaic image that shows the entire area seamlessly. Drone mapping software with orthomosaic capabilities, such as DJI Terra, can be used to generate a 2D orthomosaic of a set area in real-time, allowing for rapid and accurate 2D reconstructions. On the other hand, for small flights of detecting methane leaks in mining/oil sites, the UAV's sensors may include methane detectors, which can be used to detect the presence of methane gas leaks from pipelines or other sources. The UAV's flight path may be planned to cover specific areas of interest, and the operator may make manual adjustments to ensure that the sensors are directed towards areas where methane leaks are more likely to occur.

Before takeoff, the UAV must undergo a series of pre-flight checks to ensure that it is ready for operation. To check the UAV's systems and components, the operator should follow a pre-flight checklist provided by the UAV's manufacturer. This includes checking the UAV’s systems and components, including the propulsion system, avionics, sensors, and imaging equipment. The UAV’s battery capacity and power management system should be checked to ensure that it has sufficient power for the duration of the mission as shown in Figure 35. The UAV’s communication and control systems should also be tested to ensure that they are functioning correctly, `and that the UAV can be remotely controlled from the ground [133].

Once the UAV is ready for operation, it is launched and flies along the predetermined flight path. The UAV’s flight is controlled by a ground-based operator using a combination of GPS and telemetry data. The UAV’s onboard sensors and imaging equipment collect data about the target area, which is transmitted in real-time or stored onboard for later analysis. The UAV’s flight path can be adjusted during the flight to ensure that the target area is fully covered [134].

In addition to the flight and tracking process, safety is always a top priority when operating UAVs. One of the key aspects to monitor during UAV flights is the battery life and power management system. The UAV must have sufficient power to complete the mission and return safely to the ground. The battery life and power management system need to be monitored and controlled to ensure that the UAV has enough power for the entire duration of the flight as mentioned in Figure 35. This can be done by setting up alerts for low battery levels or by implementing automated return-to-home features when the battery level reaches a critical level. These systems can provide real-time information on battery life and health and alert the operator when the battery level is low and can also automatically trigger a return-to-home function when the battery level reaches a critical level as described in Table 38 [135].

Another critical factor is the communication and control system. The UAV’s communication and control systems must be functioning correctly and be able to maintain a stable connection between the UAV and the ground station throughout the flight. This is essential for monitoring the UAV’s location and status, as well as controlling its flight path and adjusting its mission parameters if necessary [136]. These systems can provide telemetry data on the UAV’s location, altitude, speed, and battery level, and can also allow for remote control of the aircraft if necessary.

The UAV’s flight path and altitude are also important factors to monitor during the flight. The flight path should be pre-planned and should consider the desired coverage area, imaging resolution, and accuracy. The operator must ensure that the UAV does not fly beyond its maximum altitude or outside of its operational range. This can be achieved by setting appropriate limits in the UAV's software or by using a geofencing system that prevents the UAV from flying outside of a predetermined area. The UAV’s altitude should be adjusted based on the mission requirements, including the type of imaging sensor being used, the weather conditions, and any obstacles in the flight path [137]. The flight path and altitude can be adjusted during the flight to ensure that the target area is fully covered, and that the imaging data is of high quality. Automated flight control systems are an existing control that can manage the flight path, altitude, and speed of the aircraft. These systems can be pre-programmed with flight plans and can automatically adjust the flight path and altitude to provide maximum coverage and imaging quality.

The operator needs to ensure that the UAV does not interfere with other aircraft or communication systems. This can be achieved by using a frequency management system that ensures that the UAV is operating on a frequency that does not interfere with other systems in the area.

Finally, weather conditions are another critical factor to monitor during UAV flights. The UAV's flight should be planned around weather conditions that are favorable for safe and reliable operation as shown in Figure 6. Wind, rain, and other environmental factors can impact the UAV's flight performance and can potentially cause damage to the UAV or its payload. Weather conditions should be monitored throughout the flight, and the mission should be aborted or adjusted if the weather conditions become unfavorable.

Experts are responsible for designing UAVs that meet rigorous safety standards and for developing flight and tracking systems that ensure safe and reliable operation. This includes the development of collision avoidance systems, redundant flight control systems, and other safety features that protect the UAV, its payload, and the people and property on the ground [138].

Flight tracking systems are used to monitor the movement of aircraft in real-time. These systems use a combination of technologies such as GPS, radar, and ADS-B (Automatic Dependent Surveillance-Broadcast) to determine the location and movement of aircraft. Flight tracking systems have become an essential tool for aviation enthusiasts and professionals alike, providing real-time information about flights all around the world. There are many flight tracking platforms available, each with its own unique features and capabilities [139]. For instance, FlightAware is a widely used platform that combines FAA data, ADS-B, and radar to track flights worldwide and provides information on flight status and airport information. FlightRadar24 is another popular service that specializes in real-time flight tracking using ADS-B to track a wide range of aircraft, including commercial airlines, private jets, and military planes. Plane Finder uses a combination of ADS-B, MLAT, and radar data to track aircraft worldwide while offering detailed flight status, airport arrivals and departures, and flight routes. FlightView is another flight tracking and airport information service that combines FAA data, airline data, and airport data to provide real-time flight information, including flight status, airport delays, and weather conditions [140]. Lastly, SkyRadar is a comprehensive flight tracking system that combines ADS-B and radar data to provide real-time tracking of aircraft, as well as detailed information on flight routes, altitude, and speed, weather conditions, and airport information [141].

Additional controls can include obstacle detection and avoidance systems, imaging quality monitoring systems, and emergency response systems as mentioned in Figure 6. Obstacle detection and avoidance systems can help to avoid collisions with obstacles and can use sensors such as lidar or radar. Imaging quality monitoring systems can provide real-time information on the quality of the imaging data being collected. Emergency response systems can automatically trigger a return-to-home function or emergency landing if the UAV experiences a critical malfunction or if the operator loses control of the aircraft. It is important to have contingency plans in place in case of unexpected events, such as the loss of communication with the UAV or an emergency landing. This may include having backup communication systems or a predetermined emergency landing area.

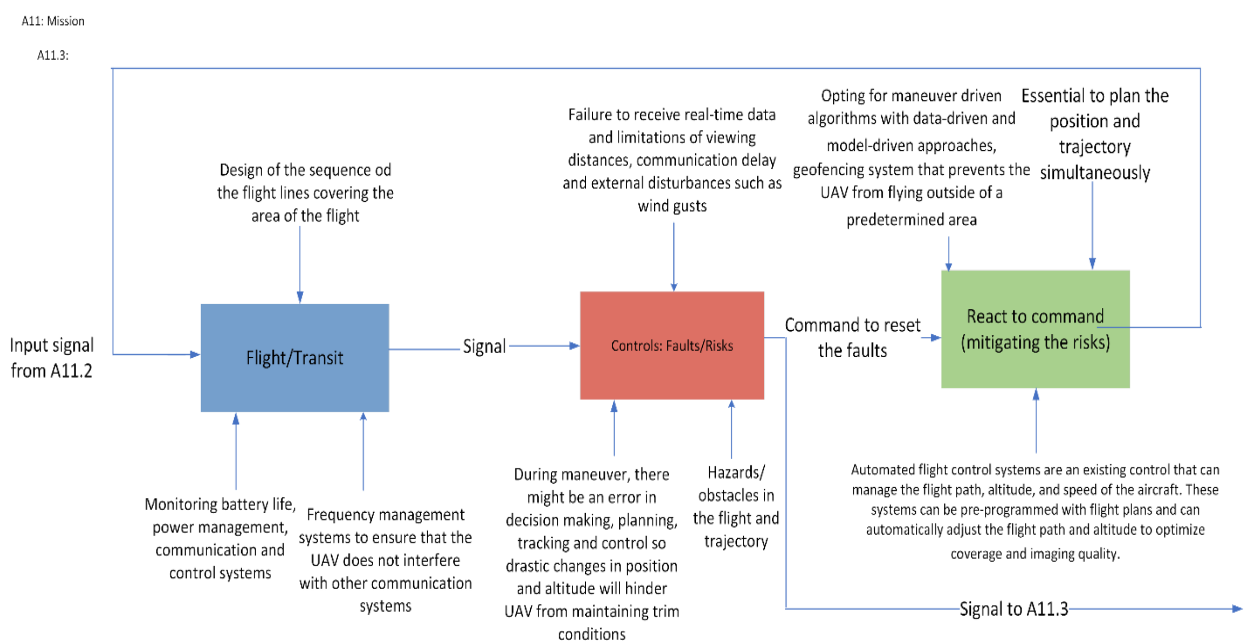

Figure 34: Flight/Tracking stage of the company

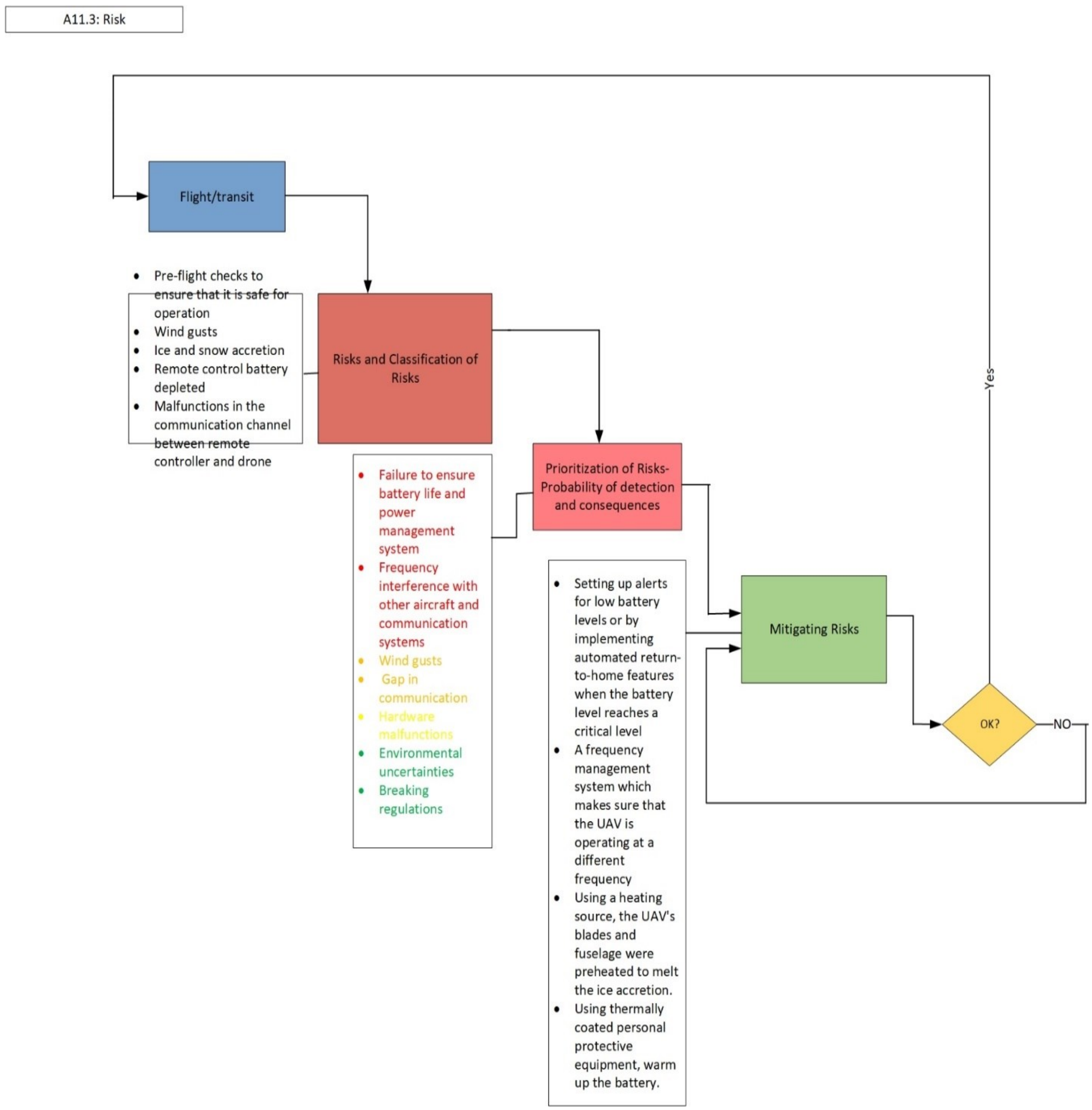

Figure 35: Ranked Risks associated with Flight/Tracking stage of the company

The table below demonstrates a qualitative analysis of the risks associated with the "Flight" stage of the UAV mission, the RPN values associated with them, the controls implemented to mitigate them, the residual risk after the controls are implemented and the trigger for the failures in the stages:

