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Product Development Process for Small Unmanned Aerial Systems

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PRODUCT DEVELOPMENT PROCESS FOR SMALL UNMANNED AERIAL SYSTEMS

THESIS

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DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

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PRODUCT DEVELOPMENT PROCESS FOR SMALL UNMANNED AERIAL SYSTEMS

THESIS

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Degree of Master of Science in Systems Engineering

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PRODUCT DEVELOPMENT PROCESS FOR SMALL UNMANNED AERIAL SYSTEMS

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Abstract

The DoD has recognized the need for persistent Intelligence, Surveillance and Reconnaissance (ISR) over the last two decades. Recent developments with commercial drones have changed the market structure; there is now a thriving and extensive market base for drone based remote sensing. This research provides system engineering methods to support the DoD use of this burgeoning market to meet operational ISR needs. The three contributions of this research are: a process to support Small Unmanned Aerial Systems (SUAS) design, tools to support the design process, and tools to support risk assessment and reduction for both design and operations. The process and tools are presented via an exemplar design for an ISR SUAS mission. The exemplar design flows from user needs through to an allocated baseline with an assessment of system reliability based on a compilation of commercial component reliability and failure modes.

Acknowledgements

First and foremost, I would like to thank all our special forces personnel who work relentlessly everyday defending our freedom and performing heroic missions that none of us will ever hear about. The thesis is aimed towards providing you better tools and equipment to perform you mission smarter, better, quicker, and more reliably. Next, I would like to think my advisor, Lt Col Amy Cox, for guiding me through the winding road of technical writing. Thank you for your candor, inspiration, and most importantly your time. Finally, to my wife, thank you for your support, understanding, and motivation. I love you more each day and I cannot imagine where I would be without you in my life, you are truly my better half.

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PRODUCT DEVELOPMENT PROCESS FOR SMALL UNMANNED AERIAL SYSTEMS

I. Introduction

Demand is increasing for operational and tactical information superiority in the deployed environment. Due to the diversity of enemy tactics, varying terrain, and users, each mission type may require specific system requirements to meet performance objectives. Small Unmanned Aerial Systems (SUAS) are excellent tools to provide deployed operators increased situational awareness on the battlefield. Tactical deployed operators desire low transport size and weight, rapid customization, and low system complexity, SUASs meet this need.

An opportunity exists within the commercial drone industry due to rapid technical advancement from increased competition and lower technical entry barriers. This market can be leveraged to design simple SUASs that meet mission requirements with low development time and financial commitment. The following thesis will use current system engineering tools and methods to establish a SUAS product design process that meets mission requirements and mitigates system risks.

DoD program offices currently contract out design and platform support for SUAS. This current structure limits the programs office's ability to own the technical baseline. Where the owning this baseline involves understanding how the SUAS performs and is operated; facilitating shifts in the design to new or emergent mission sets. With ownership, the program office can respond in a timely manner to operator needs, reducing product time to the field. A detailed knowledge of the system also enables the program office to understand technology trends to map to future capability gaps of the warfighter. This research presents a process to enable DoD program offices to align tactical and operational customers' demands with a reliable

SUASs. We assess that this process will have multiple benefits, alleviating UAS budgetary pressure and contractor limitation of the SUAS design model.

Cost is a Mitigated Factor for Military SUAS

Within a military context, funds are projected through a five-year view titled the Future Years Defense Program (FYDP). Figure 1 projects the approximate spending through the FYDP for group four and five drones, the data indicates an in increase procurement and operation and maintenance cost over that time (Morris, 2018). Group four and five drones weigh greater than 1320 lbs and are predominately made up of the Air Force's RQ-4 Global Hawk, MQ-9 Reaper, MQ-1 Predator, the Army's MQ-1 Grey Eagle and MQ-5 Hunter (Dempsey, 2010).

Global Hawks cost $140 to $211 million per system and the other systems are in the $5-30 million range. Beyond unit cost, one can see in Figure 1 that maintenance costs are projected to grow through 2021 due to the increasing number of deployed drones and increased capabilities. To underline the growth in cost and capability, a new Reaper squadron costs $160 million annually, in contrast to $70 million for a legacy Predator squadron.

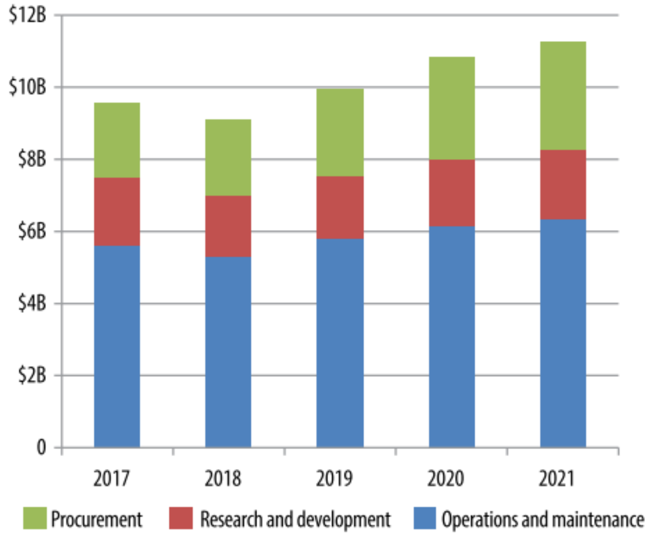


Figure 1. Future Years Defense Program for Department of Defense UAS (Morris, 2018).

The growth in cost, both procurement and maintenance are constrained by available budget. How does the DoD fulfill its need for persistent ISR within fiscal constraints? One path to reduce UAS costs is to field more capable large group UAS, while decreasing overall inventory and maintenance cost. Another path is fielding smaller, mission specific UAS controlled by soldiers on the ground (Morris, 2018). Implementation of smaller UAS would include mass customized systems with short life spans, focusing on reducing maintenance cost in favor of platform flexibility to new or evolving mission sets.

Separate from the growing demand for persistent Intelligence, Surveillance, and Reconnaissance (ISR) in the DoD, other technological advances have spurned a rapidly expanding and active commercial market. The Commercial drone sector supports aerial photography, shipping, disaster management, search and rescue, geological mapping, building safety, crop monitoring, unmanned cargo transport, law enforcement and border control, and storm tracking. “Projections to 2025 show commercial drones could be an $82 billion industry with a 100,000 job boost to the U.S. economy” (Jenkins and Vasigh, 2013). As demand increases for drone functionality and technology, investments will increase from industrial conglomerates, electronic parts companies, and information technology firms, this increased activity in turn lowers prices and increases available functionality (D. Joshi, 2017). There are overlaps between DoD and commercial needs. This overlap poses an opportunity whereby the DoD can benefit from the commercial sectors investments. The DoD can exploit the diverse functionality provided by the market to meet its needs at a lower cost.

Figure 2 displays the cost in millions of dollars in comparison to the payload weight in pounds for the five DoD defined UAS groups. Group one, Mini UAS, is 3 orders of magnitude of cost smaller than a group five, High Altitude Long Endurance UAS, or 2.5 orders of magnitude smaller than a group four, Medium Altitude Long Endurance UAS. For every group five UAS, 1,250 group one UAS can be bought or 163 for every group four UAS. While individually less capabile, the individual cost, risks, and barriers of smaller UAS pose an opportunity. SUAS provide disaggregated risk (lose of one SUAS versus one HALE), lower cost and possibility of mass customoziation for user need (Joseph Pine, 1992).

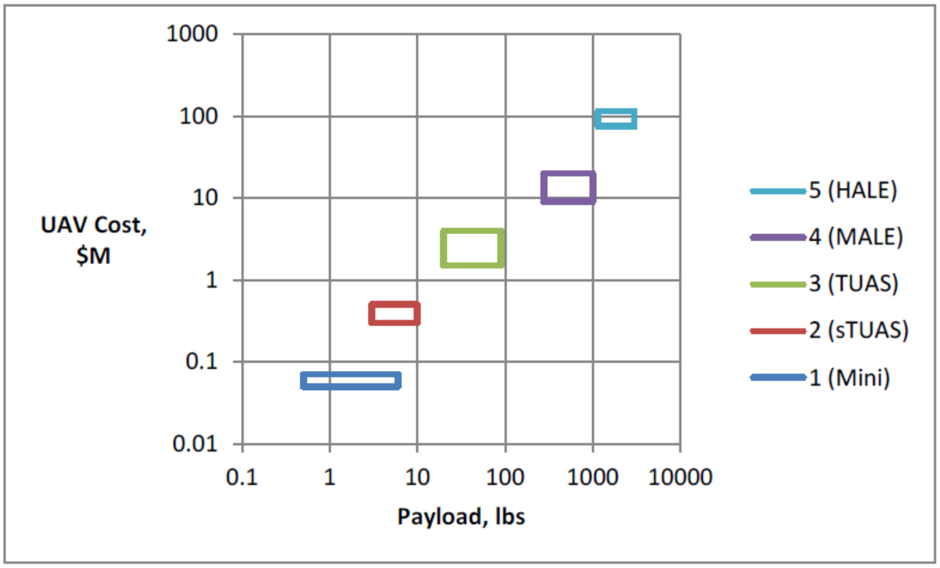


Figure 2. UAV Cost and Payload Capacity Ranges for DoD UAV Groups (Fladeland, Schoenung, & Lord, 2017)

Commercial drones are a further price point reduction from contracted military drones. “Purchase prices for small drones are currently on the order of, for hobbyist devices, $100 to $1,000, and for low-end professional use $5,000 to $10,000. For some applications, the indicative costs per hour of flight are currently on the order of $25 for small drones compared with $750 for manned fixed-wing aircraft and $1,350 for manned rotorcraft. For applications for which the limitations are acceptable, such as the gathering of moderate-quality image and video, small drones are now vastly more economic than aircraft, and much more economic than large drones. This is naturally giving rise to both substitution effects and new customers.” (Clarke,

2014) For comparison a military group 1 UAS, RQ-11B Raven, costs $250,000 for the complete system including the air vehicle, ground station, and support equipment (Army Technology, 2018).

Problem Statement

Currently the design of SUAS systems is left to functional experts or DoD contractors due to perceived system complexity. This research asserts that the ease and maturity of the commercial drone market has reduced entry barriers allowing for a broader base of system designer. The DoD can leverage these newly available technologies to design SUASs for military utility. A specific methodology does not exist for engineers or program managers with technical backgrounds to design a SUAS, using commercial parts, for a given reference mission.

Scope and Assumptions

The analysis has been restricted to Group 1 UAS. All vehicle weights must be under 20 lbs (Federal Aviation Administration, 2016). Group 1 UAS size fits within the parameters of commercially available components for drones, which is the focus of this research. Group 1 UAS size also fits the transportation requirements of the selected Intelligence, Surveillance, and Reconnaissance (ISR) exemplar of this research.

Time constraints only permitted one reference system to be demonstrated. The reference system aligns with current capabilities of SUAS and are focused at a duration between 30-60 minutes for an ISR payload capability. Requirements from this mission set have been established and will be the basis for the component and system performance criteria within the research.

Commercial components that are available to the public are the focus of the analysis, since the commercial drone market has matured to a point in which the DoD can leverage it for military utility. Commercial components were required to be available and accessible from online drone manufactures or hobbyist sites in order to be analyzed in this thesis. DoD Contractors such as Boeing, Lockheed Martin, and Northrop Grumman and their SUAS components were outside the scope of this research. The performance for these components has been previously documented and demonstrated via DoD programs of record.

The reference SUAS is an initial concept only and does not consider ruggedizing, weatherproofing, or cyber security integration. The research is focused on developing a concept development process for SUASs and is not focused on production level system maturity. Follow-on research is required to develop and validate testable measures for the reference SUAS performance for defined operational conditions.

The reference SUAS design space considers only multirotor platforms using a battery power system. This limitation enables the design space for the reference SUAS to be manageable, yet thorough, and within the constraints of thesis research. A multirotor platform was chosen due to the authors experience and familiarity with such platforms through the Air Force Institute of Technology (AFIT) SUAS design sequence. Battery power sources were only considered due to the popularity within the commercial drone market.

Investigative Questions

1. What systems engineering methods are appropriate for a tailored rapid SUAS design process?
2. What baseline design tools and heuristics are required to support decisions for vehicle performance, trades, reliability, assessment and follow-on designs?
3. What SUAS components are critical to mission success and can reliability rates be found, documented, and analyzed for these components?

Materials and Equipment

- Cameo Systems Modeler SysML modeling tool by No Magic
    - Use Case Diagrams
    - Functional Architecture
    - Physical Architecture
- Free Fault Tree Analysis Software, Fault Tree Analyser (ALD, 2018)

- Microsoft Excel documenting
    - Fault Tree Tables
    - Requirements
    - Operator Checklists
    - Design Trade Space/Checklist
    - Reliability Analysis

Other Support

UAS manufacturers of critical parts often have reputation among hobbyists and enthusiasts. These individuals possess a level of knowledge on the operational performance of critical components that must be captured in order to completely assess the reliability. The Air Force Institute of Technology possesses the Autonomy, Navigation, and Timing (ANT) lab which tests SUAS in various configuration. Interviews will be conducted with ANT lab design experts on critical components to establish which manufactures of parts they prefer (of high quality and reliability) and which manufactures they do not prefer (of low quality and reliability). These staff members have decades of experience with remote controlled aircraft as well as the recent growing SUAS market. Interviews will provide input into the component selection process for the ISR mission design exemplar.

In addition to interviewing the ANT Lab staff, the greater drone and hobbyist community provides a wealth of knowledge on drone designs, reliable components, and measured performance. Various hobby websites are used to gather these inputs and to make informed engineering decisions. Appendix B provides a list of online drone sources used throughout section IV, including the focus of the website.

Overview

Chapter II focuses on pertinent literature supporting system design for a small UAS. The review includes an investigation into previous system designs for SUAS and any documented methodologies. In Chapter III, the general System Engineering Process is defined and applied to a specific SUAS Product Development Process. This process is then used in Chapter IV for an Information Superiority SUAS mission set, and outputs a reference SUAS. Finally, Chapter V documents the benefits of the SUAS Product Development Process and key products produced for the program office.