Table 38: FMEA sequence of the Flight stage

Faults and related conditions	Likelihood	Severity	Detectability	RPN (uncontrolled)	Risk Control	Residual RPN	Trigger
Failure to ensure battery life and power management system	3	3	3	27	Implementing battery alerts and automated return-to-home features can address low battery levels. These systems provide real-time battery information, issue alerts for low levels, and activate return-to-home functions in critical situations.	2	Erratic flight, altitude loss, or unresponsiveness to commands indicate power management issues. Landing the UAV immediately is crucial to prevent crashes or damage.
Frequency interference with other aircraft and communication systems	3	3	3	27	This can be achieved by using a frequency management system that ensures that the UAV is operating on a frequency that does not interfere with other systems in the area.	1	Monitoring the electromagnetic spectrum with a frequency scanner helps identify conflicting frequencies, while automated flight planning tools consider the frequency spectrum to avoid interference during UAV flights.
Communication malfunctions between remote controller and drone during flight.	2	3	3	18	The operators can set up a data communication link which gives performance and failure data in real time which can aid in adjusting the operation of drone in emergencies by the GCS	1	Loss of real-time flight data. Factors contributing to communication gaps include radio frequency interference, limited range, and incorrect settings. These issues can lead to drone malfunction or shutdown.
Environmental uncertainties: Wind gusts Ice and snow accretion	2	3	2	12	Collaborating with a supplier of UAV hardware and software to create advanced collision avoidance algorithms. If the engineers used a heating source to preheat the UAV's blades and fuselage to melt the ice accretion.	3	Windspeed sensors on the drone's wings detect unusual flight speed. Moisture sensors on outer extremities detect snow and ice accumulation. Ice and snow accumulation impact aerodynamics, weight, and power consumption.
Hardware malfunctions: Remote control battery depleted	2	3	2	6	The design engineers can use athermally coated personal protective equipment, warm up the battery.	1	Voltage sensors detect battery depletion in the UAV. Aging, wear and tear, extreme conditions, and incorrect usage can also lead to remote control

							failure or power loss.

The following tables demonstrate the Risk calculation for each of the mitigation strategies for a specific failure which might occur during a Transit stage:

Table 39:Failure- Problems in the battery life and power management.

For this failure, there are two possible risk controls and for 2 possible states, there are four possible conditional risk scenarios.

	Implementing battery alerts and automated return-to-home features can address low battery levels.			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.65	0.35	P(x|w2)	0.3	0.7
λ(α1|w1)	0.0045	17	λ(α2|w2)	10	10
	0.002925	5.95		3	7
R1	**5.95**		R2	10	
	Minimum Bayes Risk				

Table 40:Failure- Frequency interference with other aircraft and communication systems.

For this failure, there are two possible risk controls and for 2 possible states, there are four possible conditional risk scenarios.

	Using a frequency management system that ensures that the UAV is operating on a frequency that does not interfere with other systems in the area.			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.75	0.25	P(x|w2)	0.8	0.2
λ(α1|w1)	0.0033	15	λ(α2|w2)	8	8
	0.002475	3.75		6.4	1.6
R1	**3.75**		R2	9	
	Minimum Bayes Risk				

Table 41:Failure: Malfunctions in the communication channel between remote controller and drone during drone flight.

For this failure, there are two possible risk controls and for 2 possible states, there are four possible conditional risk scenarios.

	The operators set up a data communication link which gives performance and failure data in real time to aid in adjusting the operation of drone in emergencies by the GCS			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.65	0.35	P(x|w2)	0.6	0.4
λ(α1|w1)	0.0045	17	λ(α2|w2)	5	5
	0.002925	5.95		3	2
R1	**5.952925**		R2	5	
	Minimum Bayes Risk				

Table 42:Failure: Environmental uncertainties: Wind gusts Ice and snow accretion

For this failure, there are three possible risk controls and for 2 possible states, there are six possible conditional risk scenarios.

	Collaborating with a supplier of UAV hardware and software to create advanced collision avoidance algorithms			The engineers use a heating source to preheat the UAV's blades and fuselage to melt the ice accretion			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.5	0.5	P(x|w2)	0.45	0.55	P(x|w3)	0.65	0.35
λ(α1|w1)	18	0.003	λ(α2|w2)	13	0.0015	λ(α3|w3)	9	9
	9	0.0015		2.5	6		5.85	3.15
R1	9.0015		R2	**5.85**		R3	6	
				Minimum Bayes Risk				

Table 43:Failure- Hardware malfunctions

For this failure, there are two possible risk controls and for 2 possible states, there are four possible conditional risk scenarios.

	The design engineers use athermally coated personal protective equipment, warm up the battery.			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.55	0.45	P(x|w2)	0.7	0.3
λ(α1|w1)	0.0035	19	λ(α2|w2)	10	10
	0.001925	8.55		7	3
R1	**8.551925**		R2	10	
	Minimum Bayes Risk				

5.4 Arrival:

The UAV operator should conduct a site survey to identify potential obstacles, hazards, and other factors that could affect the mission's success. This information is used to plan the flight path and ensure safe and efficient operation. Based on the site survey, the UAV operator develops a flight plan that includes the flight path, altitude, and speed required to collect the required data. The UAV operator should also consider the weather conditions and airspace restrictions when planning the flight. Before the flight, the UAV operator conducts a series of pre-flight checks to ensure that the UAV, sensors, and cameras are functioning correctly. This includes inspecting the UAV, checking the battery levels, and calibrating the sensors and cameras.

For adequate risk management, it is important to apply the risks and mitigation strategies identified in the arrival stage of a general UAV mission to agricultural surveys and methane leak detection. During the data collection stage, there are various risks that could interrupt the process. One of them is the inaccessibility of sensors, which can be mitigated by establishing a localization network with a beacon node. If a camera malfunctions or communication breaks down, backup cameras or alternative data collection methods can be used as mentioned in Figure 36. Weather conditions such as rain or fog can also impact data collection, but can be addressed by using illumination gadgets, GPS navigation, and backup plans. Lastly, workload on the human operator can be managed by assigning multiple people to the task.

During this stage of the mission, system failures can occur due to hardware or software malfunctions, causing the UAV to crash or lose connectivity with the ground station. To mitigate these failures, regular maintenance and testing of the UAV system are required to ensure that it is operating correctly. Human errors such as pilot error or miscommunication can also lead to mission failure [142]. To mitigate these failures, the UAV operator should undergo regular training and adhere to strict protocols and procedures during the mission as show in Figure 36. UAVs rely on GPS signals to navigate and maintain their position, and if the GPS signal is lost, the UAV can become disoriented or lost. To mitigate this failure, the UAV operator should ensure that the UAV's GPS system is functioning correctly and have a backup navigation system in place as shown in Figure 36.

The onboard sensors and cameras are critical to the success of the UAV mission, and if they malfunction, the UAV can fail to capture the required data as mentioned in Figure 36. For instance, Light Detection and Ranging (LiDAR) sensors are used to capture detailed 3D images of the terrain or structures, and any malfunction can cause the UAV to capture incomplete or inaccurate data [143]. This can occur due to technical issues such as hardware failure or alignment errors. To avoid this, the UAV operator should regularly inspect and maintain the LiDAR sensor and have backup LiDAR systems available [144]. Additionally, the UAV operator should ensure that the LiDAR sensor is properly aligned and calibrated before flight as shown in Table 44.

Another example of sensor malfunction is TARP (Tactical Airborne Reconnaissance Pod) used on military aircraft for intelligence, surveillance, and reconnaissance (ISR) missions [145]. The TARP system includes a pod-mounted sensor package that can capture images and other data from the air. If the TARP system malfunctions during a mission, it can result in incomplete or inaccurate data collection, which can impact mission effectiveness. The specific failures that can occur with the TARP system will depend on the cause of the malfunction, which can include technical issues such as hardware failure, software errors, or electromagnetic interference. To avoid TARP system malfunctions, the aircraft operator should conduct regular inspections and maintenance of the system, including pre-flight checks to ensure that all components are functioning correctly. The operator should also ensure that the TARP system is correctly configured and calibrated for the mission requirements and should monitor the system during the mission for any signs of malfunction [146]. If a TARP system malfunction does occur, the operator may be able to fix the problem by troubleshooting the system and making any necessary repairs or adjustments. In some cases, it may be necessary to replace a component or to switch to a backup system. The aircraft operator should have contingency plans in place for TARP system failures, including backup systems and procedures for rescheduling or reconfiguring the mission [147].

Calibrating the Inertial Measurement Unit (IMU) is a critical step in accurately recording the attitude of the sensor system during an aerial acquisition, which is necessary for detecting methane/oil leaks in pipelines or collecting aerial imagery for large agricultural farms [144, 145]. In the case of the MPU6050 IMU, for example, unique offset values must be found for each sensor, which can be achieved by uploading the IMU_Zero program to the Arduino board and ensuring proper connections are made between the sensor and board [148]. To collect aerial imagery for large agricultural farms or detect methane/oil leaks in pipelines, the sensor system must also be equipped with a GNSS receiver that accurately captures altitude, latitude, and longitude coordinates during the acquisition flight. This allows for the absolute location of the sensor to be recorded and the collected data to be properly georeferenced.

The specific method for detecting methane/oil leaks in pipelines using aerial imagery can vary, but generally involves capturing spectral data in the infrared region that is specific to methane/oil and analyzing this data to identify any areas where the gas is escaping from the pipeline. This method can be used to capture spectral data in the infrared region that is specific to methane or oil using a miniaturized sensor with high sensitivity and low drift [148]. The data is then analyzed to identify any areas where the gas is escaping from the pipeline. This method can be used in conjunction with IMU and Global Navigation Satellite System (GNSS) data to precisely locate the leaks and facilitate repairs. The IMU records the attitude (pitch, yaw, and roll) of the sensor system during the acquisition flight, while the GNSS receiver accurately captures altitude, latitude, and longitude coordinates of the sensor, so the absolute location of the sensor is recorded [149].

For large agricultural farms, aerial imagery can be used to map the land and identify areas with varying levels of vegetation stress. This can be done using remote sensing technology that captures data on the reflectance of different wavelengths of light from the crops, which can be used to generate maps of vegetation indices, such as the normalized difference vegetation index (NDVI). These maps can then be used to identify areas of the farm with lower vegetation health, which can help optimize crop yield [150].

Radio interference can disrupt the communication between the UAV and the ground station, causing the UAV to lose control or crash. To mitigate this failure, the UAV operator should avoid flying near areas with high radio interference and use frequency-hopping spread spectrum (FHSS) technology to reduce the risk of interference. During the flight, the UAV can collide with obstacles such as trees, power lines, or buildings, causing it to crash. To mitigate this failure, the UAV operator should carefully plan the flight path and avoid flying near obstacles. The UAV can also be equipped with obstacle avoidance sensors and cameras to detect and avoid obstacles.