II. Literature Review

Chapter Overview

The goal of this chapter is to investigate literature on system engineering techniques, and trades in order to inform the creation of a tailored product development process for Small Unmanned Aerial System (SUAS). This review also provides a background on SUAS and the associated military applications. This background informs our tailored systems engineering process, which will be outlined in Chapter III and demonstrated in Chapter IV. This thesis provides a system design methodology for SUAS based on established military operational reference missions. Trades will be performed on air vehicle designs, critical component types, materials, integration, and redundancy in order to determine the highest system reliability that still meets the operational reference mission requirements.

SUAS Technology Overview

A SUAS is defined as a controllable air vehicle providing increased functionality to the operator on the ground. Domestically, civil use of SUAS is limited to aircraft weighing less than 55 lbs in, operating below 400 ft above ground level at speeds below 100 mph (Federal Aviation Administration, 2016). Control of the air vehicle is established through a ground control station (GCS), which receives flight inputs from the operator and sends instructions via radio transmitter to the onboard flight computer. Control can be passed in two modes. The first is through a GCS software module enabling input for Global Positioning System (GPS) coordinates and flight paths. The software can be run on a laptop, tablet, or phone. This control mode can be performed semi-autonomous where the user is actively sending command to the air vehicle through the GCS, or autonomous where the flight program is loaded on the ground and the air vehicle performs the mission without airborne commands from the GCS. The second mode is through a

Radio Controller enabling the operator to control the vehicle directly. In this mode the operator usually has a form of visual feedback for their control inputs, the most common type is first person point of view goggles (FPV). The flight computer or autopilot sends commands signals to the air vehicle's motors, servos, and sensors. Furthermore, the computer keeps track of telemetry data including altitude, air speed, direction, battery voltage, and GPS coordinates; this information is routed back to the GCS software providing situational awareness for the operator. The different control modes can be seen in Figure 3.

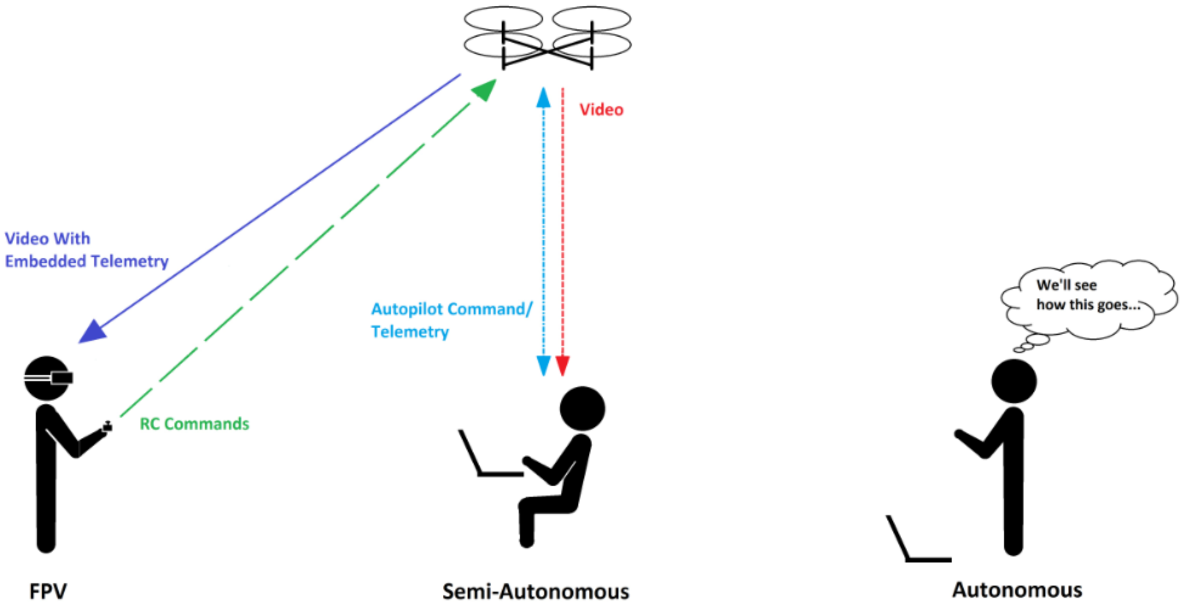


Figure 3. Flight Control Modes

Batteries are the common fuel choice for SUASs, enabling powered flight and sensor functionality. Power is routed to the flight computer and motors. Electronic speed controllers (ESCs) regulate the power output and control signals from the flight computer to the motors.

The number of motors is dependent on the architecture of the air vehicle. For example, quadrotors have four motors, hexrotors have six, and octorotors eight. Motors are rated in KVs defined as revolutions per minute per volt applied or RPM/Volt. Higher KV motors spin faster and pair with smaller propellers, while lower KV motors spin slower and pair with larger propellers ("How to Build a Drone - A Definitive Guide For Newbies," 2018). Power available is ultimately a function of the number of propellers and motors, their RPM, and torque. Propellers on SUAS spin in opposite directions to their neighbors in order to balance torque effects in air. Simpler SUAS design usually have an even set of motors to attain this balance. Further changes in balance are leveraged to attain yaw, pitch, and roll or general aerial control.

Battery elimination circuits (BECs) are similar to ESCs, but regulate voltage from the battery and enable a step down of 5V or 12V for critical electronics (Alex, 2015). Sensors enable increased situational awareness, which is the main functionality of the drone. Sensors are mounted on the SUAS's frame or on a gimbal. A gimbal allows movement for the sensor in one or multiple axes with operator input through the GCS. Figure 4 provides a visual description of the SUAS system.

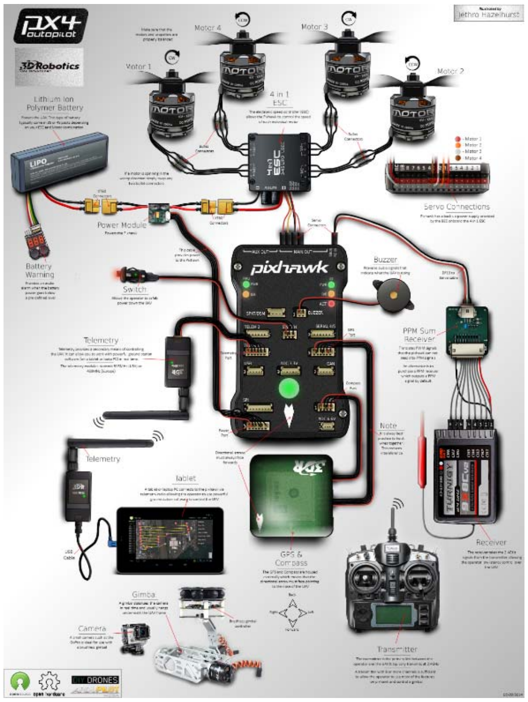


Figure 4. Electrical and Component Layout of a Typical Drone("Pixhawk Autopilot," 2015)

Mission Need

Demand for information superiority is constantly on the rise in the deployed environment. Increasing budget pressure due to the 2011 Budget Control Act and reliance on unmanned technology and capabilities have forced the Department of Defense (DoD) into one of two paths to cut costs. The first path involves reducing the number of large Unmanned Aerial Systems (UAS), while focusing on increased functionality of the individual systems. The second path is fielding smaller, less capable UAS controlled by soldiers on the ground (Morris, 2018).

SUAS components have decreased in cost due to reduced FAA drone restrictions. By reducing restrictions, the drone industry is more accessible to the public and industry, promoting a rise in functionality and application of drones in the civil sector. Higher demand has resulted in increased supply of drones and their components, which has led to reduced cost. The rise of the hobbyist industry has diffused information of drones, components, building, and configuration to the public through online blogs and forums. This diffusion has reduced complexity and entry barriers to the drone community. The DoD can leverage this industrial movement to procure, build, test, and push the functional boundaries of SUAS, while mitigating cost, airworthiness risks, and reliability risks.

Currently, a system design methodology is lacking for the military in building and mapping SUASs to a given operational or design reference mission with quantitative requirements. This thesis will focus on establishing a reference missions within the scope of current SUAS capabilities, then utilizing model-based systems engineering processes to build a representative system. The objective of the design process is to build the a reliable SUAS system through systems and component level trades while meeting the reference mission requirements.

The goal of the thesis is to provide a simplified process allowing the DoD to own the technical baseline of the SUASs.

Scope

This work is bounded by the following constraints. They have been chosen to allow for a less ill-structured problem; a space amenable to a defined design process. The process is demonstrated and validated with a specific design reference mission.

- Total air vehicle weight is below 20 lbs
- Only electrical power systems will be analyzed with a focus on current accepted and proven battery composition of lithium polymer batteries
- Air vehicle frame types will include multirotor types only
- Commercially and widely available components, frames, and materials will be evaluated
- System modeling will focus on the concept development phase of systems engineering

SUAS Military Applications

A 2007 study performed by Office of the Secretary of Defense showed unmanned systems are better suited for mission which are either dull, dirty, and/or dangerous, opposed to manned systems. Dull missions involve long hours of low stimulus to the operator or warfighter. Examples include surveillance missions or regional coverage mission. If the UAS handles the information collection and detection for these missions, it is superior to manned systems where fatigue can set in creating mistakes. Dirty missions include conditions which pose longer term risks to manned air crews such as radiation or chemical measurements. UASs excel in this mission set with specific sensors which keep the operators out of harm’s way. Dangerous mission sets include conditions which pose an immediate risk to human operator; an example include neutralization of improvised explosive devices. Unmanned systems lower human cost if the mission is unsuccessful (Office of the Secretary of Defense, 2007).

The United States Air Force SUAS Flight Plan: 2016-2036, outlines that SUAS technology and operational evolution should aim at bridging the gap between tactical and strategic mission sets. The document argues “historically tactical SUASs are now mature enough to augment or assume Air Force requirements with operational and strategic impact.” (U.S. Air Force, 2016) This evolution of SUASs utility requires correct integration of technology, mission development, and human-system integration.

Envisioned SUAS applications or vignettes for future operations for the Air Force are: Suppression/Destruction of Enemy Air Defense (SEAD/DEAD), Strike Coordination and Reconnaissance (SCAR), Counter-UAS (C-UAS), Beyond-Line-Of-Sight (BLOS), “Perch and Stare”, Sensor Air Drop, Weather Sensing, Airborne Layered Network (ALN), Nuclear Weapons Enterprise Operations Support, and Information Superiority (U.S. Air Force, 2016). The SUAS applications and their descriptions are outlined in Table 1.

Table 1. SUAS Military Future Military Applications

Mission	Description
SEAD/DEAD	Involves sending SUASs from a host vehicle to destroy, jam, or overwhelm the enemy's air defense forces. Focus attributes include weapons capability, high speed, long range, and sensor detect payload.
SCAR	Provides valuable intelligence back to larger platforms, host or operators. Intelligence includes detect and attack targets, minimization of collateral damage, and battle damage assessments. Focus attributes include locating and verifying target, communication with other assets, passing updates.
C-UAS	Employs SUASs to jam, destroy, or deceive enemy drones which pose a threat.
BLOS	Enables SUAS to operate over the horizon with increased range. Technique envisioned include air vehicle relays on SUASs or other larger vehicles.
"Perch and Stare"	Focuses on having SUASs in a loiter mode with low power levels to collect, analyze, communicate, and monitor over long duration mission. Focus areas are battery technology, solar power, utilization of the enemy's power grid, and cyber-surveillance technology.
Sensor Air Drop	Enables delivery of various sensor types via the air including communication, seismic, acoustic, magnetic, daylight and infrared imagers. This capability keeps military members off the front lines and away from potential enemy risks. An additional use is geolocation information for covert emplacements and gathering critical intelligence before the emplacements are destroyed or defeated.
Weather Sensing	Provides real time weather data on demand for mission planning. Employing more SUASs improves regional weather reports into the Area of Command (AOC) weather data base; operators can pull up accurate and timely weather data for their locations.
Airborne Layered Network	Enables multi-platforms, multi-sensor SUAS networks to support future concepts including swarming. Position, sensor data, and communication can be shared across multiple platforms allowing SUAS to focus on specific functionality within a network, increasing the swarm's overall capability and resiliency. See Figure 5 for typical ALN configuration.
Nuclear Weapons Enterprise Support	Focuses on domestic protection of Intercontinental Ballistic Missile (ICBM) complexes with capabilities of enemy detection, enemy attack, and information gather for possible intruders.
Information Superiority	Critical decisions require rapid decision-making process. SUAS promote rapidly transmitted photos and video for command decisions on enemies, troop movement, and situational awareness.

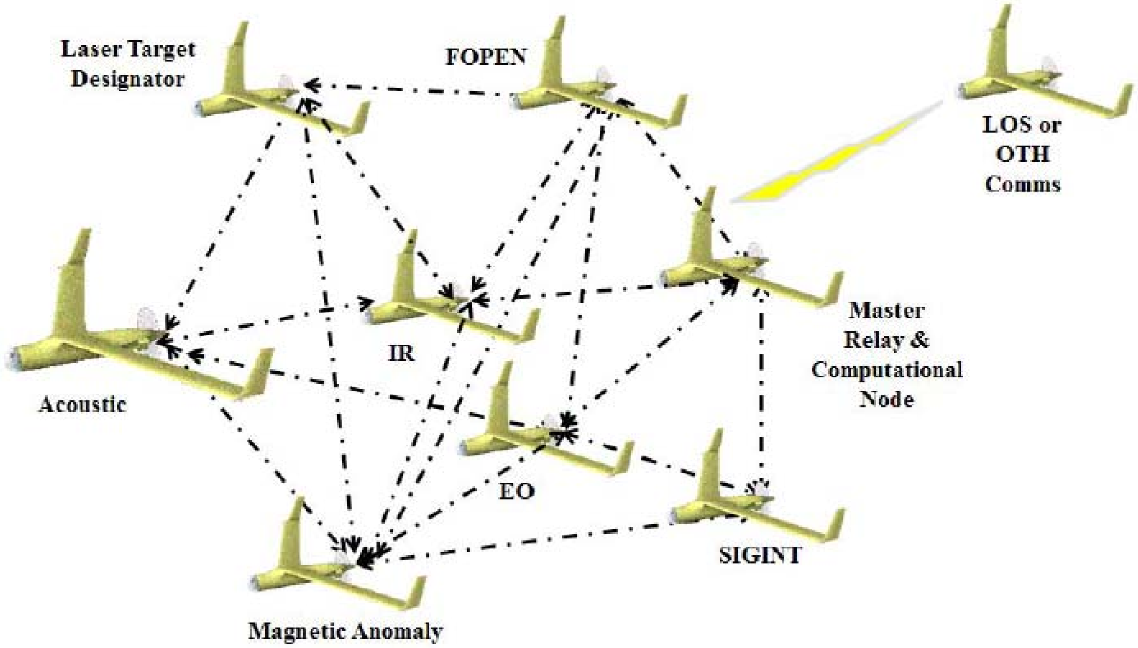


Figure 5. Possible Airborne Layered Network Configuration (U.S. Air Force, 2016)

Previous Systems Engineering Studies Applied to SUAS

While limited, SUAS research exists for military applications with some system design case studies available providing information. The first step in the design process is to define requirements and minimum performance criteria for the system, based on mission scenarios and profiles. Mission profiles should establish typical and maximum altitudes, cruise and maximum speed, loiter speed, climb rate, endurance, and operational radius. Common performance requirements include: reliability, maintainability, availability, mobility, transportability, deployability, sustainability, environmental and electromagnetic effects, survivability, vulnerability, safety, interchangeability, and upgradeability (Torun, 2002).

Careful attention should be paid to prioritizing requirements for system level trades. The design team should investigate representative systems that can meet proposed requirements and document strengths and weaknesses (Ozdemir et al., 2014). With the establishment of representative systems, component trades can be performed based on available technology.

When performing trades there must be discriminators to base trades around. Discriminators are based around either prioritized requirements or costs. With discriminator criteria established the air vehicle design process can ensue. This process is done in a bottom up approach by designing and evaluating subsystems first and then the complete system. Subsystems include propulsion, controls, structural, and payload.

A specific system engineering method is the systems architecting with ilities (SAI). This method is appropriate for the concept development phase of the systems engineering process. This process supports architecture development where "architecting is the process of structuring the components of a system, their interrelationship, and their evolution over time" (Dagli & Kilicay-Ergin, 2009). Sturdivant and Chong detail the steps of the SAI method in their 2017 journal article;

- *Step 1 – Determine Value Proposition and Constraints*: this involves identifying and prioritizing requirements in the context of the overall architecture.
- *Step 2 – Identify Potential Perturbations:* What are the risks or modes which can interfere with delivery of value from the system?
- *Step 3 – Identify Initial Desired Ilities:* Ilities are the longer term aspects and behavior of the system, the designer must rank and prioritize ilities including but not limited to reliability, maintainability, and availability.
- *Step 4 – Generate Initial Architecture Alternatives:* generate alternatives and trades which promote requirements.
- *Step 5 – Generate Ility-Driving Options:* generate alternatives and trades which promote desired ilities.
- *Step 6 – Evaluate Potential Alternatives:* model alternatives with desired metrics (cost, attributes, and ilities). This analysis can occur through modeling and simulation or higher abstraction levels.
- *Step 7 – Analyze Architecture Alternatives:* perform evaluation of tradeoffs which exists from step 6 and document impact to overall architecture.
- *Step 8 – Trade-off and Select "Best" Architecture with Ilities:* utilize results from step 7 to determine preferred architecture to move forward into design (Sturdivant & Chong, 2017).

An additional system engineering method utilized for reliability analysis is Failure Mode and Effect Analysis (FMEA), which determines what can go wrong in the system with representative probabilities and consequences. FMEA focuses on the early design phase, “minimizing the probability of failure or the effect of failure” (Dermentzoudis, 2004). There are basic questions the designer needs to answer when performing FMEA

1. How can each part of the system possibly fail?
2. What are mechanisms might produce these modes of failure?
3. What could the effects be if the failures occur?
4. Is the failure in the safe or unsafe direction?
5. How is the failure detected?
6. What inherent provisions are provided in the design to compensate for the failures?(Hoyland & Rausand, 1994)

When performing FMEA it is important to know that failures are not weighted equally; some failures can create an unrecoverable event and others are recoverable. In the case of SUAS, if a motor fails on a hexacopter it is recoverable, due to motor redundancy, versus a quadrotor where the vehicle unrecoverable. It is also important to know the customers’ requirements for the system. For example, if the SUAS is for Special Forces personnel they may emphasize packing of the system into a backpack, as opposed to Security Forces personnel who may emphasize packing the system into a Humvee. In both cases, being unable to pack and transport the SUAS in the required area is deemed a required function. Each function in the system must have a purpose and objective. By identifying these in the design process, faults can be better understood. Focus must always be placed on a fault prevention orientation (Stamatis, 1995).

FMEA is an iterative process. The system should be diagramed to show physical components and functionality so the design team can understand component and subsystem interactions. Once diagrammed, the design team should evaluate and collect any data on the components of the system in order to evaluate and brainstorm for potential failure modes.

When the failure modes are determined they are prioritized based on severity. If then statements are useful at this phase of the analysis to determine consequences. Some operationalization of the consequence severity must be established to compare failures against each other; a 1-10 scale is often used. The probability of a failure for a part can be determined by using failure data of the part. If data is not available, the failure probability must be estimated; knowing causes of failure can produce a better estimate. Finally, a risk priority number (RPN) is assigned to each part or component of the system based on the parts severity of failure multiplied by the probability of failure. RPN can be summed for a total system RPN. Additionally, the RPNs can be listed from highest to smallest. In the concept development phase FMEA process can be performed cyclically to buy down the RPN level and identify critical component trades (Stamatis, 1995)(Dermentzoudis, 2004).

UAS Reliability

Reliability is defined as “the capacity of a component or a system to perform its required function under stated operating conditions for a specified period of time.” (Ebeling, 2005) In the case of SUASs, operating conditions are bounded by the defined requirements and environment over the mission duration. Reliability is measured and estimated through modeling of parameters including Mean Time to Failure (MTTF) or Mean Time Between Failures (MTBF). MTTF is used to measure parts which are non-repairable while MTBF is used for reparable parts (Petritoli, Leccese, & Ciani, 2017). Evaluating reliability is often done by measuring the unreliability of the system or the likelihood of failure over a set time (Justin & Murtha, 2009).

Determining mission success for a SUAS revolves around the system’s ability to perform its critical functions and providing use to operator on the ground. Utility, in the case of an Information Superiority mission, is the ability for the operator to have increased situational awareness beyond their current location. There are three critical functions which enable an increase of situational awareness. The first is flight; this enables the air vehicle to provide increased perspective to the operator. Then next is control; the operator can provide instructions to the air vehicle and the air vehicle responds to these commands. For purposes of this thesis, control is semi-autonomous where the system can perform functions on its own but at some point requires instructions from the operator to perform actions (Flenar, 2018). The next category is surveillance; the capability provided is visual, audio, or environmental measurements and must be obtainable by the operator. The system must also be transported to the deployment location with a high level of confidence of functionality. Finally, the air vehicle and support equipment must have power in order to perform all required functions.

If any of these critical functions fail, then the system is not performing the required functions and is considered a system failure. Flenar presents a semi- autonomous use case diagram in his thesis shown in Figure 6. Use cases define the modes or phases the system operates or exists in within the environment. All the use cases can be related to a critical function or multiple critical functions. Perform Setup enables flight, control and payload activation. Launch and Ingress, Egress and Recover, and Loiter support flight and control, if designated navigation points are established. Perform Surveillance, Follow Target, and Deliver Payload support control and payload operation. Plan Mission supports control. The use cases provide further allocation of the critical functions, while aligning closer to the operation mission and requirements.

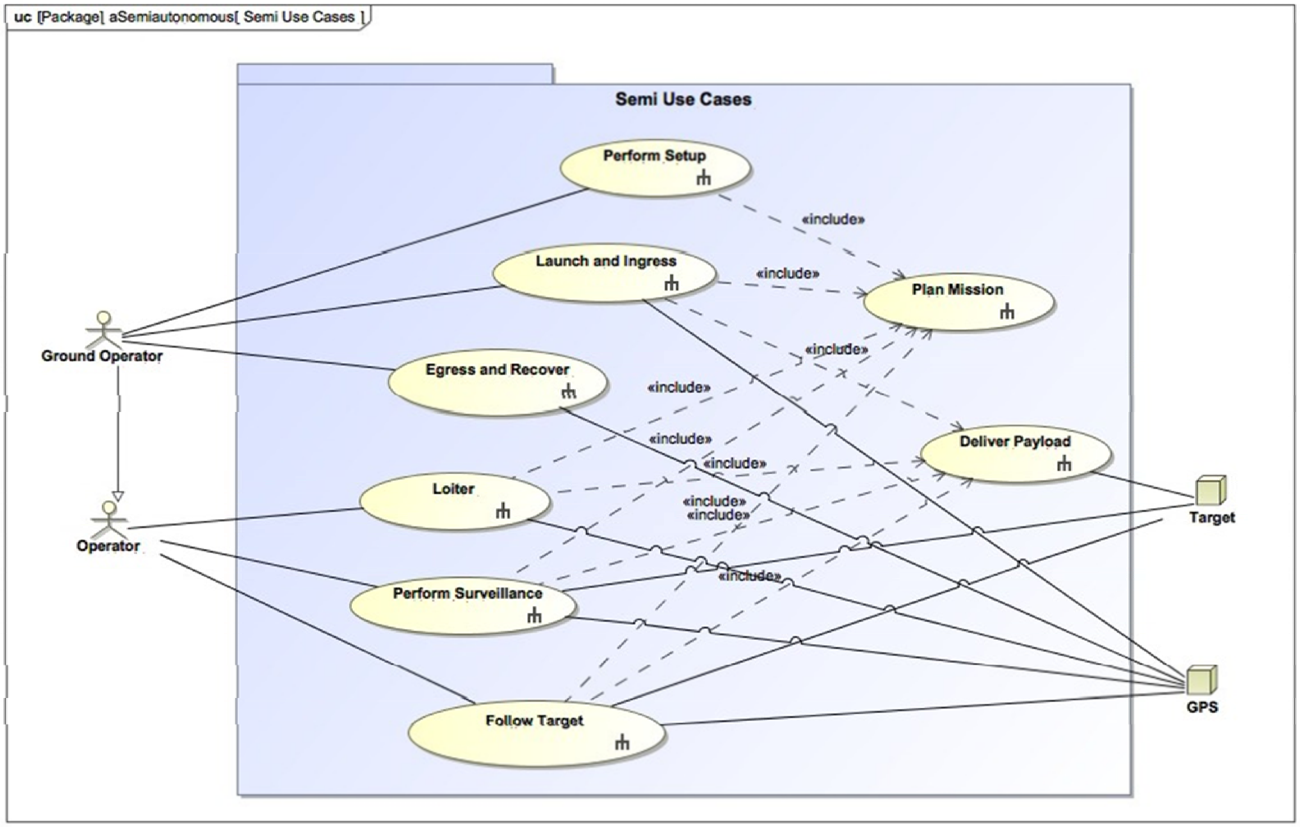


Figure 6. Semi- Autonomous Use Case Diagram (Flenar, 2018)

Components contribute to reliability ratings of critical functions. These effects can be seen in Figure 7. As more parts are added, N, the overall system reliability decreases exponentially. This function is true for componentry in serial configuration, meaning if one component in the architecture fails the entire system fails. For SUAS serial configuration is a fair assumption since design emphasis is placed on light, low cost systems. When considering design trades the number of components become as important as the individual reliability of components (Ebeling, 2005). Component count can also have a large impact the systems sustainment, changeability, and modularity. If failures are isolated and attributed to easily replaceable components or modules, then reliability analysis becomes more manageable.

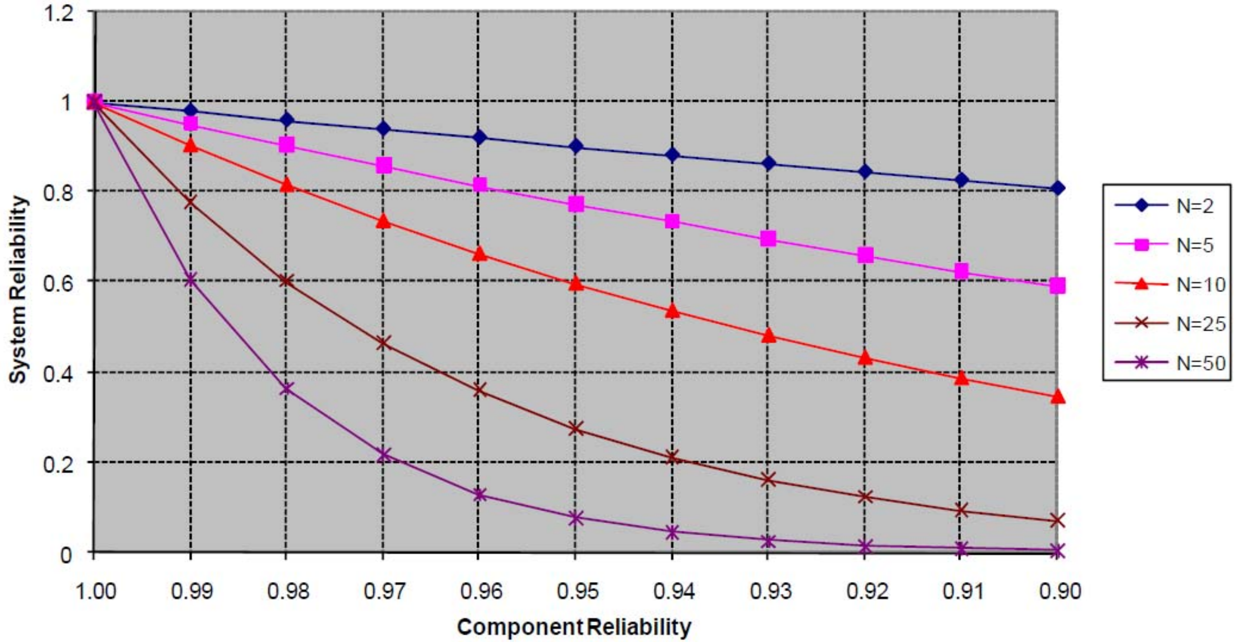


Figure 7. Serial System Reliability as a Function of Component Reliability (Ebeling, 2005)

Measures of Performance (MOPs) are required to measure system reliability of SUAS. MOPs are historical in nature, meaning an event must occur to achieve a data point. In order to capture and record historical data, a database must be available and used to record this information. At this point in time neither the DoD nor the U.S. Air Force maintains a consolidated database for SUAS performance.