Once the pre-flight checks are complete, the UAV is launched and follows the flight path as planned. During the flight, the sensors and cameras capture data, which is transmitted to the ground station for real-time analysis and processing. UAVs can be equipped with high-resolution cameras to capture detailed images of crops and fields as mentioned in Figure 8. One such example is Hyperspectral Imagery. Hyperspectral imaging is a powerful tool for collecting aerial imagery of agricultural sites and fields from drones. The technology works by capturing images at multiple wavelengths, allowing for detailed analysis of the data collected.

The hyperspectral sensors used in drone-based imaging can scan in two ways: Push Broom and Whisk Broom. is Push Broom scanning particularly ideal for drone use because it captures full spectral data simultaneously as the drone moves forward using a line of sensors that runs perpendicular to the drone's flight direction [151]. The imaging sensor used for drone-based hyperspectral sensing is capable of capturing images across the electromagnetic spectrum. The sensors operate by collecting a series of narrow and contiguous wavelength bands, providing a high level of performance in spectral and radiometric accuracy. The datasets produced by hyperspectral imagers are in the form of a three-dimensional cube or a set of two-dimensional images that can be processed and analyzed to identify specific features or characteristics of the agricultural site or field being imaged [152]. To ensure accurate data collection, hyperspectral sensors require adequate sensor settings, which may vary from site to site depending on the deposit being surveyed [153]. The collected data can then be georeferenced to a specific location, allowing for spatial analysis and mapping of the features or characteristics of the agricultural site or field.

Detecting pipeline leaks using hyperspectral imaging requires capturing spectral data in the infrared region that is specific to methane, and then analyzing this data to identify any areas where methane gas is escaping from the pipeline. The captured data is then analyzed using algorithms that can differentiate between methane gas and other materials present in the scene. This allows for the identification of areas where methane gas is escaping from the pipeline [154]. Hyperspectral imaging is just one of the many methods used for pipeline leak detection.

RGB cameras are commonly used for visual imaging, while multispectral cameras can capture data on specific wavelengths of light to analyze plant health and other characteristics. LiDAR sensors use laser pulses to create a 3D map of the terrain and vegetation. This can be useful for analyzing the topography of the farm and identifying areas of elevation or slope that may impact crop growth. Thermal cameras can detect differences in temperature, which can be used to identify areas of stress or disease in crops. This can help farmers to identify problems early and take corrective action. GPS technology can be used to track the location and movement of the UAV during the flight. This can help to ensure that the imagery is accurately georeferenced and aligned with other geospatial data. Flight planning software can be used to create a flight path for the UAV that ensures the collection of aerial imagery. This can help to ensure that the entire farm is covered, and that the imagery is captured at the appropriate resolution and frequency. Other methods include acoustic, pressure, as well as aerial surveillance and ground-based monitoring systems. The choice of method depends on various factors, such as the location and size of the pipeline, the type of material being transported, and the level of accuracy required for detection.

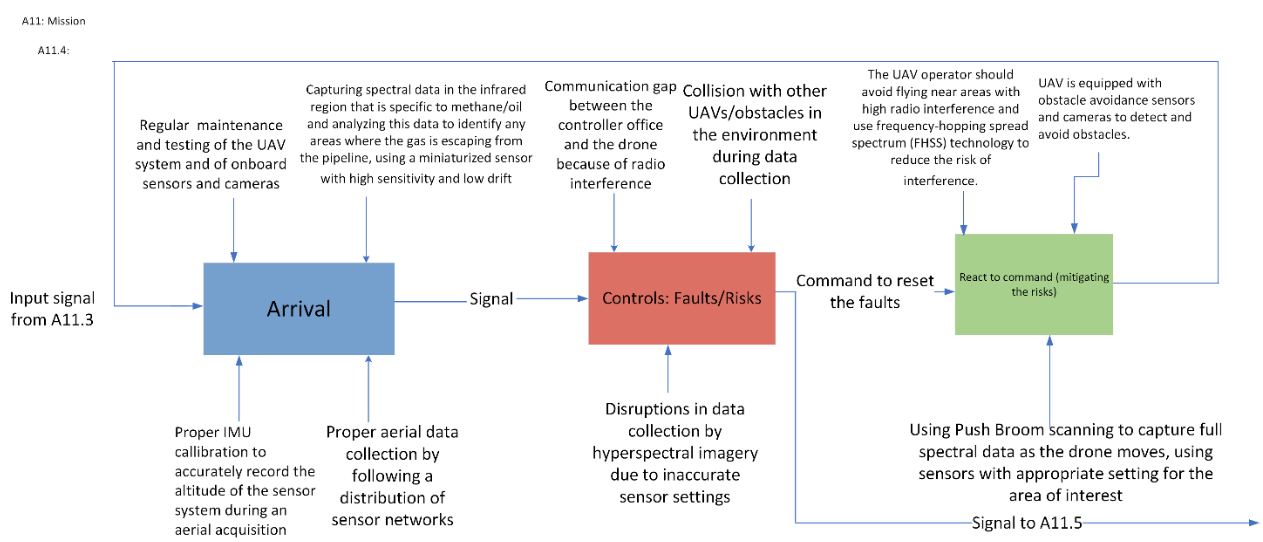

Figure 36: Arrival stage of the company

A11.4: Risk

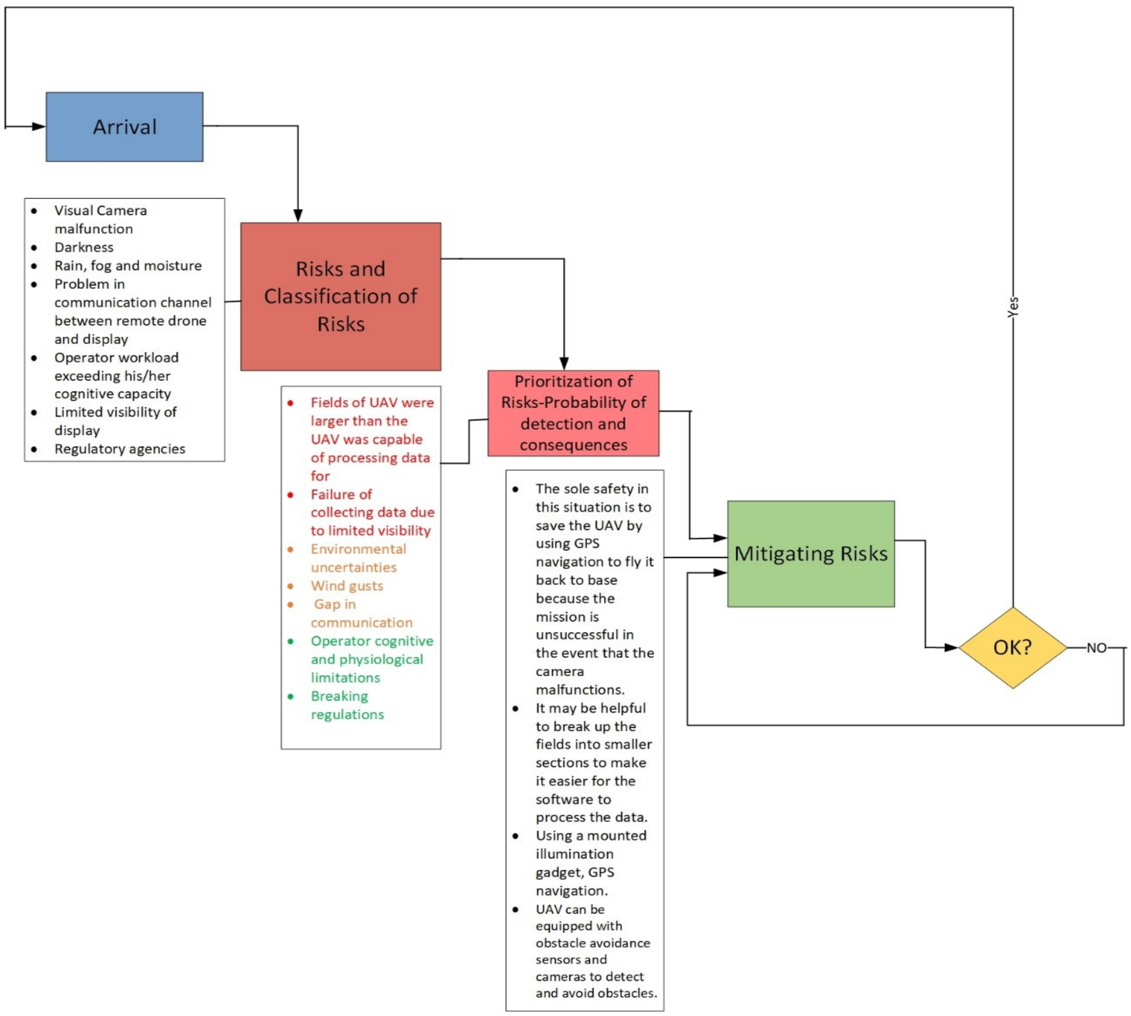

Figure 37: Ranked Risks associated with the Arrival stage of the company

The table below demonstrates a qualitative analysis of the risks associated with the "Arrival" stage of the UAV mission, the RPN values associated with them, the controls implemented to mitigate them, the residual risk after the controls are implemented and the trigger for the failures in the stages:

Table 44: FMEA sequence of the Arrival stage

Faults and related conditions	Likelihood	Severity	Detect ability	RPN (uncontrolled)	Risk Control	Residual RPN	Trigger
Fields of the mission were larger than the software was capable of processing data for.	3	3	3	27	Thoroughly test the UAV and software capabilities prior to the mission. Communicate with the manufacturer to ensure software compatibility with field size. Break up large fields into smaller sections for easier data processing.	4	To find issue, perform a practice run of the UAV operation on a smaller field area and assess the software's data processing abilities. Consult with software supplier to validate system capabilities for larger fields.
Failure of collecting data due to limited visibility: Visual Camera malfunction Darkness	3	3	3	27	The sole safety in this situation is to save the UAV if the operators use GPS navigation to fly it back to base because the mission is unsuccessful if the camera malfunctions. The engineers can mount illumination gadget, GPS navigation.	3	Data collection can be hindered due to issues like camera malfunction, darkness, obstacles, and operator error. Discrepancies between real-time data and prototype simulations can lead to data inaccuracies.
Environmental uncertainties: Rain, fog and moisture, Wind gusts	3	3	1	9	Awareness of weather patterns, proper equipment, safety measures, and monitoring for any changes are essential for safe operation in different weather conditions.	4	Windspeed sensors detect gusts, weather patterns cause rain and moisture, temperature changes create fog, and topography can lead to turbulence.
Operator cognitive and physiological limitations	2	3	1	6	Operators should be trained and stress-free. They need proper equipment and monitoring of workload and factors affecting their performance during drone operation.	2	Multitasking, limited visibility, fatigue, stress, and lack of training can lead to operator mistakes and difficulties in controlling the drone.
Breaking regulations: Regulatory agencies	2	1	2	4	Operators must proper regulations of the AOI which will prevent from any legal lawsuit issues and accidents	0	Warning or lawsuit cases from area officials and regulatory agencies.

The following tables demonstrate the Risk calculation for each of the mitigation strategies for a specific failure which might occur during the arrival stage:

Table 45: Failure: Fields of the mission were larger than the software was capable of processing data for.

For this failure, there are three possible risk controls and for 2 possible states, there are six possible conditional risk scenarios.

	Communicating with the manufacturer to ensure software compatibility with field size.			Break up large fields into smaller sections for easier data processing			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable	c	Reliable	Unreliable
$P(x\mid w_1)$	0.5	0.5	$P(x\mid w_2)$	0.45	0.55	$P(x\mid w_3)$	0.65	0.35
$\lambda(\alpha_1\mid w_1)$	18	0.003	$\lambda(\alpha_2\mid w_2)$	13	0.0015	$\lambda(\alpha_3\mid w_3)$	9	9
	9	0.0015		2.5	6		5.85	3.15
R1	9.00		R2	**5.85**		R3	6	
				Minimum Bayes Risk				

Table 46:Failure: Failure of collecting data due to limited visibility: Visual Camera malfunction, Darkness

For this failure, there are three possible risk controls and for 2 possible states, there are six possible conditional risk scenarios.

	The operators use GPS navigation to fly it back to base if the camera malfunctions.			The engineers can mount illumination gadget, GPS navigation.			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable	c	Reliable	Unreliable
$P(x\mid w_1)$	0.3	0.7	$P(x\mid w_2)$	0.55	0.45	$P(x\mid w_3)$	0.75	0.25
$\lambda(\alpha_1\mid w_1)$	20	0.0055	$\lambda(\alpha_2\mid w_2)$	8	0.0035	$\lambda(\alpha_3\mid w_3)$	10	10
	6	0.00385		4.4	0.001575		7.5	2.5
R1	6.00		R2	**4.40**		R3	10	
				Minimum Bayes Risk				

Table 47:Failure: Environmental uncertainties: Rain, fog and moisture, Wind gusts

For this failure, there are three possible risk controls and for 2 possible states, there are six possible conditional risk scenarios.

	The operator in charge plans the mission with accurate weather forecasts on clear days			The UAV-assisted inspections are stopped in the event of severe rain.			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable	c	Reliable	Unreliable
$P(x\mid w_1)$	0.4	0.6	$P(x\mid w_2)$	0.65	0.35	$P(x\mid w_3)$	0.55	0.45
$\lambda(\alpha_1\mid w_1)$	18	0.0035	$\lambda(\alpha_2\mid w_2)$	7	0.0045	$\lambda(\alpha_3\mid w_3)$	9	9
	7.2	0.0021		4.4	0.001575		4.95	4.05
R1	7.20		R2	**4.55**		R3	9	
				Minimum Bayes Risk				

Table 48:Failure: Operator cognitive and physiological limitations: Operator workload exceeding his/her cognitive capacity, Limited visibility of display

For this failure, there are three possible risk controls and for 2 possible states, there are six possible conditional risk scenarios.

	The operator utilizes a noise-reduction technique that is case-specific			Optimum amount of rest provided to the operators and shifting duty is allocated accordingly			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.65	0.35	P(x|w2)	0.45	0.55	P(x|w3)	0.55	0.45
λ(α1|w1)	8	0.0055	λ(α2|w2)	16	0.0075	λ(α3|w3)	9	9
	5.2	0.001925		8	0.00375		4.95	4.05
R1	**5.20**		R2	8.00		R3	9	
	Minimum Bayes Risk							

Table 49:Failure: Breaking regulations: Regulatory agencies

For this failure, there are two possible risk controls and for 2 possible states, there are four possible conditional risk scenarios.

	Operators are penalized for not following proper regulations of the AOI, to prevent from any legal lawsuit issues and accidents			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.55	0.45	P(x|w2)	0.3	0.7
λ(α1|w1)	0.0022	12	λ(α2|w2)	10	10
	0.00121	5.4		3	7
R1	**5.40121**		R2	10	
	Minimum Bayes Risk				

5.5 Disembark/Landing:

After the UAV has completed its mission, the UAV should be flown back to a pre-designated landing site. The landing site should be free of obstacles, and the pilot should be familiar with the area to avoid any surprises during the landing process. Once the UAV is close to the landing site, the pilot should bring it down to a safe altitude for landing. The pilot should monitor the UAV's altitude and speed to ensure a safe descent. It is important to avoid descending too quickly, as this can cause the UAV to crash into the ground. When the UAV is close to the ground, the pilot should reduce the throttle to bring it down gently.

It is important to avoid landing the UAV too hard, as this can cause damage to the aircraft and any payloads it may be carrying. The pilot should also ensure that the UAV is level and straight before landing to avoid tipping over or crashing. In addition to these general steps, there are some additional considerations for specific types of UAV missions. For example, in agricultural imaging missions, it may be necessary to land the UAV in a specific area to avoid damaging crops. In methane leak detection missions, the pilot may need to use additional sensors or tools to ensure a safe landing in potentially hazardous environments.

The landing stage risks and mitigation strategies for a general UAV mission should be applicable to and considered for agricultural surveys and methane leak detection to ensure thorough risk management. There are several factors that need to be carefully considered to ensure a safe and successful touchdown. One such factor is the passing waypoint, which refers to a specific location on the flight path that the drone must pass through before reaching the landing site as mentioned in Figure 38. This pre-determined point helps ensure that the drone reaches the landing site without deviating off course. However, errors in altitude threshold and crab angle at touchdown can lead to damage to the UAV or prevent a smooth landing. To mitigate these risks, pilots must carefully manage the descent rate, crab angle, and thrust of the aircraft. Additionally, pilots use various techniques such as flaps, slats, and thrust reversers to increase drag and help slow down the aircraft. They must also carefully tune the rolling mode to ensure that there is no coupling with the natural frequency of the yaw controller as mentioned in Figure 9. The highest priority risk during descent is a collision with humans, animals, or man-made objects, so GPS navigation can assist in re-calculating the path if the wind is pushing the UAV off course. Finally, ensuring that no third-party equipment is using the same frequency and bandwidth as the UAV can prevent collision malfunctions, and regular system checks can prevent hardware malfunctions and recovery failure. By carefully considering all these factors, pilots can ensure a safe and successful landing for their UAV.

For agricultural UAVs, the type of wing design can have an impact on the landing process. For example, a high-wing design may make it easier to land the UAV as it provides more clearance for the landing gear and allows for better visibility of the landing site. Conversely, a low-wing design may make the landing more difficult due to the lower clearance and limited visibility as mentioned in Figure 39. In addition, ailerons and flaps can also affect the landing process. Ailerons can help control the UAV during crosswinds, while flaps can reduce the speed of the UAV during landing, making it easier to control. In the case of UAVs used for detecting methane leaks in mining and oil sites, the landing process can be affected by the weight and size of the UAV, as well as the type of propulsion system used. For example, a heavier UAV may require a longer runway for landing, while a smaller UAV may be more susceptible to crosswinds. The type of propulsion system used, such as a fixed-wing or rotary-wing system, can also have an impact on the landing process. Rotary-wing systems, such as quadcopters, are generally more maneuverable and can land in smaller areas but may be more susceptible to turbulence and wind gusts.

In addition to the design of the UAV itself, other factors such as the landing site and weather conditions can also affect the landing process. A clear and level landing site is ideal for UAVs, as it reduces the risk of damage to the aircraft during landing. Wind conditions, especially crosswinds, can also make landing more difficult, and pilots should be trained to handle these situations.

The landing gear stiffness plays a crucial role in determining the landing process's success, and it is essential to ensure that the stiffness is appropriate at all landing points [155]. One of the critical factors to consider when landing a UAV is the wind condition. The wind can affect the UAV's stability, trajectory, and speed, which can lead to unexpected behaviors and failures [156]. One way to assess the wind conditions is by using sensors that can measure the wind speed, direction, and turbulence. These sensors can be mounted on the UAV itself or on the ground, and the data can be transmitted to the control system for analysis and adjustment [157]. To mitigate this, it is crucial to assess the wind conditions and adjust the automatic control system accordingly. Additionally, it is important to have a failsafe mechanism that can take over the control system in the event of a failure. One way to achieve this is by implementing redundancy in the control system. Redundancy involves having multiple independent control systems that can take over if one of them fails. For example, a backup controller can be included in the UAV, which can take over if the primary controller fails. In this way, the UAV can continue to operate safely even in the event of a failure [158].

Another critical factor to consider when landing a UAV is the environmental characteristics of the landing site. The autonomous landing of UAVs in static scenes could be divided into two different types: autonomous landing based on cooperative targets and autonomous landing based on natural scenarios [159]. When landing on large agricultural farms, cooperative targets may not be readily available, and thus, the UAV must rely on identifying environmental characteristics to land safely. One of the failures that may occur is the UAV detecting the wrong environmental characteristics or failing to detect the right ones, leading to a crash as demonstrated in Figure 9. To mitigate this, it is crucial to ensure that the UAV's sensors are adequately calibrated and that the environmental characteristics of the landing site are well understood beforehand. Sensors that need to be calibrated include, but are not limited to, those that measure soil moisture and water potential in agriculture [160] and those that use triangulation principles to detect distance to sensing objects [161]. Calibration involves adjusting and setting the sensors to accurately measure the desired environmental characteristics, such as wind speed and direction, temperature, humidity, and other variables relevant to the UAV's flight conditions as shown in Figure 39. This can be done by following the manufacturer's instructions, regularly testing and adjusting the sensors, and ensuring that the sensors are kept clean and in good working condition as described in Table 50.

When landing on small flights of detecting methane leaks in mining/oil sites, there is a risk of collision with obstacles such as pipelines and equipment as shown in Figure 39. One of the failures that may occur is the UAV colliding with these obstacles, leading to damage or loss of the UAV. To mitigate this, it is crucial to have a well-designed obstacle avoidance system that can detect and avoid obstacles. A well-designed obstacle avoidance system will use multiple sensors to enhance the accuracy of the system's data. Sensor fusion involves combining data from multiple sensors to provide a more complete understanding of the environment around the system. Additionally, it is crucial to ensure that the UAV's sensors are appropriately calibrated and that the flight path is well-planned and well-understood beforehand [162].

After the flight, the data is processed and analyzed to extract the required information, such as crop health and yield prediction for agricultural farms or methane leak location and severity for mining/oil sites. The collected data is analyzed using software tools to extract useful information. For agricultural farms, the imagery can be processed to create detailed maps of crop health and yield, which can be used to optimize fertilizer and irrigation applications. For methane leak detection, the imagery can be analyzed to identify potential leaks, which can be addressed to prevent environmental damage and safety hazards. The analyzed data can be stored for future reference or used to create 3D models or other visualizations [163]. For instance, data collected from drones or satellites can be used to create 3D models of agricultural fields or mining/oil sites, which can be used to visualize and identify patterns that may not be easily visible in 2D maps. Additionally, data visualization tools like Tableau, Power BI, or Python's Matplotlib can be used to create interactive dashboards that provide real-time insights into the collected data. The data can also be stored for future reference or used to create 3D models or other visualizations.