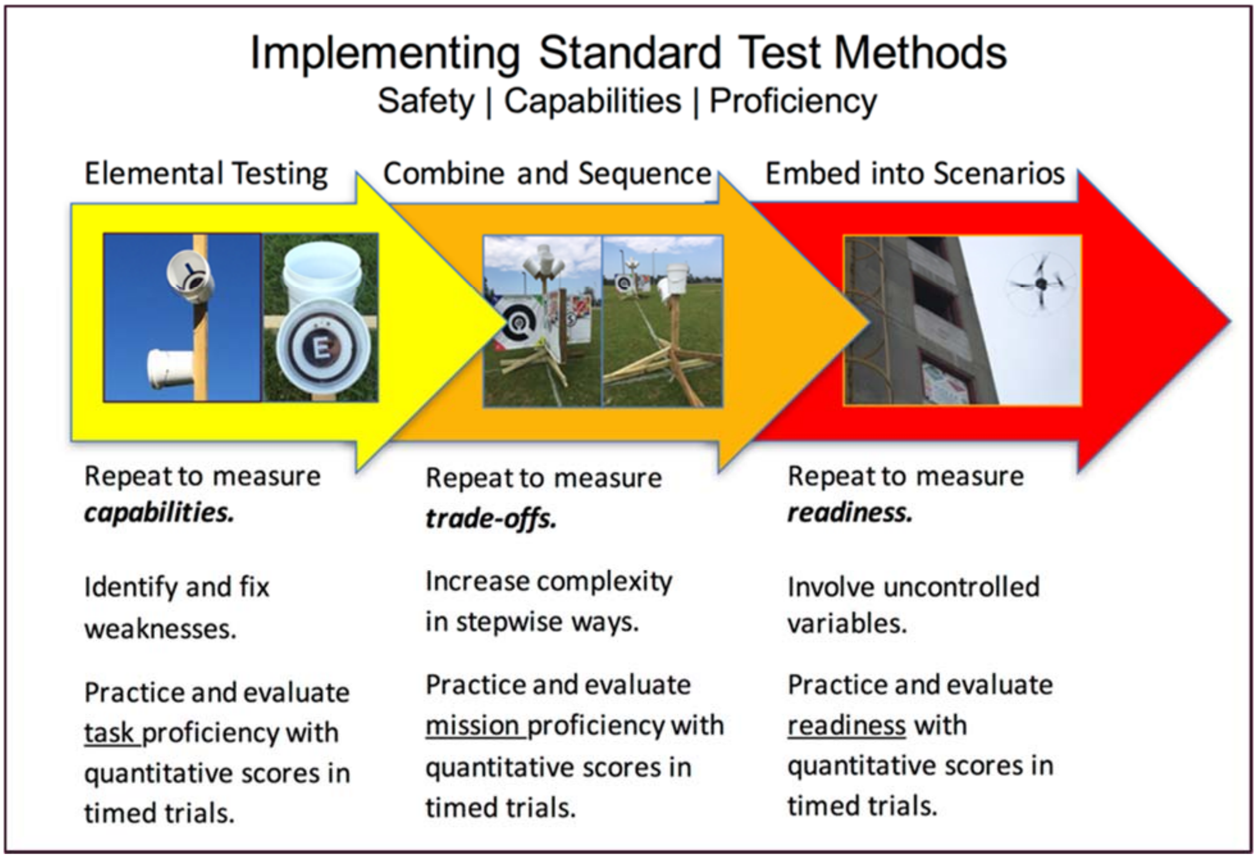
Dermentzoudis (2004) discusses measures for a system with limited data. He states the number of flight hours and the number of crashes are usually known for a given deployed air vehicle. With this information, the only MOPs available for reliability measures are crash rate, current crash rate, and crash rate “X”. Crash rate is the current number of crashes divided by the total number of flight hours. Current crash rate is the same measure except for recording from the last know system modification. This measure is useful as a comparison data point to ensure the system modification is increasing reliability. Finally, crash rate "X" is the number of crashes per a set number of hours enabling a view of trends including: weather impacts, supply chain disruptions, part burn in, or lifecycle analysis (Dermentzoudis, 2004).

The National Institute of Standards and Technology (NIST) managed by the U.S. Department of Commerce established the Standard Test Methods for Responsive Robots. The test program's objective is to "measure a baseline of robot/operator capabilities necessary to perform operation tasks defined by the user" (Jacof et al., 2013). The tests are designed to project whether the robot can perform operationally through testing.

The NIST testing strategy encompasses SUAS below 2 kg, 30 knot speed, and frangible composition. Specific SUAS test include station keeping in both horizontal and vertical positions, endurance and power test for a set path, and safety tests of impact and lost communication behavior. In addition to SUAS tests, NIST test sensor performance including latency, range, audio, color accuracy, and mapping. The overall system test "measures robot, maneuvering, mobility, manipulation, sensing, endurance, radio communication, durability, reliability, logistics, and safety"(Jacof et al., 2013), with a goal of providing quantitative data for different platforms to support operator training, purchase decisions, and operational performance. Individual test trials are run to achieve 80 % reliability with 80% confidence. Tests are run in 30 repetitions and only 3 failures of meeting test objectives are allowed for statistical significance (Jacof et al., 2013).

A fault condition is defined as "A failure of the robotic system preventing completion of 10 or more continuous repetitions. This could include a stuck or disabled vehicle requiring maintenance, or software issues at the remote operator control unit. All such failures are catalogued during testing to help identify recurring issues." (Jacof, 2017). Figure 8 details the

NIST methodology for SUAS testing. The first testing mode is elemental, focusing on individual capabilities for the system and repeatable outcomes. The system then graduates to combination testing of capabilities to determine system tradeoffs and performance. Finally, the system is tested in operational scenarios where variables are uncontrolled aiding in predicting performance for a representative environment (Jacof, 2017).



Implementing Standard Test Methods

Safety | Capabilities | Proficiency

Elemental Testing

Repeat to measure ***capabilities.***

Identify and fix weaknesses.

Practice and evaluate task proficiency with quantitative scores in timed trials.

Combine and Sequence

Repeat to measure ***trade-offs.***

Increase complexity in stepwise ways.

Practice and evaluate mission proficiency with quantitative scores in timed trials.

Embed into Scenarios

Repeat to measure ***readiness.***

Involve uncontrolled variables.

Practice and evaluate readiness with quantitative scores in timed trials.

Figure 8. NIST Test Methodology for SUAS (Jacof, 2017)

Component Variation SUAS-Trades

This section will evaluate the design and component variation with SUASs. The focus is on the multirotor platform family powered by lithium polymer batteries. This focus aligns with the analysis section and keeps the scope focused.

Frame design variations predominately revolve around the number of motors used. Bicopter includes two rotors, tricopeter include three rotors, quadcopter includes four rotors, and so on up to octocopter. The higher the number of motors the more lift the platform can generate, equating to larger payload capability.

More motors also equate to redundancy and increase system robustness. For example, a hexacopter (six rotors) can theoretically have three motors go out and still be recovered, if the non-functioning motors are opposite of each other. Downsides to increasing the number of rotors are larger platform size and weight, decreased power efficiency, larger costs, reduced transportability, and additional parts/maintenance (Liang, 2016). The most popular configurations for multirotors are even number builds: quad, hexa, and octo. Even build multirotors alternate the spin direction to cancel out torque forces to stay balanced in flight (Liang, 2016). Quadcopters benefit from being light and small but will fail in flight immediately if a single motor fails. Hexacopters and octocopters benefit from motor redundancy and increased lift.

Multirotor drones can fly at high speeds, perform vertical take-offs and landings, and excel at surveillance (Hassanalian & Abdelkefi, 2017). Loiter or hover positions are not ideal for endurance due to the high-power consumption for stabilized flight. With the multiplicity of motors, the operators has a high level of control of movements which enables the platform to be extremely agile and responsive (Hassanalian & Abdelkefi, 2017). Focus must be paid to pairing motors and propellers in alignment with the air vehicles size and weight to gain optimal efficiency of the rotors. Multirotors also benefit from simplified control systems promoting lower complexity and higher reliability (Hassanalian & Abdelkefi, 2017).

Future trends project that SUASs will continue to reduce in size and weight. Most of the improvements will come from the hobby industry due to market demand and supply. Higher energy density in fuel choices, including batteries, will increase endurance and range (Herrera, Dechant, Green, & Klein, 2017) . Herrera also details that capabilities will continue to increase due to advancement in other industries and suppliers including robotics, communication, power, sensors, and networking. Projections are that SUASs will eventually be able to carry more payload than the air vehicle weight (Herrera et al., 2017). Additionally, Herrera states, vehicles will continue to be more autonomous with an increase of intra platform data management and sharing; task distribution will shift from the operational user to the air vehicle and increased autonomy will lead to SUAS swarming functionality. Swarming capability establishes a paradigm shift in SUAS enabling new functionality: large scale mapping, coordinated attack, and communication relays (Herrera et al., 2017). The improvements listed above all point to an increase of operational mission sets for SUAS in the near future.

Design for Multiple Functions

One large benefit of UASs are their ability to be customizable and flexible to different mission sets and functions. Size, weight, and power trades within the UAS architecture provide options for the air vehicle to increase performance dependent on the mission set. One way this is realized is through the ability to swap payloads to gain alternative functionality of reconnaissance, munitions, night time imagery, environment measurement, payload delivery, etc.

Different payloads can impact system weight, communication, level of autonomy, and range requirement. These changes effect design and drive the need for modular adaptable platforms to keep cost low and mission flexibility high. To achieve this platform flexibility “a parameterized product line architecture can be used to capture system commonalities while expressing variabilities in physical characteristics such as navigation, collision avoidance, flight control, remote command and control, communication, and telemetry.” (Madni, 2012) . Madni explains the system should be reconfigurable dynamically, enabling swappable components without inducing failure modes.

The process of platform selection and final configuration would involve selection of an overarching concept of operations (CONOP) which involves specific mission profiles. Then a product line architecture (PLAS) is created which supports the various mission profiles, or a family of profiles. PLAS promotes reduced time to deployment, reduced cost, increased productivity, superior quality, simplified training, reduced logistics, increased competition, and leverage of human capital (Madni, 2012).

Fricke and Schulz (2005) detail that the changeability of a system is distinguished by four aspects: flexibility, adaptability, agility, and robustness. During the concept development phase trades can be performed between these aspects to gain design options or trade space to better align with operator requirements. Flexibility is defined as “the measure of how easily a system’s capabilities can be modified in response to external change.”(Ryan, Jacques, & Colombi, 2013) The first key components of this definition is the measure of ease, defined by Ryan (2010) as time or money. The second is capabilities, defined as “value assessment of the desired system characteristic” (Ryan et al., 2013). Values should align with system prioritized requirements.

Adaptability is defined as “the measure of how effectively a system can modify its own capabilities in response to change after it has been fielded” (Ryan et al., 2013). Critical to this definition is the measure of how effectively the system can modify itself. Agility is contrasted with adaptability, “the system’s ability to be change rapidly, where changes from external sources must be implemented to cope with changing environment” (Fricke & Schulz, 2005). Finally, robustness is “a systems ability to be insensitive towards changing environments, where intended functionality is delivered under varying operating conditions” (Fricke & Schulz, 2005). System design can influence the amount of robustness a system requires by defining the operational criteria or bounds early in the design process. Figure 9 summarizes the four aspects of changeability, showing that trades can be performed across the aspects to determine degree of changeability required and the degree of external change allowed.

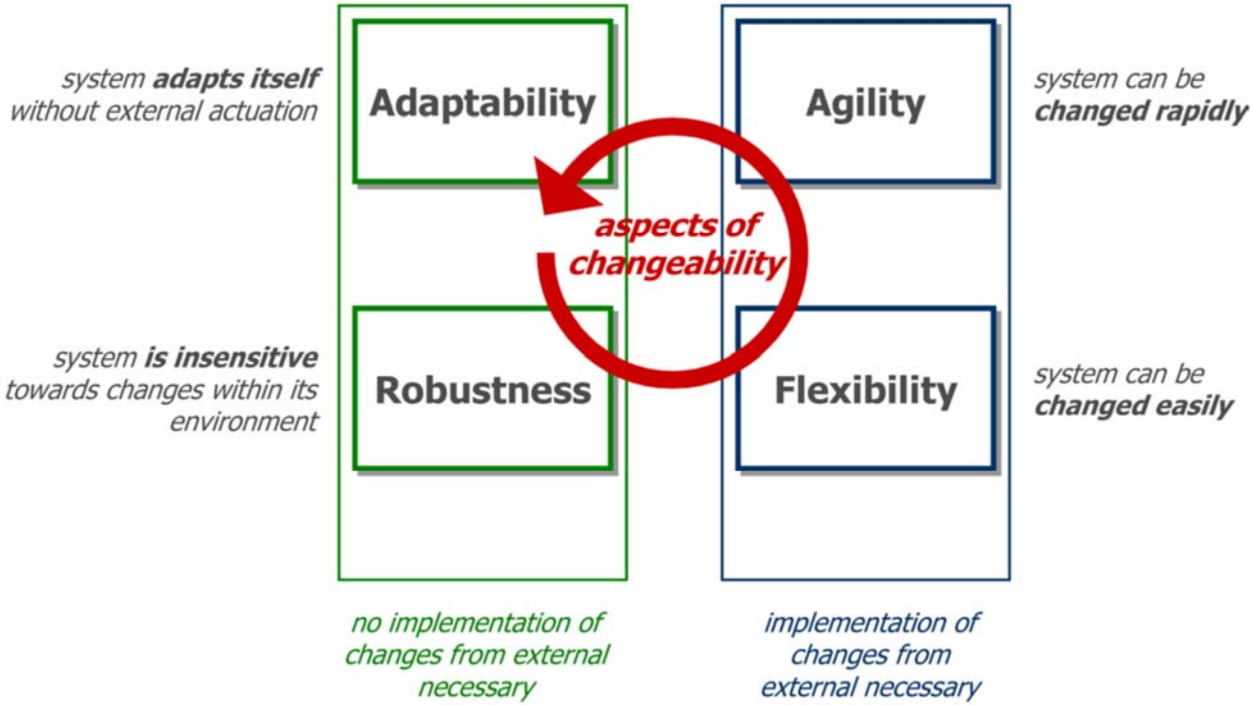


Figure 9. The Four Aspects of Changeability (Fricke & Schulz, 2005)

Another critical concept in SUAS design is modularity. “Modules are units in a larger system that are structurally independent of one another, but work together” (Baldwin & Clark, 2000). The SUAS’s frame is what provides an architecture to integrate modules to perform functions and task. Modularity can mitigate system complexity by isolating systems to modules which reliably perform their assigned tasks. Simple interfaces connect the modules together in a manner which reduces task loading to the operator. Current examples of modules within SUASs are propulsion system (motor and propeller pair), 4 in one electronic speed controllers, flight computer, payloads, and GPS.