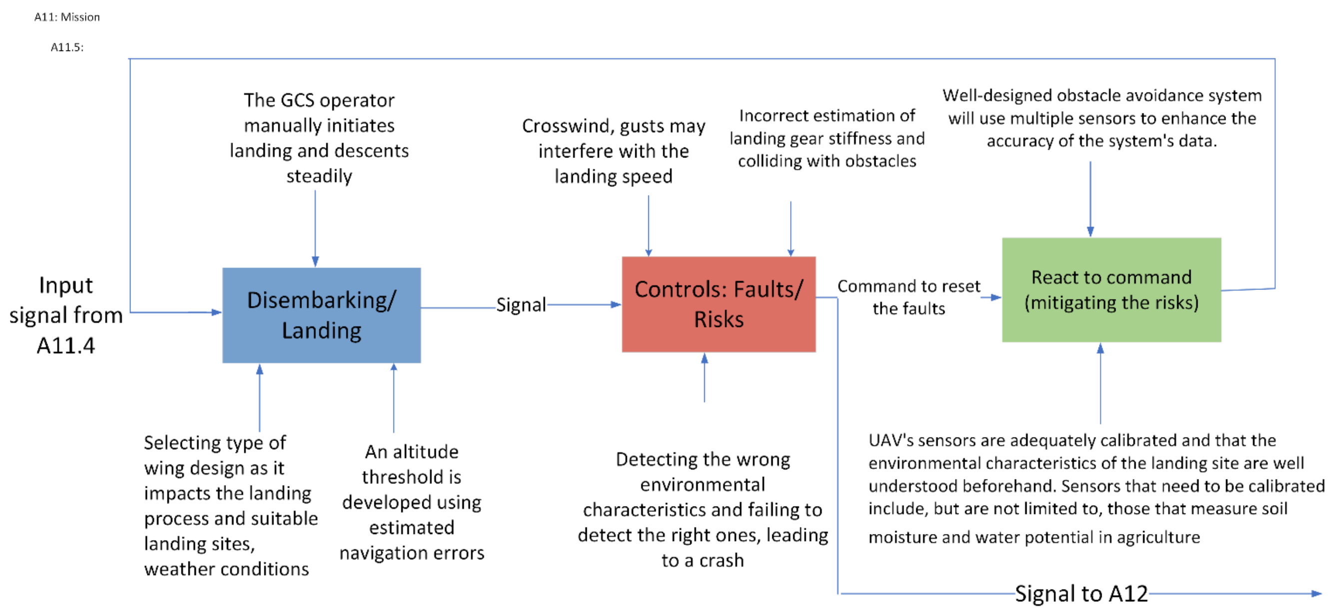

Figure 38: Departure/Landing stage of the company

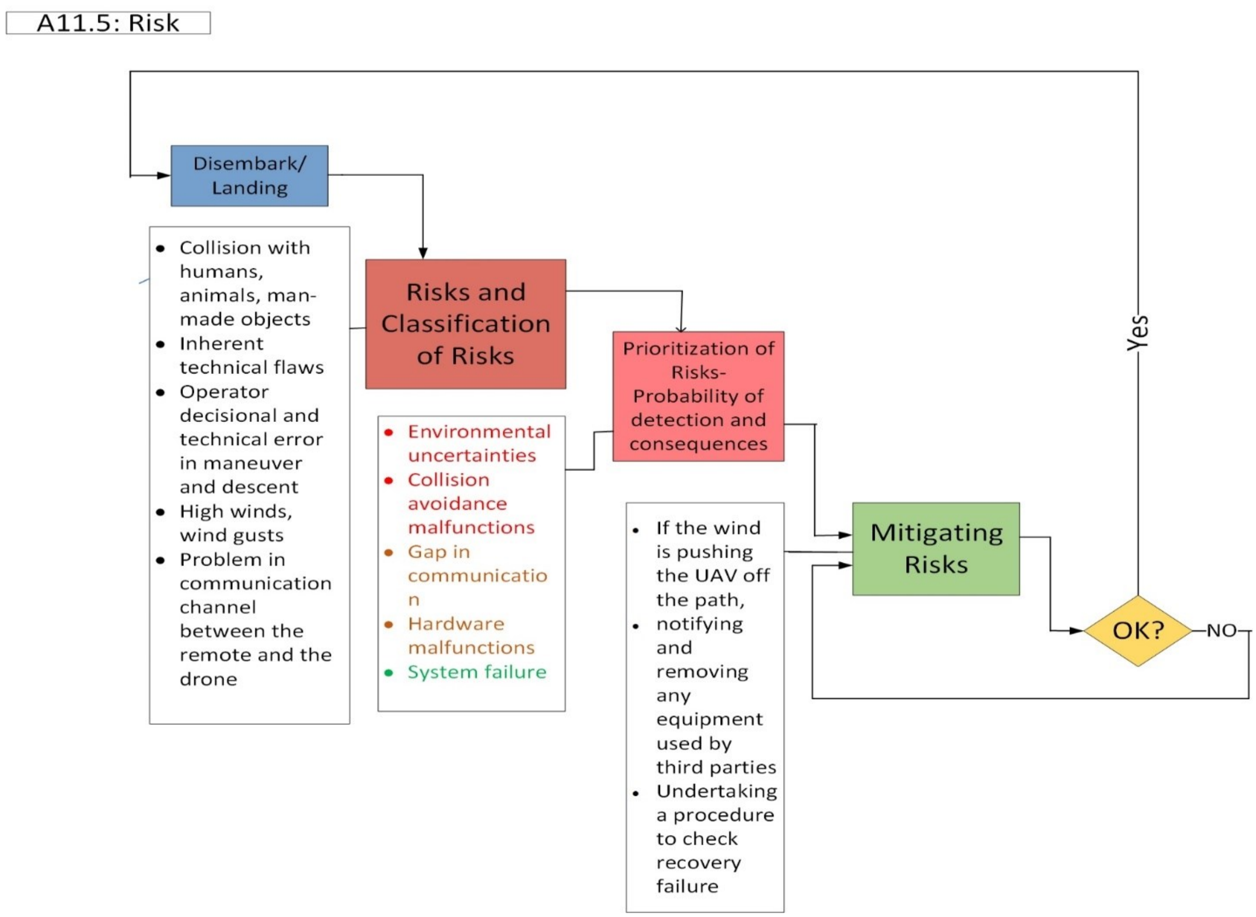

Figure 39: Ranked Risks associated with the Departure/Landing Stage of the company

The table below demonstrates a qualitative analysis of the risks associated with the "Landing" stage of the UAV mission, the RPN values associated with them, the controls implemented to mitigate them, the residual risk after the controls are implemented and the trigger for the failures in the stages:

Table 50: FMEA sequence of the Departure/Landing stage

Fault and related operating conditions	Likelihood	Severity	Detectability	RPN (uncontrolled)	Risk Control	Residual RPN	Trigger
Collision avoidance malfunctions can lead to collisions with humans, animals, and ground vehicles.	2	3	3	18	Software engineers can use advanced algorithms for collision avoidance and navigation. Removing third-party equipment operating on the same frequency band can help. Redundant equipment like a second ground station can be employed if available.	6	FBG strain sensors placed on the airframe can detect unusual stresses with a high degree of accuracy
System failure: System Recovery failure	3	2	3	18	Design engineers need to undertake an investigative procedure to check recovery failure	4	UAV landing failures can occur due to sensor or control system malfunctions, environmental factors like wind or turbulence, and landing site conditions.
Operator decisional errors during maneuver and descent.	1	3	3	9	Operator must be well-trained by the management to be well-acquainted with the descent procedure of the UAV for the mission assigned.	4	Delay in mission completion time or failure to follow predefined mission flight plan.
Gap in communication: Problem in communication channel between the remote and the drone	2	2	2	8	The operators can set up a data communication link which gives performance and failure data in real time which can aid in adjusting the operation of drone in emergencies by the GCS.	4	Windspeed sensors attached to the wings of the drone will detect unusual flight speed which is an indicator of wind gusts. Weather patterns, such as thunderstorms or high humidity, can lead to rain and moisture.
Inherent technical flaws and battery depletion	1	2	2	4	The design engineers can use athermally coated personal protective equipment, warm up the battery.	1	Battery sensors detect depletion, improper charging, and wear in the remote control. Extreme temperatures, physical damage, and

							lack of maintenance can also cause power loss.

The following tables demonstrate the Risk calculation for each of the mitigation strategies for a specific failure which might occur during the arrival stage:

Table 51:Failure: Collision avoidance malfunctions: Collision with humans, animals, man-made objects, etc. Collision with the ground vehicle

For this failure, there are three possible risk controls and for 2 possible states, there are six possible conditional risk scenarios.

	Software engineers utilize sophisticated algorithms vision-based navigation.			Removing any equipment used by third parties using the same frequency band from operation site.			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.3	0.7	P(x|w2)	0.65	0.35	P(x|w3)	0.75	0.25
λ(α1|w1)	15	0.0035	λ(α2|w2)	10	0.0015	λ(α3|w3)	10	10
	4.5	0.00245		6.5	0.000525		7.5	2.5
R1	**4.50**		R2	6.50		R3	10	
	Minimum Bayes Risk							

Table 52:Failure: System failure: System Recovery failure

For this failure, there are two possible risk controls and for 2 possible states, there are four possible conditional risk scenarios.

	Design engineers need to undertake an investigative procedure to check recovery failure			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.85	0.15	P(x|w2)	0.3	0.7
λ(α1|w1)	0.0075	18	λ(α2|w2)	9	9
	0.006375	2.7		2.7	6.3
R1	**2.70**		R2	9	
	Minimum Bayes Risk				

Table 53:Failure: Operator decisional and technical error in maneuver and descent

For this failure, there are two possible risk controls and for 2 possible states, there are four possible conditional risk scenarios.

	Operator is well-trained by the management to be well-acquainted with the descent procedure of the UAV for the mission assigned.			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.65	0.35	P(x|w2)	0.4	0.6
λ(α1|w1)	0.0045	15	λ(α2|w2)	9	9
	0.002925	5.25		3.6	5.4
R1	**5.252925**		R2	10	
	Minimum Bayes Risk				

Table 54:Failure: Gap in communication: Malfunctions in the communication channel between remote controller and drone during drone flight

For this failure, there are two possible risk controls and for 2 possible states, there are four possible conditional risk scenarios.

	The operators set up a data communication link which gives performance and failure data in real time to aid in adjusting the operation of drone in emergencies by the GCS			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.75	0.25	P(x|w2)	0.7	0.3
λ(α1|w1)	0.0025	15	λ(α2|w2)	10	10
	0.001875	3.75		7	3
R1	**3.75**		R2	10	
	Minimum Bayes Risk				

Table 55: Failure: Hardware malfunctions: Inherent technical flaws and battery depletion

For this failure, there are two possible risk controls and for 2 possible states, there are four possible conditional risk scenarios.

	The design engineers can use athermally coated personal protective equipment, warm up the battery.			DO NOTHING	
c	Reliable	Unreliable	c	Reliable	Unreliable
P(x|w1)	0.75	0.25	P(x|w2)	0.6	0.4
λ(α1|w1)	0.0025	20	λ(α2|w2)	10	10
	0.001875	5		6	4
R1	**5.00**		R2	10	
	Minimum Bayes Risk				

5.6 Concluding remarks on the reliability model for an Aerospace Data company

This chapter offers an industrially oriented exploration into the operational endeavors of UAVs, focusing on their pivotal role in acquiring aerial imagery for agricultural farms and detecting methane leaks within pipelines. The escalating deployment of UAVs in surveillance capacities is underpinned by their demonstrable efficacy and heightened precision. Within this context, we introduce a novel reliability model that seamlessly combines qualitative and quantitative analyses, poised to strategically address failures by addressing optimal mitigation strategies and leveraging the Minimum Bayes Risk calculation. The proposition of this model holds promise in augmenting the dependability and economic viability of drones operating within these specific applications.

In the forthcoming trajectory of this research, avenues for further advancement materialize. A refinement of the reliability model could be undertaken, substantiated by the validation process employing a diverse range of mission data. Moreover, an augmentation of data collection techniques can be envisaged through the assimilation of cutting-edge sensing technologies. This evolution extends to the optimization of flight planning and control algorithms, intrinsically contributing to heightened operational efficiency.

Collaborative engagement with both industry stakeholders and regulatory authorities is a foreseeable avenue. Such collaborative efforts are envisaged to yield the establishment of standardized protocols and best practices, fortifying the operational framework and regulatory compliance. The pursuit of continuous monitoring and evaluation mechanisms emerges as an essential trajectory, ensuring an iterative process of enhancement and refinement, and thus culminating in sustained operational augmentation.