Modularity for a system is managed by six module operators. These operators are implementation methods for design which enable functions of the system. The operators are: splitting or segmenting into modules, substituting modules, adding modules, excluding modules, creating new design rules, and connecting modules (Baldwin & Clark, 2000). Benefits of modularity in SUAS include: isolation of fault analysis to a component with proper characterization, multiple component swaps at a given time for a design cycle or mission plan, and flexibility for future tasks (Baldwin & Clark, 2000).

In additional to multiple functionality, SUASs have many target operators within the DoD. The target career field for SUASs include: Security Forces, Civil Engineering, Special Operations, Battlefield Airman, Firefighter, Office of Special Investigation, Intelligence, Combat Camera, and Weather (U.S. Air Force, 2016). These groups of warfighters will use SUASs in either duress or non-duress situations and in austere or non-austere locations.

A duress situation means the systems needs to be intuitive, rapidly deployable, and highly reliable. Increased complexity, measured in time to gain functionality, is undesirable due to the value weighting of the user’s time. Austere locations place emphasis on the characteristics of reliability, transportability, availability, ease of repair. Reliability can be allocated to individual parts or subsystem driving factors of how many spare parts are required, mean time to repair, and system design life. Furthermore, low reliability can stress the logistical system in austere locations causing systems to be inoperable if supplies are inadequate.

Transportability can be allocated to system weight, size, modularity, and durability. The system needs to be the right size and weight to be transported and then assembled at the location, while still performing its required mission. System design life must also be considered; is the system designed for 6 months or a year? If the system has a shorter lifespan have considerations been established for system resupply? If the system has a longer lifespan what is the repair plan like? These questions must be answered early in the design process to ensure functions correctly for the operator.

Summary

This literature review has documented findings that provide system engineering input for SUASs concept development. Focus was shown on developing critical system functions which are in alignment with mission profiles. The concept development process success is heavily dependent on identifying potential system faults and criticality of faults; these faults must then be traced and assigned to subsystems or components for documentation. Reliability provides a measure of probability the SUAS will perform a system function. The measurement of reliability is performed at the component level and assimilated to the system level for given functions, where increasing the number of components has a large effect on overall reliability. Documentation was provided by NIST on current methodologies employed on measuring SUAS reliability.

Multirotor SUASs provide excellent platforms for system modularity, specifically the number of motors/propellers and size. This enables agility and flexibility for the system for evolving mission sets and unintended future uses. Modularity also promotes traceable reliability to specific modules when coupled with fault analysis. When designing a SUAS, focus must be paid to the operational user, their background, and the environment they will face. The system must align with these characteristics to be useful tool. The better the match between the ease of use of the system and multiple functionality, the better the system will perform. The mission set is continuously evolving for SUASs and smart system design must be employed to harness new technology and push the bound of operational effectiveness for the warfighter.

The next section of this paper, Chapter III, will discuss the methods for performing a concept development for a SUAS. The chapter will outline how to define and appropriate reference missions. Then it will detail the system engineering methodology used for the analysis focusing on important aspects of design trades, critical faults, and functionality allocation. The method section will discuss reliability rating for component and system level parts and how they are found, measured, and documented.

III. Methods

Chapter Overview

The goal of this thesis is to provide a Small Unmanned Aerial System (SUAS) product development design template for military program offices, outputting critical SUAS components, operator checklists, reliability analysis, and a hazard matrix to aid in the development of a reliable SUAS that meets mission requirements. The product development process is split into two sections, Mission/System Alignment and System Design. Mission/System Alignment focuses on a generalized system engineering process to align stakeholder's initial design criteria with a reliable system design. This process develops operator checklists that mitigate critical faults, promoting reliable system performance in operational conditions. The second section, System Design, focuses on establishing trade space from developed requirements in the Mission/System Alignment section, and follows a system design process to output a SUAS design that meets established requirements. Both processes are meant to be repeatable and simplistic using SUAS components and architectures that are available commercially. The following chapter provides system engineering techniques and trades which enable the analysis to be performed in Chapter 4.

Theory

The system engineering process is used to establish a methodology and progress through a design analysis. Concepts include identification of stakeholder(s), development of a design reference mission, system requirements, functional allocation, fault tree analysis, reliability analysis, physical allocation, trade space analysis, and requirement analysis. The goal of the process is to define a system that meets, at a minimum, threshold requirement aligned with stakeholder definition.

Figure 10 shows the Initial DoD System Engineering Process on which the SUAS product design process was based. Process inputs involve customer or stakeholders needs, mission type, mission environment, available technology, and project constraints. The requirement analysis is used to translate customer requirements into functional and performance requirements that can be measured and documented. Functional analysis allocates down system functions to the lowest level and then maps those functions to documented requirements. This process allows the system designer to understand what the system is doing and how it is doing it, leading to selection and optimization of physical components. Design synthesis establishes a physical architecture based on information from the requirement analysis and functional analysis. Components must map to functions that then map to requirements, the process is iterative balancing requirements with a functional architecture and physical design. System analysis and control is used to measure the progress of the design alternatives against requirements. Inputs to this process occur at all points within the system engineering process. The system analysis ensures design impacts are measured, documented, traced, and evaluated providing critical information for final design selection (DAU, 2017).

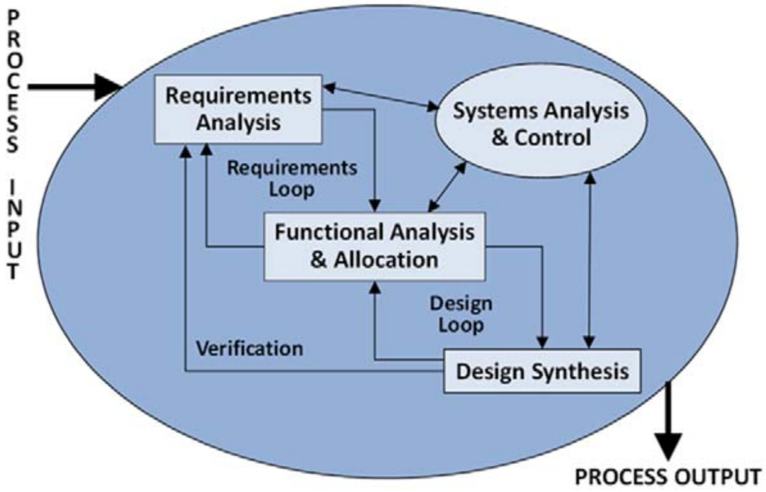


Figure 10. Initial DoD System Engineering Process Model (DAU, 2017)

Material and Equipment

Modeling was the primary tool for developing the system, performing component trades, and analyzing requirements. The system modeling tool used was Cameo Systems Modeler version 18.5. This tool enabled the building and augmentation of various system level views. Views documented include: System Functional Allocation, Physical Architecture, Internal Block Diagram, and Use Case. These views from Cameo Systems Modeler are presented in analysis section of this thesis. For predicting failure modes of the proposed SUAS architectures a free fault tree analyzer was used to document fault traceability to components (ALD, 2018). Microsoft Excel was leveraged to capture fault tree tables, document requirements, build operator checklists, establish design trades, and perform component reliability analysis. Focus was placed on using tools available to military program offices to ensure a repeatable and distributable process.

Procedures and Process

The overall system design process is outlined in Figure 11. The process is split into two sections. The first section is the Mission/System Alignment process which involves stakeholders and a program office working together to define the mission and requirements for the SUAS system, where the program office includes program managers and engineers. In this section, the critical functions are defined by the program office, these are functions that must be performed by the system to successfully complete the defined mission. Next, fault tree diagrams are used to map the critical functions to components and identify potential failures. Fault tree diagrams enable the program office and stakeholders to identify critical system components and to build operator checklists. The operator checklists mitigate system risk prior to mission deployment of the SUAS and ensure the most reliable in-flight performance. Program management tool outputs of this Mission/System Alignment are critical component reliability analysis and a hazard matrix which promote system reliability monitoring.

The second section is the System Design. This process is performed by the program office team once the design documents have been created. The design process involves building a system physical architecture, a design checklist, and establishment of a design trade space. These system level products provide an architecture, rule set, and trade space to select SUAS componentry. The component selection process is cyclical and requires constant evaluation of design trades and requirement evaluation. The system design process constrains componentry as the design is matured. Once the system is designed, system budgets are developed for frequency, weight, and power informing the requirements analysis process. Finally, the reliability analysis performed in the Mission/System Alignment section paired with the physical architecture provides input for a system reliability analysis. This process allows the program office and stakeholders to own the technical baseline for the SUAS system, providing critical system level architectures and analysis to inform future design decisions or design iterations.

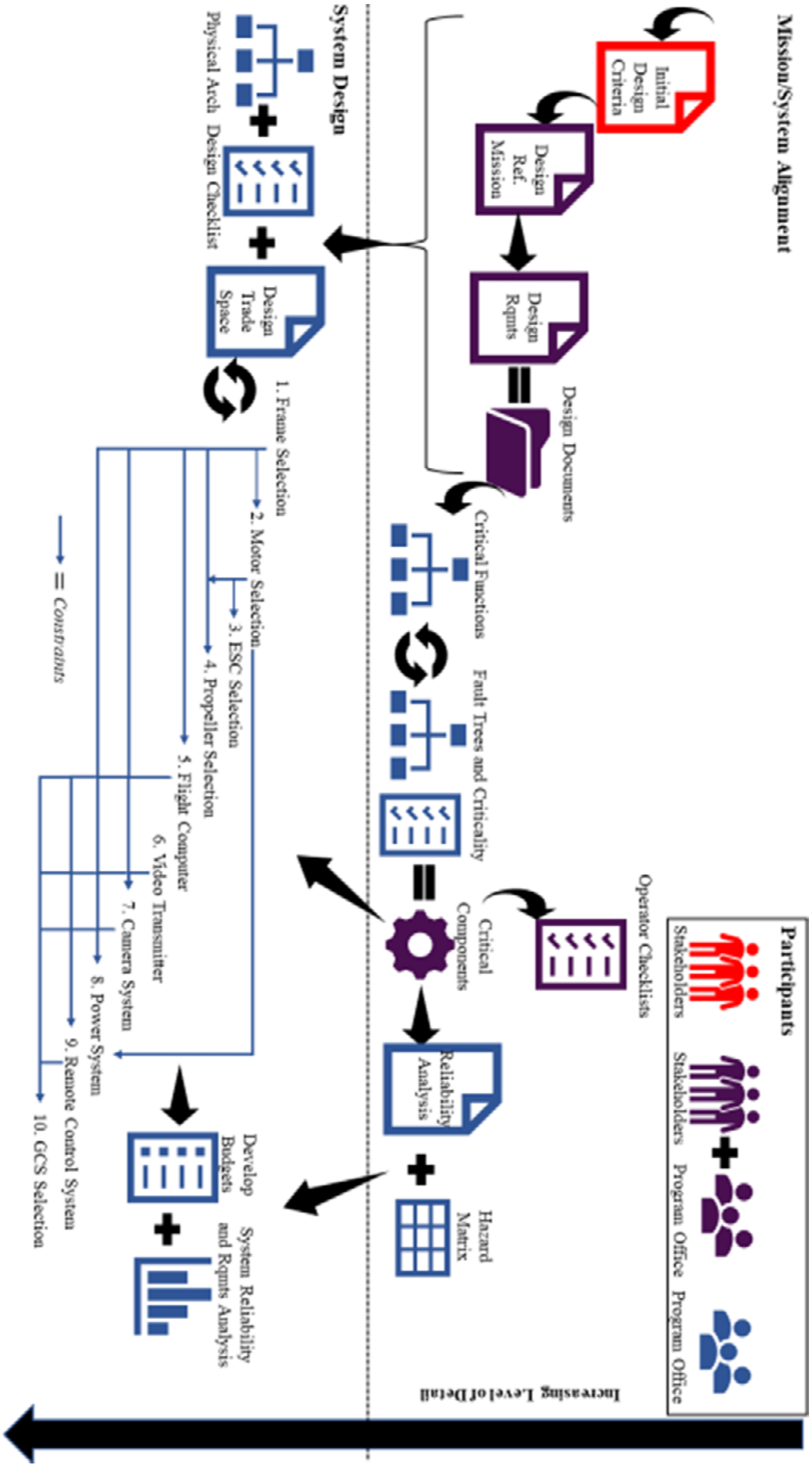


Figure 11. SUAS Product Development Process

Identify the Stakeholders

For the design process to be successful, the stakeholders of the system must be understood. The main stakeholders in this design process are the operators of the systems, as they have the most interaction with the system. For this design Special Forces operators are considered the main stakeholder. An interview was conducted with USAF 371st Special Operations Combat Training Squadron (SOCTS) Detachment 1, who performs user training for DoD special operators, security contractor personnel, and security forces on SUAS platforms. Initial design criteria discussed in this conversation included: low system weight, quick set up time, low audible signature, intuitive use, quick reparability. Section IV will operationalize these stakeholder requirements in more detail.