In summation, these envisaged advancements collectively harmonize to amplify the reliability, safety, and efficacy of UAV operations within the domains of agricultural farm aerial imagery collection and methane leak detection within pipelines. This symbiotic progress ultimately unfurls new horizons within these industrial sectors, underscoring the transformative potential of UAV technology and its pivotal role in redefining operational paradigms.

6.1 Conclusion:

The study offers a comprehensive risk assessment and mitigation analysis for a general-purpose UAV mission, along with demonstrating an industrial implementation in agricultural surveys and methane leak detection. Employing various tools and techniques, the research identified critical risk factors, including hardware malfunctions, communication gaps, environmental uncertainties, operator errors, and regulatory compliance issues.

To address these risks, advanced algorithms, vision-based navigation, redundant equipment, sensor fusion techniques, and athermally coated protective equipment were proposed to enhance collision avoidance, system recovery, obstacle avoidance, and hardware reliability. Meticulous mission planning, optimized UAV design, and the utilization of GIS software were emphasized to ensure efficient and safe operations [164]. Data processing and analysis were streamlined using sophisticated software tools like Tableau, Power BI, and Python's Matplotlib, enabling real-time insights into crop health assessment, yield prediction, methane leak identification, and 3D modeling. Furthermore, simulations and UAV flight simulators were utilized to optimize landing procedures, and pilot training was emphasized to handle diverse landing scenarios, including crosswind situations.

The study advocates for collaborative efforts between industry stakeholders, research institutions, and regulatory bodies to establish and uphold safety standards, facilitated by collaborative platforms and communication channels. Overall, the findings of this study contribute to enhancing the safety and efficiency of UAV missions in critical applications such as agricultural surveys and methane leak detection, paving the way for advancements in the field of UAV technology and its widespread adoption in various industries.

In conclusion, the main observations or key findings of this study can be summarized as below:

- Risk Identification: The thesis identifies various potential risks associated with UAV missions, including hardware malfunctions, communication gaps, environmental uncertainties, operator errors, and regulatory compliance issues.

- Mitigation Strategies: The research proposes several mitigation strategies to address the identified risks. These strategies involve using advanced algorithms for collision avoidance, redundant equipment for system recovery, training operators to handle decisional errors, establishing data communication links for real-time adjustments, and using athermally coated protective equipment to prevent hardware failures.

- Mission Planning and Design: The research emphasizes the importance of careful mission planning and UAV design to optimize data collection and processing. It discusses the significance of choosing appropriate flight paths, sensor configurations, and wing designs to ensure efficient and accurate data gathering.

- Data Processing and Analysis: The thesis highlights the significance of data processing and analysis in agricultural surveys and methane leak detection missions. Advanced software tools are essential for extracting valuable information from collected data, aiding in crop health assessment, yield prediction, methane leak identification, and data visualization.

- Collaborative Efforts: The thesis emphasizes the need for collaborative efforts between industry stakeholders, research institutions, and regulatory bodies to establish and uphold safety standards, ethical considerations, and legal compliance in UAV operations. Sharing best practices and continuous learning are essential for safe UAV integration.

6.2 Future Work

There are applications for the dynamic risk assessment of UAVs, in both research and industry. This section presents future possibilities for improvement of the developed reliability model, as well as its industrial applications.

6.2.1 Recommendation for future studies:

- Improving FMEA analysis: We may revisit the number of levels of Severity, Detectability and Occurrence, to improve the granularity of the RPN calculation.
- Advanced Collision Avoidance Algorithms: In the future, the development of more sophisticated collision avoidance algorithms for UAVs can be explored. These algorithms can leverage advanced

computer vision and artificial intelligence techniques to detect and avoid potential collisions with humans, animals, and man-made objects during UAV missions [165]. By implementing such algorithms, the safety and reliability of UAV operations in complex and crowded environments can be significantly enhanced.

- Integration of Artificial Intelligence (AI): The integration of AI technologies into UAV systems can be investigated by researchers. AI can be utilized to analyze real-time data from various sensors, enabling UAVs to make informed decisions and autonomously adapt to changing environmental conditions. This can lead to more efficient mission execution and improved risk management during UAV operations.

- Enhanced Sensor Technology: Future work can focus on the development of enhanced sensor technology for UAVs. This includes the use of advanced sensors for improved data collection, such as high-resolution cameras, LiDAR, and hyperspectral sensors. The integration of cutting-edge sensors can enhance the accuracy and reliability of data collected during agricultural surveys and methane leak detection missions.

- Optimization of Flight Path Planning: Researchers can explore the optimization of flight path planning for UAV missions. This involves utilizing algorithms and tools to determine the most efficient and safe routes for UAVs, considering factors like wind conditions, terrain, and obstacles. Optimized flight paths can reduce mission time, energy consumption, and potential risks.

- Multi-UAV Coordination and Swarming: Investigate the coordination of multiple UAVs in collaborative missions. Swarming techniques and communication protocols can be explored to enable seamless cooperation between UAVs, allowing them to work together efficiently and distribute risks across the swarm.

- Cybersecurity and Data Protection: The emerging concern of cybersecurity threats in UAV operations can be addressed by developing robust encryption and authentication mechanisms to safeguard data transmission and prevent unauthorized access to UAV systems, protecting sensitive information collected during missions [166].

- Energy-Efficient UAV Design: Research can be conducted on energy-efficient UAV design and propulsion systems to extend flight endurance and reduce the risk of battery depletion during missions. Implementing alternative energy sources or optimizing power consumption can lead to longer and more reliable UAV operations.

- Beyond Visual Line of Sight (BVLOS) Operations: The challenges and risks associated with BVLOS UAV operations can be studied. Investigate technologies such as sense-and-avoid systems, satellite-based navigation, and detect-and-avoid capabilities to enable safe and efficient BVLOS missions.

- Human Factors in UAV Missions: Examine the influence of human factors on UAV operations, such as operator workload, cognitive load, and situational awareness. Conduct studies to understand how human-machine interaction can be optimized to minimize human-induced errors.

- Integration with Internet of Things (IoT): Investigate the integration of UAVs with IoT technologies to enable seamless data exchange and communication between UAVs and ground-based systems. This can lead to enhanced real-time data analysis and decision-making during missions.

- Public Perception and Acceptance: Conduct studies to understand public perception and acceptance of UAV technology in various industries. Identifying potential barriers to acceptance and addressing public concerns can foster greater support for the integration of UAVs in society [167].

- Multi-Domain UAV Operations: Explore the possibilities of UAV deployment in multi-domain missions, such as combining aerial, ground, and underwater UAVs for comprehensive data collection and analysis. Develop strategies to mitigate risks associated with multi-domain operations.

- UAV Health Monitoring: Investigate the implementation of UAV health monitoring systems to proactively detect potential malfunctions and failures. Implementing real-time diagnostics and predictive maintenance can enhance UAV reliability and reduce downtime.

- Climate Change and Environmental Monitoring: Study the use of UAVs in climate change research and environmental monitoring. Investigate the risks and challenges associated with UAV missions in extreme environmental conditions and remote locations.

6.2.2: Industrial applications

The industrial application of this thesis holds significant potential for various sectors, benefiting from the comprehensive risk assessment and mitigation strategies for UAV missions in agricultural surveys and methane leak detection as shown in this thesis. The findings and tools presented in this study can be applied to real-world scenarios, revolutionizing existing practices and driving advancements in the following industries:

- Agriculture and Precision Farming: The agricultural sector can leverage the risk assessment techniques and advanced algorithms for collision avoidance during UAV-assisted surveys. UAVs equipped with high-resolution cameras and sensor fusion capabilities can provide detailed crop health assessments and yield predictions. Precision farming practices can be optimized, enabling efficient allocation of resources like fertilizers and irrigation, leading to increased crop productivity, and reduced environmental impact.

- Oil and Gas Industry: In the oil and gas sector, this risk analysis can be employed to enhance safety and efficiency during methane leak detection missions. Advanced sensor technologies like LiDAR and hyperspectral sensors can detect and locate leaks more accurately, reducing environmental hazards and optimizing maintenance efforts. Swarming and coordination of UAVs can facilitate large-scale inspections of pipelines and infrastructure.

- Environmental Monitoring and Conservation: UAVs equipped with specialized sensors can be deployed for environmental monitoring and conservation efforts. The risk assessment tools help identify potential hazards and improve UAV mission planning, ensuring safer operations in challenging terrains. UAVs can aid in wildlife tracking, mapping biodiversity, and monitoring protected areas, contributing to ecological research and conservation initiatives.

- Infrastructure Inspection and Maintenance: The application of advanced algorithms for collision avoidance is crucial for infrastructure inspection missions. UAVs can be employed to inspect bridges, power lines, and telecommunications towers, identifying potential defects or damage.

With optimized flight path planning, risks associated with manual inspections can be minimized, enhancing safety, and reducing maintenance costs.

- Disaster Management and Response: During natural disasters, UAVs equipped with AI-based data analysis tools can be deployed for rapid assessment and response. The combination of real-time data collection, communication capabilities, and swarming techniques allows for efficient search and rescue operations, damage assessment, and disaster mapping.

- Aerial Surveying and Mapping: The thesis' emphasis on sensor configurations and optimized flight paths is highly relevant in the field of aerial surveying and mapping. UAVs can be employed for topographic surveys, urban planning, and construction site monitoring. GIS software can facilitate accurate data visualization and analysis, aiding in informed decision-making.

- Transportation and Logistics: The integration of UAVs into transportation and logistics industries can improve delivery and inventory management. Risk assessment tools can ensure safe and efficient last-mile deliveries, reducing delivery time and costs [168]. UAVs can also be utilized in warehouse management and inventory tracking, streamlining supply chain operations.

- Mining and Resource Exploration: UAV missions in the mining sector can benefit from risk mitigation strategies and advanced obstacle avoidance systems. UAVs equipped with state-of-the-art sensors can assist in resource exploration, mine site monitoring, and safety inspections, optimizing mining operations and reducing potential hazards.

- Infrastructure Development and Urban Planning: UAVs can play a pivotal role in infrastructure development and urban planning projects. The use of 3D modeling software and simulations can aid architects, engineers, and city planners in visualizing urban landscapes, identifying potential design flaws, and optimizing infrastructure layouts.

- Public Safety and Law Enforcement: The application of UAV technology can enhance public safety and law enforcement efforts. Swarming capabilities and real-time data analysis can support surveillance operations, crowd management, and disaster response. UAVs can assist in accident investigations, crime scene documentation, and traffic monitoring.

In summary, the insights and methodologies presented offer profound implications for the realm of UAV operations, holding considerable promise for drone companies seeking to bolster their risk management strategies and enhance the reliability of UAV missions. By meticulously assessing and addressing various risk factors, such as hardware malfunctions, communication gaps, environmental uncertainties, and operator errors, this work equips drone companies with a comprehensive toolkit to ensure safer and more efficient operations. The integration of advanced algorithms, sensor fusion techniques, collision avoidance strategies, and optimized flight path planning can significantly reduce the likelihood of incidents, thus safeguarding both equipment and personnel. Moreover, the emphasis on collaborative efforts and industry-stakeholder engagement underscores the importance of establishing and upholding safety standards, further fostering a culture of responsible UAV integration. As drone companies adopt these findings and techniques, they stand to revolutionize their operational practices, ensuring that UAV technology becomes a driving force in various industries while minimizing risks and maximizing reliability.

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Appendix: Checklist of Risks and Mitigation Strategies for Aerospace-data Company:

Boarding:

1. Risk: Inaccurate data collection due to navigation sensor errors.

   Mitigation:

   - Regularly test and calibrate navigation sensors (e.g., GPS and INS).
   - Implement redundancy in sensor systems to minimize the impact of failures.
   - Have backup navigation methods or alternative flight modes available.