Define Design Reference Missions

The next step within the Mission/System Alignment section is to define reference missions for the SUAS to be designed to. The design reference mission evaluated within this paper is Information Superiority. This mission aligns the United States Air Force SUAS Flight Plan: 2016-2036 and is focused on collecting enemy video surveillance for force protection, offensive maneuvering, or general intelligence (U.S. Air Force, 2016). Design of the reference mission is performed by the stakeholders and the program office to ensure the operators and designers of the system are in complete alignment of mission priorities.

The reference mission defines an overall Concept of Operations (CONOPS) and operator use cases for the system. These products provide a medium to transfer operator and design team system mission definition into physical products. After these system documents are created, design requirements are established for the system to be evaluated against. Requirements must be specific, measurable, attainable, realistic, and time bound, allowing for a stable evaluation points for the designed system. Additionally, the performance requirements are defined at threshold and objective level. Threshold levels must be met for the system to perform the mission while objective levels are the desired capability from the stakeholder. Requirements are prioritized and aligned with stakeholder initial design criteria. This places emphasis on certain design points influencing important trades in the System Design process.

Critical Functions of the SUAS

After identifying the needs of the stakeholder and the mission set for the system, critical functions can be established. Functions are designed and diagrammed within Cameo Systems Modeler using a functional architecture model. Critical functions are defined as any function which must occur to provide use or functionality to the operator. Use or functionality of the system is then defined by the initial design criteria, the reference mission CONOPS, and requirements. Top-level critical functions include: flight, operator control, and payload capability. These functions must be all be realized by the system in order to provide use to the stakeholders.

Failure Modes

With critical functions identified, failure modes can be defined and listed which prevent the functions from occurring. Failure modes for SUASs were researched from hobbyist websites, technical reports, and case studies. Criticality of occurrence falls into three categories. Category I is an unrecoverable event, where SUAS system failure is imminent or repair time for the system to regain functionality is unacceptable to the user. Category II is a functionality degraded event, meaning the SUAS can perform system use cases albeit at a degraded level. Category III is a recoverable event, meaning the SUAS can be recovered and repaired within a time acceptable to a user. Fault tree diagrams and tables were developed to show traceability from a component to a critical function. Fault tree tables provide input to operator checklists, which the operator can complete prior to flight to mitigate system risk. These checklists promote a reliable system by eliminating operator, environmental, and component induced risks before flight.

Failure rates for critical components that induce category I events were researched. Components investigated were motors, propellers, battery elimination circuits (BEC), electronic speed controllers, lithium polymer batteries, flight computers, GPS, vehicle frames, cameras/sensors (ESC), electrical systems, and radio receivers/transmitters. Failure rates were documented as field events, researched events, or subject matter expert event. Failure rates are listed as failures per hour and are static probabilities, assumed to be within the constant failure rate of the bath tub curve (defined in Chapter IV). The assumption ignores infant mortality or early component wear out, stressing that either the manufacture of the component or the user, tests the components prior to system integration. Corresponding component reliabilities can be aggregated for subsystems and evaluated in the physical architecture and integrated block diagram steps for an overall system reliability. A hazard matrix was built combining the failure rates of a component and the category of event to the system. The hazard matrix aids the program office in making decisions that mitigate risks to critical system components.

Generate Checklists

Fault tree diagrams and tables provide insight into the failures for the SUAS system. From these insights, operator checklists were developed to mitigate failures prior to mission deployment. The checklists developed were a pre-flight checklist, a pre-deployment checklist, an initial flight checklist, and a spares checklist. The pre-flight checklist is designed to be performed at the deployment location before any flight; the checklist items requires a low time commitment from the operator. The pre-deployment checklist is performed prior to forward deployment at a secure location and requires a medium time commitment from the operator. The initial flight checklist is performed in a controlled environment when the baseline configuration of the SUAS is altered. This checklist requires a high time commitment from the operator with the design team's assistance. The spares checklist is a recommended deployment kit to have if additional transport weight is permitted. It is focused on providing replacement for components which induce category I events.

Physical Architecture

The System Design process starts with creating a design checklist to inform the physical architecture of the system. The design checklist provides a ruleset on components for the program office to design the system in accordance with. This checklist is the most general of the physical architecture products and provides best practices for designing multirotor SUASs. It captures rules from the authors experience, online drone blogs, and members within AFIT's Autonomous Navigation and Technology (ANT) Lab.

The next product developed is the physical architecture. This diagram is built with Cameo Systems Modeler and shows how the components within the SUAS connect and interact with each other. The architecture provides a framework for the program office to identify critical interaction and trades to increase system alignment with the requirements. The physical architecture is meant to be modified throughout the system design process, as trades are identified. A more specific view of the physical architecture is the internal block diagram (IBD). This view identifies system ports which connect components, shows how information is transferred within the system, and identifies central system nodes. The view provides valuable insight into how design trades can be implemented and the potential impact to the system.

Evaluating both the design checklist and physical architecture views against the design documents reveals design trade space. The design trade space identifies architecture, configuration, or component trades which the system designer can implement to increase certain performance aspects of the system while decreasing others. As the program office progresses through the system design process, they can go back to the design trade space to boost performance areas that are below requirement threshold values. Each time a trade is accepted the design team must ensure the physical architecture models are updated. This process is complete when “builder thinks the system can be built to the client’s satisfaction” (Maier & Rechtin, 2009).

Component Selection

With the system architecture established components are then selected to fill the architecture. Components that impact the architecture the most are selected first. Each successful component selection constrains follow on component categories and may constrain none, one, or many other component categories. The component selection process benefits from identification of critical components completed in the Mission/System Alignment phase, as special attention is paid to components that have the highest impact on failure modes. Importance is placed on selecting components with trusted reputation among the commercial drone industry and components that provide detail specification and test data for follow on analysis. As the program office moves through the component selection process the overall system is refined and the design trade space shrinks. Components evaluated for the multirotor SUAS are frames, motors, ESCs, propellers, flight computers, video transmitters, camera systems, power systems, remote control systems, and ground control station (GCS).

Develop Budgets

With the components selected for the SUAS, budgets for weight, frequency, and power are developed. The weight budget is important for transportation limits established within the design requirement. The weight also is an important input to endurance calculations for the designed system. The frequency budget ensures the remote control, flight computer, and video transmitter systems are allocated within individual frequency bands, preventing command and control errors within flight. The power budget determines the current draw (mA) and voltage range (V) required for the system. Power levels determine the number and type of BECs required for the system along with non-motor power demands of the system or auxiliary power draw. The power budget also provides input into endurance calculations.

System Reliability

With the physical components selected and budgets established a reliability analysis is then performed. Failure rates researched for critical components performed in the Mission/System Alignment section are identified in the physical architecture, creating a reliability block diagram for the SUAS system. For ease of calculations, the reliability block diagrams are broken into subsystems based on critical functions. System components are either in series or parallel configuration based on established requirements. Series configuration allows for a lower system weight but puts the system at risk for a single point of failure. Parallel configuration adds in redundancy for the system at the cost of higher weight and overall complexity. Outputs of the reliability analysis are critical subsystem reliabilities, overall system reliability, system mean time to failure (MTTF), and probability to complete operational the mission.

Requirements Analysis

The final step of the System Design process is to perform a requirements analysis. The designed system is evaluated against requirements established in the Mission System/Alignment phase. The analysis proceeds through each requirement and projects how the design system will meet or fail to meet threshold and object values. Information for the analysis is collected from component manufacturing specifications, online websites/blogs, and subject matter expert input. Engineering calculations are required for certain requirements like flight endurance, image pixel density, and video latency. If certain requirements are unable to be met by the current design, the program office must revisit sections in the system design process to improve the design. If program office personnel and the stakeholders approve the requirement analysis, the design can move into production and system testing. This allows for the theoretical values of the requirements analysis to be proven out by the system.

Conclusion

This section has outlined a product development process for a SUAS to be designed to a specific reference mission and was detailed in two sections: Mission/System Alignment and System Design. Mission/System Alignment focuses on mapping design criteria established by system stakeholder to critical functions of the system. Critical functions of the system lend to fault trees being established that help identify critical components and failure mode criticality. The main output of this process is operator-based checklists, designed to mitigate risk to the SUAS before flight. With user and environmental errors mitigated before flight, the system reliability can be attributed to critical components that perform critical functions. These failure rates for such components have been researched and documented in Chapter IV. System Design focuses on establishing trade space from developed requirements in the Mission/System

Alignment and following a system design process to output a specific system that meets established requirements. This product development process is repeatable for any type of SUAS mission, establishing a tool that can be used by program office to build reliable SUAS for specific mission sets.

IV. Analysis

Chapter Overview

This chapter discusses the implementation of the SUAS product development process established in Chapter III. The overall product development process is show in Figure 11. Each section of this chapter starts with a zoomed in figure of the step being addressed within the process. Steps within the process are color coded according to participant involvement, red involves stakeholders, purple involves stakeholders and the program office, and blue involves the program office only. The product development process is split into two sections, Mission/System Alignment and System Design. Mission/System Alignment focuses on a generalized system engineering process to align stakeholder's initial design criteria with a reliable system design. This process develops operator checklists that mitigate critical faults, promoting reliable system performance in operational conditions. The second section, System Design, establishes trade space from developed requirements in the Mission/System Alignment section and follows a system design process to output a specific system that meets established requirements. The following chapter progresses through the SUAS product development process for an Information Superiority mission focused on collecting enemy video surveillance for force protection, offensive maneuvering, or general intelligence.

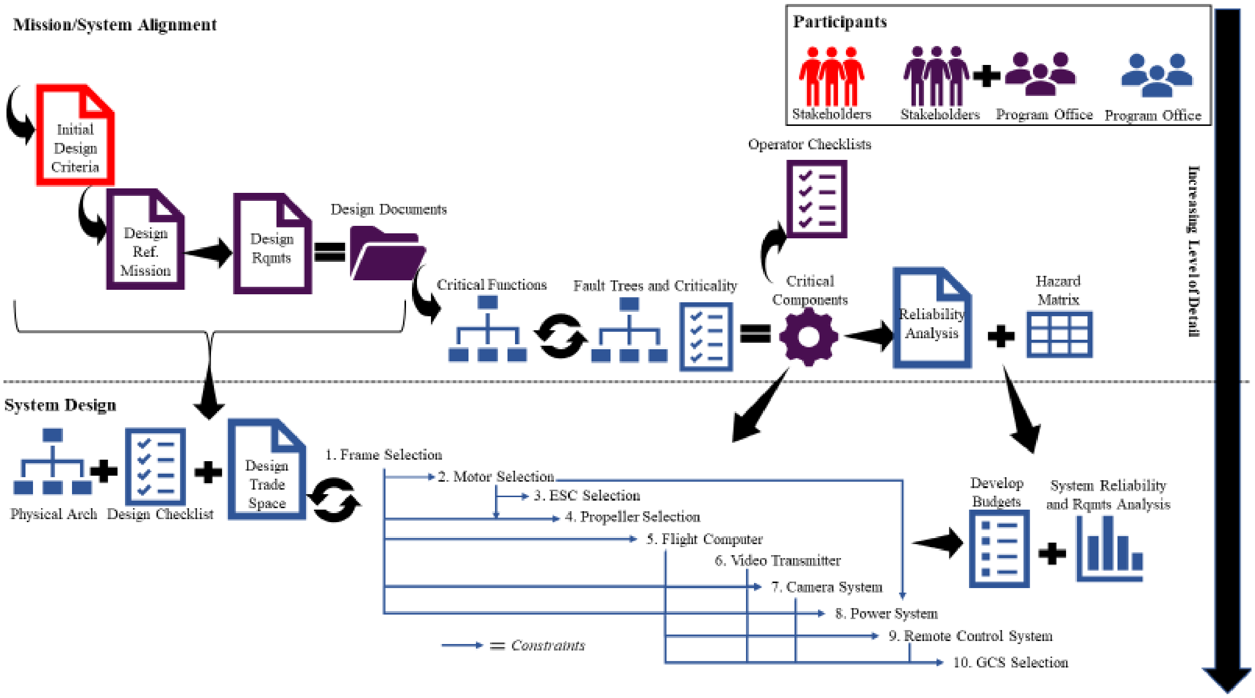


Figure 11. SUAS Product Development Process

Mission/System Alignment

Identify the Stakeholders

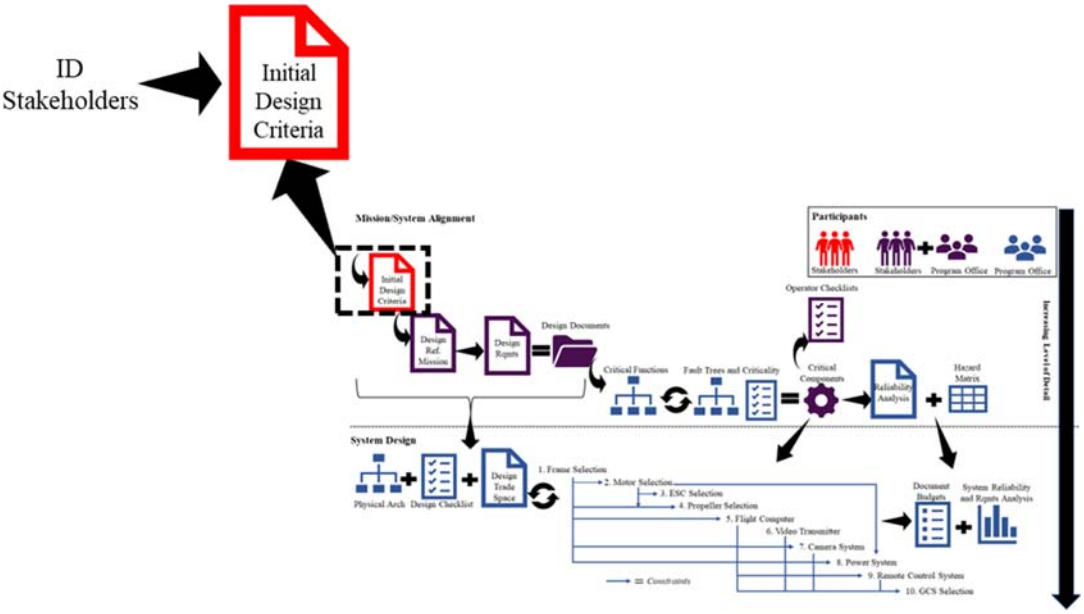


Figure 12. Initial Design Criteria section of Mission/System Alignment

USAF 371st Special Operations Combat Training Squadron (SOCTS) Detachment 1 performs user training for DoD special operators, security contractor personnel, and security forces on SUAS platforms. In an interview performed August 2018 with Detachment 1, system desires for SUAS platforms were discussed. The conversation started with asking for recommendations for the design methodology for SUASs specifically for special operator's use. It was stated that the current methodology of treating SUAS as aircraft focusing on airworthiness for long hours is flawed since SUAS are orders of magnitude lighter and cheaper than traditional aircraft. SUAS's should instead be treated as tools. A tool focus allows for intuitive and reliable design focused on very specific functions allowing for simple solutions to solve a mission need. Furthermore, teams need to move away from dedicating one to two SUAS operators and embrace the flexibility of all members performing SUAS operations. With his methodology stated operator design requirements for a SUAS system were then discussed.

The first design requirement discussed was simplicity; special operators desire a system that can be unpacked, assembled, and launched in a matter of minutes and operated with limited initial training. Detachment 1 stated that there is a desire for the baseline military SUASs to be as complicated as commercial off the shelf (COTs) drones, where the system is designed for an average consumer and is flown within hours of purchase. This would allow 371st SOCTS to focus on training the functionality of the system, including enhanced sensors, user interfaces, software modules, etc.

The next design requirement detailed was the overall utility of the system. Utility of the system must outweigh the detriments the system places on the operational user, specifically, pack weight, setup time, and user involvement. This relationship drives a design which performs a few functions well while minimizing user detriments.

Another design requirement discussed was user dependency. Special operators do not want to be overly reliant on a system. Over reliance can manifest itself in the form of interfacing with the system reducing environmental situational awareness, recovery of the SUAS in order to continue mission, and destruction of the SUAS to prevent enemy intelligence gathering. The special operators should be able to continue and succeed with a degraded or destructed SUAS.

The final requirement discussed was betrayal. It was stated that the system shall prevent betrayal of the special operation team, where the system mitigates detection by the enemy and protects the operator. Prevention of betrayal includes a low audible signature, intelligence preservation, and safe operations. The discussion above drove the initial design criteria, which must be considered for a successful design.

1. **Simplicity**: the number of parts the operator must interact with to operate or repair the system should be low and intuitive. The user interface to control the system shall have critical functions only and be intuitive. Time is the operator’s most valuable resource.
2. **Utility**: Design focus shall be placed on performing one or two functions maximizing reliability. A system that performs a large amount of functions at the expense of the operator’s time, situational awareness, or mobility is valued lower than a system which performs a few functions timely, simply, and lightly.
3. **Dependency**: Functions which are critical to mission success shall be able to be repaired quickly. Recovery of the system needs to be optional due to increase threat presence. Burden placed on the user from the system shall be minimized including recovery, operation, setup, transport, deployment, and information transfer.
4. **Betrayal**: The system shall prevent betrayal to the special operations team. Mitigations shall be integrated into the system to reduce noise footprint, intelligence preservation,

rapid deploy and stow, and safe handling. If the system promotes increased risk to the user, it reduces usefulness.

Define Design Reference Missions

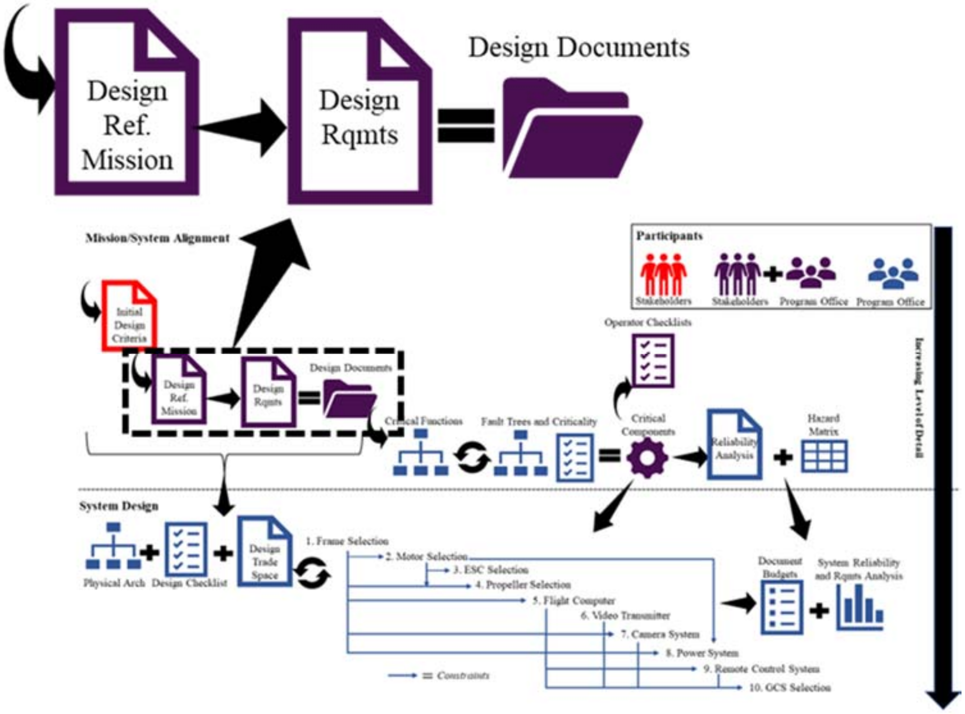


Figure 13. Design Document Process

The mission selected for this analysis is Information Superiority or Intelligence, Surveillance and Reconnaissance (ISR). In this mission a SUAS provides forward deployed ground-based units the capability to conduct low altitude, ISR and human and vehicle tracking operations from a safe standoff distance with minimal logistical support. Specifically, the use of the SUAS will allow operators to:

- Rapidly setup and deploy SUAS from austere location
- Covertly loiter over a desired target area, providing uninterrupted, or near-continuous video coverage over a target for a 30-minute interval
- Continuously track a moving human or vehicle within operating range
- Utilize payloads optimized for low altitude operations capable of providing sufficient resolution for target identification

- Monitor ISR data from safe standoff distance
- Conduct Small UAS operations while maintaining situational awareness of the location around the operator
- Provide timely ISR data for ongoing/future ground operations

Figure 14 displays a SysML use case diagram created in Cameo Systems Modeler, showing the set of actions or use cases the system will perform in conjunction with external users or actors of the system. The system is only in one use case at a time but can transfer across cases. In the ISR mission the use cases and actors are the following:

Actors: Operator, Target, Ground Control Station, GPS

- Perform Setup: The operator secures the launch location, unpacks the SUAS and required equipment. The operator assembles any required parts and perform setup checklist.
- Plan Mission: Included within the Perform Setup use case is the Plan Mission use case. The operator programs the ground control station with desired mission points and writes them to the SUAS flight computer. Plan mission is also included in the Loiter, Launch and Ingress, Acquire Target, and Perform Setup use cases. Where an include relationship is defined as "having some partial behavior that is common across several use cases." (Larman, 2006)
- Launch and Ingress: Operator confirms GPS lock is acquired if required for mission. Then the operator commands the SUAS to move to the first mission point.
- Loiter: This is the default case if the SUAS is not acquiring a target, performing surveillance, performing ingress or egress. The SUAS loiters and transmits video at a preprogramed altitude and awaits commands for the operator.
- Acquire Target: The operator identifies target through the ground control station and commands the SUAS to follow the target and perform surveillance.
- Perform Surveillance: The SUAS streams video back to the operator of the target. The SUAS follows the target as it moves within its operating radius.
- Egress and Recover: SUAS is commanded by operator to return to base or land at coordinate points. Failsafe mode of auto land or return to base if battery is below 5% is programed during Plan Mission phase.
- Ditch: SUAS can be ditched at any time during an in-flight mission, preventing betrayal to special operators. Ditch mode can be induced by the operator or pre-programed failsafe.

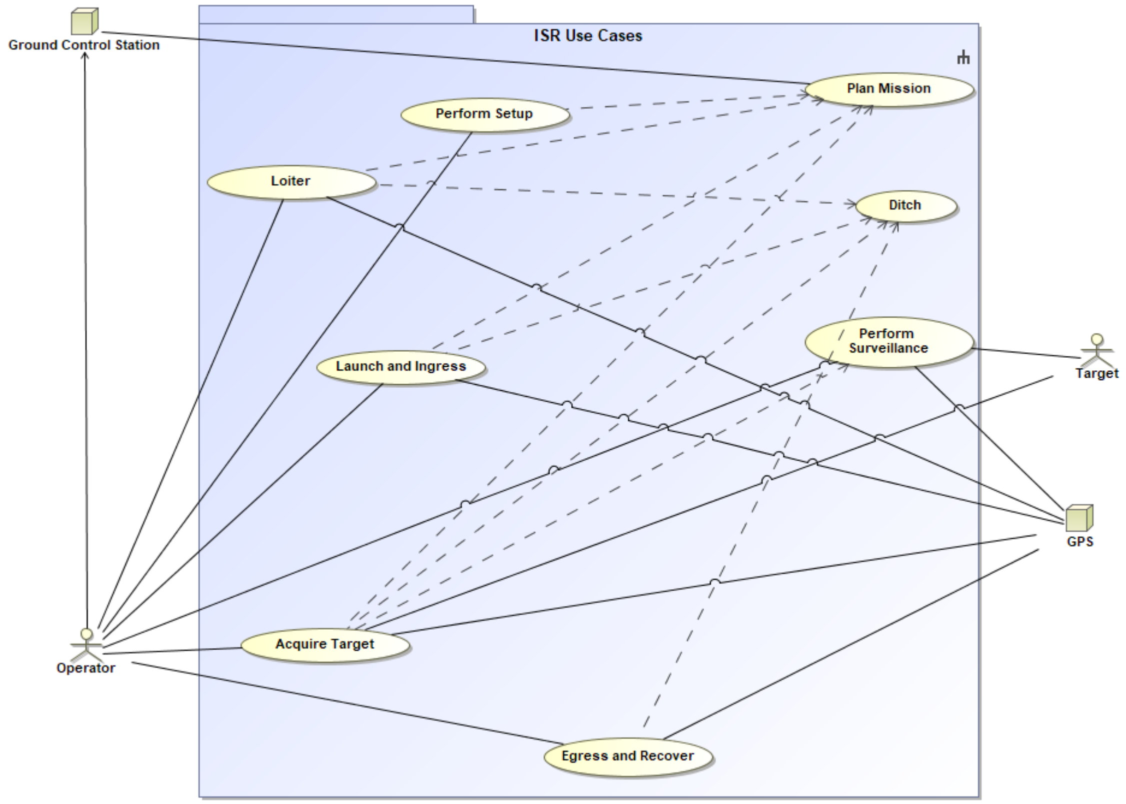


Figure 14. ISR Use Case Diagram

The next step of defining a design reference mission is to establish and prioritize requirements for the system to be designed to. Requirements have objective and threshold values for the system. Objective requirements are desires or performance goals for the system to meet. Threshold requirements must be met for the system to provide use to the operational user. The space between objective and threshold requirements establishes design space for system trades. Requirements should be established with input from the operational user, but the system designer must ensure the requirements are specific, measurable, attainable, realistic, and time-related. The design criteria defined by the operational user aids in prioritization of requirements. In the case of the ISR system the user desires a system that is simple to use and set up, keeps them safe, performs ISR reliably, and operates independently. In prioritizing requirements, the user's perspective must be kept in mind. Since this system will be used by special operator in a contested environment, time equates to life or death. In turn, from a system designer perspective emphasis must be placed on those requirements that, if unmet, will force the user to abandon the system.

Table 2 shows example ISR requirements with threshold and objective values. Requirements were established and expounded from the AFIT SUAS design sequence, reference CONOPS, which is provided in Appendix C. Each requirement is prioritized with a descending priority. The first ten prioritized requirements are influence by the user's design criteria of simplicity, utility, dependency, or betrayal. Failure of meeting these ten requirements would immediately prevent the user from using the system due to a mission safety concern. Therefore, in designing the system these requirements must be considered first.