2. Risk: Hardware malfunction during operation.

   Mitigation:

   - Follow standard operating procedures (SOPs) for UAV operation.
   - Conduct regular maintenance checks on UAV hardware.
   - Replace faulty sensors and components promptly.
   - Keep spare parts and backup equipment readily available.

3. Risk: Poor image quality or unusable data for agricultural surveys.

   Mitigation:

   - Conduct thorough research on the area to be covered.
   - Set appropriate camera settings (e.g., focal length, shutter speed) for high-quality imagery.
   - Consider weather conditions, terrain, and potential hazards that may affect data collection.
   - Establish safety protocols and guidelines for flight planning and execution.

4. Risk: Ineffective detection of methane leaks.

   Mitigation:

   - Conduct research on areas prone to methane leaks.
   - Set appropriate altitude and camera settings to optimize methane detection.
   - Consider weather conditions, terrain, and potential hazards that may impact detection accuracy.
   - Establish safety protocols and guidelines specific to methane leak detection flights.

5. Risk: Aerodynamic instability and control issues during flight.

   Mitigation:

- Ensure UAV design, weight, and balance adhere to aerodynamic principles.
- Regularly test and validate the UAV's stability and control characteristics.
- Consider environmental factors (e.g., wind conditions) when planning flights.

6. Risk: Non-compliance with aviation regulations and laws.

   Mitigation:

   - Stay updated on relevant aviation regulations and laws.
   - Obtain necessary permits and licenses for UAV operations.
   - Train and educate UAV operators and ground staff on compliance requirements.

7. Risk: Insufficient understanding of physics concepts impacting UAV operation.

   Mitigation:

   - Provide training and education on physics principles relevant to UAV operations.
   - Ensure operators understand the impact of physics on altitude, camera settings, and gas sensor functioning.
   - Collaborate with experts or consultants to address specific physics-related challenges.

8. Risk: Lack of safety protocols and emergency procedures.

   Mitigation:

   - Develop comprehensive safety protocols for different mission types.
   - Conduct risk assessments and identify potential hazards before each flight.
   - Train UAV operators and ground staff on emergency procedures and contingency plans.
   - Establish communication protocols for effective coordination during emergencies.

9. Risk: Adverse weather conditions impacting UAV operation.

   Mitigation:

   - Monitor weather forecasts and conditions before and during flights.
   - Establish weather criteria and limitations for safe operations.
   - Have a backup plan in case weather conditions deteriorate.
   - Train operators to make informed decisions based on weather information.

10. Risk: Collisions or damage to the UAV due to obstacles or hazards.

    Mitigation:

    - Conduct a thorough assessment of the flight area for potential obstacles.
    - Use obstacle detection systems or sensors on the UAV, if available.
    - Establish protocols for avoiding obstacles and hazards during flight.
    - Maintain situational awareness and monitor the flight path during operations.

11. Risk: Data security and privacy breaches.

    Mitigation:

    - Implement robust cybersecurity measures to protect data transmission and storage.
    - Encrypt sensitive data and ensure secure data transfer protocols.
    - Follow privacy regulations and obtain necessary permissions for data collection.
    - Train personnel on data handling, storage, and privacy protection.

12. Risk: Loss of control or communication link with the UAV.

    Mitigation:

    - Implement fail-safe systems and procedures for loss of control or communication.
    - Use redundant communication links or backup control methods, if applicable.
    - Establish proper communication protocols and maintain clear channels of communication.
    - Conduct regular tests and drills to ensure effective communication and control.

13. Risk: Human error during mission planning or execution.

    Mitigation:

    - Provide comprehensive training and ongoing education for UAV operators.
    - Standardize mission planning processes and use checklists.
    - Encourage a culture of safety, accountability, and continuous improvement.
    - Conduct post-flight reviews and analysis to learn from mistakes and prevent recurrence.

14. Risk: Regulatory changes impacting UAV operations.

    Mitigation:

    - Stay informed about evolving regulations and policy changes.
    - Maintain close relationships with regulatory authorities and industry associations.
    - Allocate resources to adapt to new requirements and ensure compliance.
    - Engage in advocacy efforts to influence favorable regulations when appropriate

Note: The checklist provided above is a starting point and should be tailored to the specific needs and circumstances of the drone company. It is essential to regularly review and update the checklist based on evolving risks and industry best practices.

Takeoff:

1. Risk: Sensor fouling or damage causing system failures and lateral acceleration drift.

Mitigation:

- Implement regular sensor maintenance and inspection.
- Use redundant sensor systems for critical functions.
- Conduct pre-flight checks to ensure sensor functionality.

2. Risk: Wiring connection corrosion or other electrical issues.

   Mitigation:

   - Regularly inspect and maintain wiring connections.
   - Use corrosion-resistant materials and connectors.
   - Perform electrical system checks before each flight.

3. Risk: Failure to comply with regulations and licensing requirements.

   Mitigation:

   - Educate operators on relevant regulations and requirements.
   - Establish a process for obtaining necessary licenses and permits.
   - Conduct regular audits to ensure compliance.

4. Risk: Inadequate guidance algorithms for rate of acceleration and pitch control.

   Mitigation:

   - Develop and implement robust guidance algorithms.
   - Conduct thorough testing and validation of the algorithms.
   - Continuously monitor and update the algorithms as needed.

5. Risk: Human error in controlling the UAV during takeoff.

   Mitigation:

   - Provide comprehensive pilot training on takeoff procedures.
   - Establish clear standard operating procedures for takeoff.
   - Conduct regular proficiency checks and recurrent training.

6. Risk: Non-linear relationships between lift/drag coefficients and angle of attack affecting takeoff performance. Mitigation:

   - Perform thorough aerodynamic analysis and modeling.
   - Test and validate takeoff performance in various conditions.
   - Consider design modifications to optimize takeoff performance.

7. Risk: Lack of collision avoidance and vision-based navigation algorithms.

   Mitigation:

   - Implement collision avoidance systems using sensors and cameras.

- Develop and integrate vision-based navigation algorithms.
- Conduct thorough testing of collision avoidance systems.

8. Risk: Deviation from standard operating procedures due to lack of knowledge.

   Mitigation:

   - Provide comprehensive training on standard operating procedures.
   - Conduct regular refresher training and knowledge updates.
   - Implement effective communication channels for disseminating information.

9. Risk: Inadequate pre-flight inspection leading of equipment failure.

   Mitigation:

   - Develop a comprehensive pre-flight inspection checklist.
   - Train operators on the proper execution of pre-flight inspections.
   - Conduct regular audits to ensure compliance with inspection procedures.

10. Risk: Insufficient communication and coordination between ground operators and the UAV during takeoff. Mitigation:

    - Establish clear communication protocols and channels.
    - Provide training on effective communication practices.
    - Conduct regular drills and exercises to practice communication procedures.

11. Risk: Failure to maintain a steady climb rate and control altitude and direction.

    Mitigation:

    - Provide pilot training on throttle and control inputs during takeoff.
    - Emphasize the importance of maintaining a steady climb rate.
    - Monitor telemetry data and provide real-time feedback to operators.

12. Risk: Lack of stability and control during the ascent phase.

    Mitigation:

    - Implement flight control systems with stability augmentation features.
    - Conduct flight tests to validate stability and control performance.
    - Monitor and analyze flight data to identify and address stability issues.

13. Risk: Inadequate response to wind gusts and turbulent air during takeoff.

    Mitigation:

    - Monitor weather conditions and wind gust alerts before takeoff.
    - Implement wind compensation algorithms in flight control systems.
    - Train pilots on techniques for handling wind gusts during takeoff.

14. Risk: Failure to follow pre-determined flight plans for agricultural surveys and methane leak detection. Mitigation:
    - Develop comprehensive flight planning procedures.
    - Train operators on flight plan execution and monitoring.
    - Implement real-time feedback systems to ensure adherence to flight plans.
15. Risk: Lack of real-time data on methane concentrations during methane leak detection. Mitigation:
    - Install accurate and reliable gas sensors on the UAV.
    - Establish data transmission and analysis systems for real-time monitoring.
    - Implement algorithms to adjust flight paths based on detected methane concentrations.
16. Risk: Equipment malfunction or failure during takeoff.
    Mitigation:
    - Implement regular maintenance and inspection protocols for all equipment.
    - Keep spare parts and backup systems readily available.
    - Conduct thorough pre-flight checks to ensure equipment functionality.
17. Risk: Environmental factors affecting takeoff performance (e.g., temperature, humidity, altitude).
    Mitigation:
    - Account for environmental conditions in flight planning and performance calculations.
    - Establish operating limits and guidelines based on environmental factors.
    - Monitor weather conditions and adjust as necessary.
18. Risk: Interference from external factors (e.g., radio frequency interference, electromagnetic interference). Mitigation:
    - Conduct frequency scans to identify potential sources of interference.
    - Use shielding and filtering mechanisms to reduce the impact of interference.
    - Implement redundant communication systems to ensure continuous connectivity.
19. Risk: Insufficient power or battery capacity for safe takeoff and flight. Mitigation:
    - Regularly check and maintain batteries according to manufacturer guidelines.
    - Implement battery monitoring systems and alarms.
    - Establish protocols for safe battery management and charging.
20. Risk: Inadequate training and proficiency in manual control of the UAV.
    Mitigation:
    - Provide thorough training on manual flight control techniques.

- Conduct regular flight simulations and proficiency assessments.
- Emphasize the importance of manual control as a backup option.

21. Risk: Communication failure between the UAV and ground control.

    Mitigation:

    - Establish redundant communication systems for reliable connectivity.
    - Test communication systems before each flight.
    - Develop contingency plans for communication failure scenarios.

22. Risk: Inadequate record-keeping and documentation during takeoff.

    Mitigation:

    - Implement a comprehensive record-keeping system for all takeoff procedures.
    - Train operators on proper documentation practices.
    - Regularly audit and review records to ensure compliance and identify areas for improvement.

23. Risk: Unpredictable behavior of wildlife or other airborne objects during takeoff.

    Mitigation:

    - Conduct wildlife surveys and risk assessments before takeoff.
    - Establish exclusion zones and flight restrictions in areas with wildlife activity.
    - Implement visual and radar systems to detect airborne objects.

Flight:

1. Risk: Selection of an inappropriate UAV platform for the mission requirements.

   Mitigation:

   - Conduct a thorough analysis of mission requirements before selecting a UAV platform.
   - Consider payload capacity, endurance, range, and other relevant factors.
   - Consult with experts or manufacturers for guidance on suitable UAV platforms.

2. Risk: Insufficient flight planning, including target area identification, imaging resolution, and flight parameters. Mitigation:

   - Develop a comprehensive mission plan that covers all necessary aspects.
   - Identify target areas, determine imaging resolution requirements, and set appropriate flight parameters.
   - Use specialized software or tools for mission planning and optimization.

3. Risk: Poor image quality due to GPS inaccuracies, atmospheric conditions, or instrument errors. Mitigation:
    - Use additional sensors and equipment like barometers and altimeters to enhance image quality.
    - Implement image quality monitoring systems to detect and address any issues promptly.
    - Conduct regular calibration and maintenance of instruments.
4. Risk: Failure to properly manage forward and side overlap during image capture. Mitigation:
    - Train operators on the importance of managing overlap for generating seamless mosaics.
    - Use drone mapping software with built-in overlap optimization capabilities.
    - Implement automated flight control systems to ensure consistent overlap.
5. Risk: Inadequate pre-flight checks and mission planning. Mitigation:
    - Follow a pre-flight checklist provided by the UAV's manufacturer.
    - Perform thorough checks on systems, components, propulsion, avionics, sensors, and imaging equipment.
    - Verify battery capacity, power management system, and communication and control systems.
6. Risk: Insufficient battery power for safe completion of the mission. Mitigation:
    - Monitor and control battery life and power management system throughout the flight.
    - Set up alerts for low battery levels and implement automated return-to-home features.
    - Use battery monitoring systems to provide real-time information on battery life and health.
7. Risk: Communication and control system failure during the flight. Mitigation:
    - Ensure proper functioning of the UAV's communication and control systems before takeoff.
    - Establish redundant communication systems for reliable connectivity.
    - Regularly test communication systems and develop contingency plans for failures.
8. Risk: Exceeding maximum altitude or operational range. Mitigation:
    - Set appropriate limits in the UAV's software or use geofencing systems to prevent exceeding operational boundaries.

- Adjust the UAV's altitude based on mission requirements, weather conditions, and obstacles.
- Use automated flight control systems to optimize coverage and imaging quality.

9. Risk: Interference with other aircraft or communication systems.
   Mitigation:
   - Use a frequency management system to operate the UAV on frequencies that don't interfere with other systems.
   - Stay updated on airspace regulations and restrictions.
   - Follow established communication protocols and maintain situational awareness.
10. Risk: Adverse weather conditions impacting flight safety and performance. Mitigation:
    - Plan flights around favorable weather conditions for safe operation.
    - Continuously monitor weather conditions throughout the flight.
    - Have contingency plans in place to abort or adjust the mission in case of unfavorable weather.
11. Risk: Insufficient safety features and systems. Mitigation:
    - Design UAVs to meet rigorous safety standards.
    - Implement collision avoidance systems, redundant flight control systems, and emergency response systems.
    - Regularly update safety features based on industry advancements and regulations.
12. Risk: Inadequate monitoring of battery life and power management system. Mitigation:
    - Continuously monitor and control battery life and power management system during the flight.
    - Use battery monitoring systems to provide real-time information and alerts.
    - Implement automated return-to-home features based on critical battery levels.
13. Risk: Communication and control system malfunction. Mitigation:
    - Regularly test and maintain communication and control systems.
    - Establish redundant communication systems for reliable connectivity.
    - Develop contingency plans for communication system failures.
14. Risk: Inaccurate flight path or altitude.
    Mitigation:
    - Use accurate GPS and telemetry data for precise flight path and altitude control.
    - Implement automated flight control systems to minimize human error.

- Regularly calibrate instruments and sensors for accurate measurements.

15. Risk: Interference with other aircraft or communication systems.

    Mitigation:

    - Follow airspace regulations and guidelines.
    - Use a frequency management system to avoid interfering with other systems.
    - Maintain situational awareness and follow established communication protocols.

16. Risk: Inadequate imaging quality or data collection.

    Mitigation:

    - Regularly calibrate and maintain imaging equipment for optimal performance.
    - Use high-quality cameras and sensors suitable for the mission requirements.
    - Implement imaging quality monitoring systems to identify and address any issues.

17. Risk: Human error during flight operations.

    Mitigation:

    - Provide comprehensive training to operators on flight procedures, emergency protocols, and safety practices.
    - Use checklists and standard operating procedures to minimize human errors.
    - Encourage a culture of safety and promote ongoing training and education.

18. Risk: Insufficient data backup and storage.

    Mitigation:

    - Implement redundant data storage systems to ensure data integrity and prevent loss.
    - Regularly back up collected data to secure and reliable storage solutions.
    - Have a data recovery plan in place in case of data loss or system failure.

19. Risk: Inaccurate or incomplete airspace information.

    Mitigation:

    - Stay updated on local airspace regulations, restrictions, and temporary flight restrictions (TFRs).
    - Utilize reputable sources for airspace information, such as official aviation authorities or specialized platforms.
    - Double-check NOTAMs (Notices to Airmen) before each flight to ensure compliance.

20. Risk: Lack of emergency response preparedness.

    Mitigation:

- Develop and practice emergency response plans for various scenarios, including equipment failure, loss of control, or accidents.
- Equip operators with emergency procedures and training for quick and effective response.
- Establish communication channels and coordination with relevant authorities or emergency services.

21. Risk: Lack of compliance with regulatory requirements.

    Mitigation:

    - Stay informed about current and evolving regulations for drone operations.
    - Maintain compliance with licensing, registration, and certification requirements.
    - Establish a compliance management system to track and ensure adherence to regulations.

Arrival:

1. Risk: Inadequate site survey leading to obstacles or hazards affecting the mission.

   Mitigation:

   - Conduct a thorough site survey to identify potential obstacles and hazards.
   - Use the survey data to plan the flight path and ensure safe operation.
   - Consider weather conditions and airspace restrictions during flight planning.

2. Risk: Sensor inaccessibility during data collection.

   Mitigation:

   - Establish a localization network with a beacon node for sensor tracking.
   - Implement backup cameras or alternative data collection methods.

3. Risk: Adverse weather conditions affecting data collection.

   Mitigation:

   - Use illumination gadgets to enhance visibility in challenging weather conditions.
   - Implement GPS navigation and have backup plans for rescheduling data collection.

4. Risk: High workload on the human operator.

   Mitigation:

   - Assign multiple people to the task to distribute workload effectively.

5. Risk: System failures due to hardware or software malfunctions.

   Mitigation:

- Regularly maintain and test the UAV system to ensure proper operation.
- Undergo regular training and adhere to protocols and procedures.

6. Risk: GPS signal loss causing disorientation or loss of the UAV.

   Mitigation:

   - Ensure the UAV's GPS system is functioning correctly.
   - Have a backup navigation system in place.

7. Risk: Sensor malfunction leading to incomplete or inaccurate data collection.

   Mitigation:

   - Regularly inspect and maintain sensors.
   - Have backup sensors available.
   - Properly align and calibrate sensors before flight.

8. Risk: TARP system malfunction impacting data collection.

   Mitigation:

   - Conduct regular inspections and maintenance of the TARP system.
   - Configure and calibrate the TARP system correctly.
   - Monitor the system during the mission for signs of malfunction.
   - Have contingency plans and backup systems in place.

9. Risk: Inaccurate IMU calibration impacting data accuracy.

   Mitigation:

   - Calibrate the IMU properly before aerial acquisitions.
   - Follow manufacturer guidelines and use calibration programs.

10. Risk: Radio interference disrupting communication with the ground station.

    Mitigation:

    - Avoid flying near areas with high radio interference.
    - Use frequency-hopping spread spectrum (FHSS) technology.

11. Risk: Collisions with obstacles during flight.

    Mitigation:

    - Carefully plan the flight path and avoid flying near obstacles.
    - Equip the UAV with obstacle avoidance sensors and cameras.

12. Risk: Failure of the UAV to capture required data during flight.

    Mitigation:

    - Implement backup systems and alternative data collection methods.

- Regularly inspect and maintain cameras and sensors.

13. Risk: Inadequate georeferencing of collected data. Mitigation:
    - Use GPS technology to track UAV location during flight.
    - Ensure accurate georeferencing and alignment of imagery.
    - Integrate flight planning software for optimal data collection.
16. Risk: Lack of proper analysis and interpretation of collected data.

    Mitigation:
    - Employ trained personnel with expertise in data analysis and interpretation.
    - Implement robust data processing and analysis workflows.
    - Utilize advanced algorithms and techniques for accurate analysis.
17. Risk: Legal and regulatory compliance issues.

    Mitigation:
    - Stay updated with relevant drone regulations and permits.
    - Ensure proper licensing and certifications for operators.
    - Maintain records of flight operations and adhere to privacy laws.
18. Risk: Environmental impact and public safety concerns.

    Mitigation:
    - Follow guidelines and regulations related to environmental impact.
    - Conduct risk assessments to identify potential safety hazards.
    - Maintain clear communication with stakeholders and authorities.
19. Risk: Insufficient training and competence of UAV operators.

    Mitigation:
    - Provide comprehensive training programs for UAV operators.
    - Regularly assess and update operator skills and knowledge.
    - Foster a culture of safety and continuous learning within the organization.
20. Risk: Poor communication and coordination within the operational team.

    Mitigation:
    - Implement effective communication protocols and channels.
    - Foster a culture of open communication and teamwork.
    - Conduct regular briefings and debriefings to ensure clarity.

Landing:

1. Risk: Obstacles at the landing site.
    - Mitigation: Ensure a pre-designated landing site that is free of obstacles.
    - Mitigation: Pilot should be familiar with the area to avoid surprises during landing.
2. Risk: Unsafe descent rate and speed.
    - Mitigation: Monitor UAV's altitude and speed during descent.
    - Mitigation: Avoid descending too quickly to prevent crashes.
3. Risk: Hard landing causing damage to the UAV.
    - Mitigation: Reduce throttle to bring the UAV down gently.
    - Mitigation: Ensure the UAV is level and straight before landing.
4. Risk: Landing in specific areas for agricultural surveys.
    - Mitigation: Plan and designate landing areas to avoid damaging crops.
5. Risk: Landing in potentially hazardous environments for methane leak detection.
    - Mitigation: Use additional sensors or tools for a safe landing in hazardous environments.
6. Risk: Design factors affecting the landing process (e.g., wing design, ailerons, flaps).
    - Mitigation: Choose appropriate wing design for ease of landing.
    - Mitigation: Use ailerons and flaps for control and speed reduction during landing.
7. Risk: Weight, size, and propulsion system affecting the landing process.
    - Mitigation: Consider the weight and size of the UAV for landing requirements.
    - Mitigation: Account for different characteristics of fixed-wing and rotary-wing systems.
8. Risk: Landing site conditions and weather affecting the landing process.
    - Mitigation: Ensure a clear and level landing site for safe UAV landing.
    - Mitigation: Train pilots to handle challenging wind conditions, including crosswinds.
9. Risk: Landing gear stiffness and environmental characteristics.
    - Mitigation: Ensure appropriate landing gear stiffness.
    - Mitigation: Calibrate sensors for accurate measurement of environmental characteristics.
10. Risk: Failure to detect obstacles during landing.
    - Mitigation: Implement an obstacle avoidance system using multiple sensors.
    - Mitigation: Ensure sensors are calibrated and flight paths are well-planned.
11. Risk: Unclear or misinterpreted environmental characteristics during landing.
    - Mitigation: Calibrate sensors for accurate measurement of environmental characteristics.
    - Mitigation: Understand and analyze environmental characteristics of the landing site.
12. Risk: Wind conditions affecting UAV stability and trajectory during landing.

- Mitigation: Assess wind conditions using sensors for speed, direction, and turbulence.
- Mitigation: Adjust the control system based on wind conditions to ensure stability.

13. Risk: Failure or malfunction of the control system during landing.
    - Mitigation: Implement redundancy in the control system with backup controllers.
    - Mitigation: Regularly test and maintain the control system to prevent failures.
14. Risk: Collision with humans, animals, or man-made objects during descent.
    - Mitigation: Use GPS navigation to re-calculate the path if wind pushes the UAV off course.
    - Mitigation: Ensure no third-party equipment uses the same frequency and bandwidth as the UAV.
15. Risk: Hardware malfunctions or recovery failure during landing.
    - Mitigation: Perform regular system checks to identify and address any hardware malfunctions.
    - Mitigation: Implement failsafe mechanisms and redundancy in the control system.
16. Risk: Failure to extract required information from collected data.
    - Mitigation: Process and analyze data using appropriate software tools.
    - Mitigation: Ensure the data analysis techniques align with the mission objectives.
17. Risk: Inaccurate calibration of sensors affecting data analysis.
    - Mitigation: Follow manufacturer's instructions to calibrate sensors accurately.
    - Mitigation: Regularly test and adjust sensors to maintain their accuracy.