Table 2. ISR Design Requirements

Requirement	Description	Objective	Threshold	Priority Level	Design Criteria
ISR-1	Setup of system from unpacking to ready for launch shall be	5 min	10 min	2	Simplicity
ISR-2	Mission planning time from coordinates provided to operator to ready for launch	5 min	10 min	3	Simplicity
ISR-3	Operators required for setup	1	2	5	Dependency
ISR-4	System shall have a range from deployment location of	2 miles	1 mile	11	
ISR-5	System shall provide resolution for tracking a vehicle		30 pixels/m^2	7	Utility
ISR-6	System shall loiter over the target and provide 10 minutes video of target for	100% of time	85% of time	8	Utility
ISR-7	System shall transmit geo-location to		15 ft	17	
ISR-8	System shall require dedicated operators for control and operations	1	2	6	Dependency
ISR-9	Operator shall be able to identify ground targets while controlling vehicle		X	10	Utility
ISR-10	System shall display near real time imagery to the operator(s)	2 sec delay	5 sec delay	12	
ISR-11	Operators required for recovery, landing, and retrieval of the system	0	1	18	
ISR-12	Endurance of the system while transferring video shall be	60 minutes	45 minutes	9	Utility
ISR-13	System shall perform "return launch" if communication is lost with operator		X	15	
ISR-14	System shall indicate to operator if GPS is lost and allow for manual recovery mode		X	14	
ISR-15	System shall provide status of battery to operator		X	13	
ISR-16	System altitude shall be greater than 100 ft except at launch and recovery		X	19	
ISR-17	System shall have the capability swapping in a night capable camera of 0.001 LUX or lower	X		16	
ISR-18	System shall have a low noise profile of 50 db or lower at minimum safe flight altitude		X	4	Betrayal
ISR-19	Air vehicle shall weigh less than 5kg and be packable in 2 standard ruck sacks 22" X 14" X 9"		X	1	Utility

Critical Functions of the SUAS

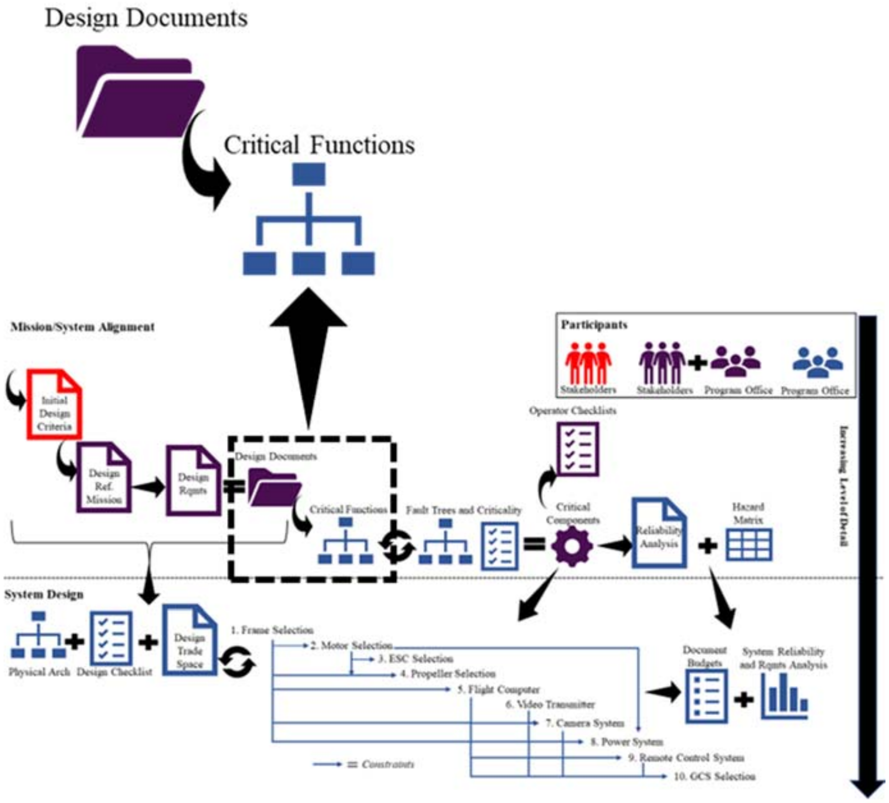


Figure 15. Critical Function Process

Critical functions are defined as functions that must be performed for the SUAS to provide capability to the operator. At the top level these functions are: Flight, Transport, Power, Control, and Surveillance. If any of these functions are unable to be performed, then the entire system is unusable for the operator. Figure 16 displays the functional allocation of the SUAS system. The critical functions are broken down into different levels, with lower level functions enabling the top-level functions. For example, the top-level function of flight is enabled by generate lift, provide stability, launch, and recover. If one or more lower level functions are unrealized for the system, then the top-level function is either unrealized or degraded.

Functions colored green shown in Figure 16, are functions that attribute degraded performance to top level functions if unrealized, while functions in light orange force the top-level functions to be unrealized. In the instance of the top-level function of flight, when recovery is unrealized then flight is degraded, meaning the function still has use to the operator. Conversely, if generate lift is unrealized so too is flight and therefore the system unable to provide capability to the operator. System design will focus on preventing failures for the lower level orange functions or critical functions. Descriptions of each function are described in Table 3.

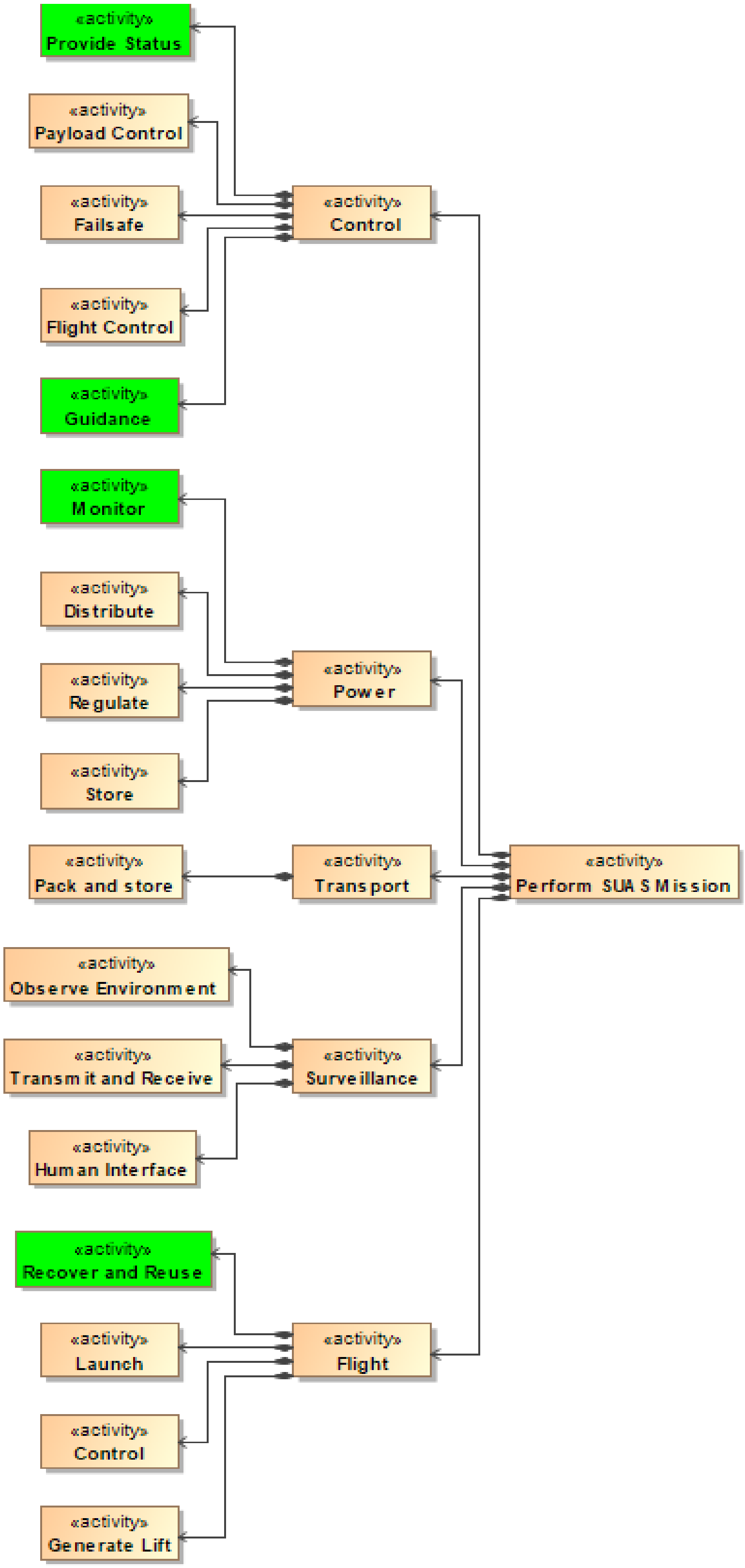


Figure 16. Functional Allocation of ISR SUAS System

Table 3. Functional Description of ISR SUAS System

Top Tier Function	Second Tier Function	Description	Critical
Flight	Generate Lift	SUAS shall create lift for a vantage point to enable increased situational awareness for the operator.	X
	Provide Stability	SUAS shall remain stable while airborne enabling controlled flight for the operator.	X
	Launch	SUAS shall be commanded to launch by the operator and transition from launch to flight.	X
	Recover and Reuse	SUAS shall be commanded to recover by operator and transition from flight to recovery/landing.	
Transport	Pack and Store	SUAS shall be man packable for transport. SUAS shall be assembled and disassembled from the stored state and prepared for launch by operator.	X
Power	Monitor	Operator shall be able to monitor the power levels of the SUAS while in flight.	
	Distribute	SUAS shall distribute power to components.	X
	Regulate	SUAS shall regulate required voltage levels to components	X
	Store	SUAS shall store energy on board the aircraft.	X
Surveillance	Observe Environment	SUAS requires sensor to visually observe the environment.	X
	Transmit and Receive	SUAS shall transmit sensor data down to the operator.	X
	Human Interface	Operator shall be able to process and record data from the sensor including: GPS coordinates, target type, speed, etc.	
Control	Payload Control	Operator shall have control over functions within the payload i.e. movement, zoom, filter.	X
	Flight Control	Operator shall have control over flight of the SUAS.	X
	Failsafe	SUAS shall have a failsafe programmed if control is lost from the operator. Failsafe’s include return to launch point, auto land, or self-destruct.	X
	Guidance	SUAS shall have GPS guidance system for semi-autonomous flight.	
	Provide Status	Operator shall receive status from the SUAS including air speed, altitude, heading, and current flight mode.	

Fault Tree Analysis

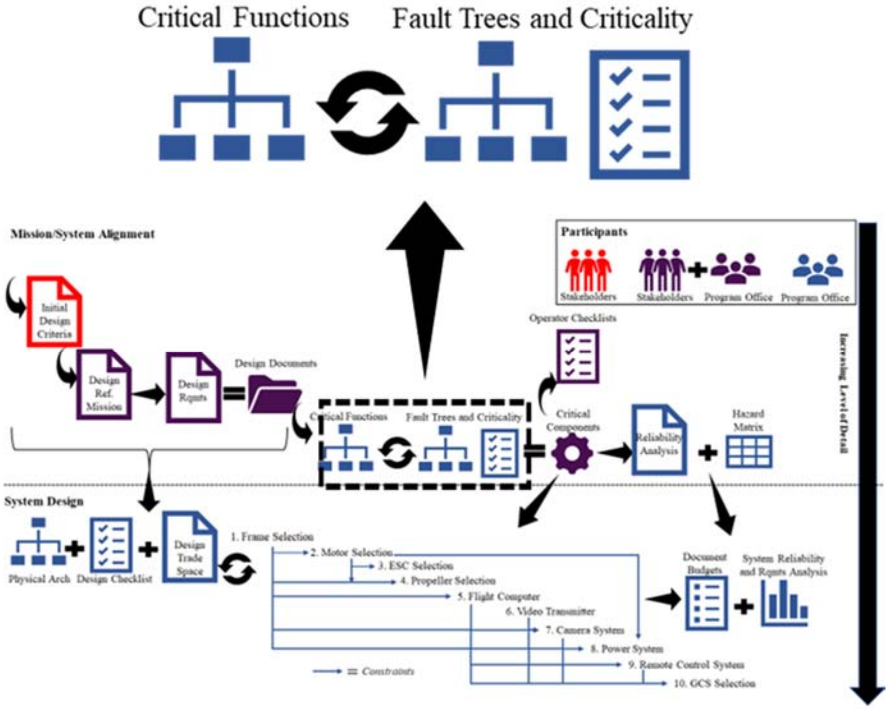


Figure 17. Failure Mode Analysis

Critical functions of the SUAS were then placed into Fault Tree Analysis diagrams enabling the following benefits to the conceptual design process (Schenkelberg, 2018):

- Identification of failures deductively through sequencing of events
- Highlighting important elements of the system in relation to system failure
- Establishing figures for system analysis
- Evaluating failure modes one at a time
- Revealing system behavior and interactions

Failures are attributed to system components and assigned categories. Three categories were established which measure the impact or criticality to the overall system if the failure occurs. Category I is an unrecoverable event, meaning the SUAS can no longer be flown with system failure imminent. Repair time for the system to regain functionality is too high for the operator to accept. The amount of time is dependent on operational conditions; in a contested environment the allowable repair time will be lower than in a non-contested environment. Category II is a functionality degraded event, meaning the SUAS can perform system use cases, albeit at a degraded level. Category III is a recoverable event; repair time required is within tolerance for the operator. From an operator's perspective, category I events end the mission for the SUAS and must be prevented. Category II events may be tolerated by the operator depending on the system degradation. For example, an intolerable event would include a gain tuning failure for stable flight control between the ground control station and flight computer which degrades flight control to the point that stable video is unable to be viewed at threshold level of 85% loiter time. An example of a tolerable event would be if the remote-control feature of the air vehicle failed but the autopilot mode still functioned. Category III events may be resolved by the system itself or with assistance from the operator via recovery, or transmitted command. For mitigated impact to the operator, time is evaluated. An example would be a GPS failure due to environmental effects which resolves by flying the aircraft away from the degraded region within an acceptable time based on operational conditions. Category III events can elevate to category II or I events if left unmitigated. For purposes of this analysis category I failure prevention is focused on first, followed by categories II and III.

Fault tree diagrams for each critical function are located in Appendix A. Probabilities for specified failures within components are set to 0 as a placeholder since data exist for only component failures and not specified events. Table 4 through Table 20, display the fault tree diagrams in table form. The tables display the criticality of the failure, the failure, and if the failure is a checklist item. An X mark in the checklist item column indicates a majority of the system risk can be mitigated by a low time commitment inspection or test. A / mark means a larger time commitment is required to mitigate risk. For example, in the Generate Lift Fault Tree

Table, Table 4, the poor attachment failure, attributed to the motor component, can be mitigated by a physical inspection of the motor attachment before flight, denoted by an X. The large propeller failure, attributed to the motor component, requires detailed motor propeller testing to reveal any overheating issues that may arise, denoted by a /. This test requires a longer time commitment and analysis opposed to simply checking a motor attachment.

The generate lift fault tree table, part of the flight functionality, is shown in Table 4. Generating lift requires nominal performance from motors, propellers, ESCs, and the flight computer. Design redundancy in motors, propellers, and ESCs can reduce the criticality of a component failure from I to II. A design implementation of this redundancy is a hexarotor or 6 motor system. This design can tolerate a failure in up to two motors, ESCs, and/or propellers and still achieve flight, albeit degraded. Conversely, a quad rotor system can only perform flight with all motors, ESCs, and propellers functioning nominally.

Table 4. Flight: Generate Lift Fault Tree Table

Criticality	Component	Failure Level 1	Failure Level 2	Checklist Item
I: if Four motors or less else II	Motor Failure	Faulty Wiring		X
		Manufacturing Defect		
		Poor Attachment		X
		Overheating	Large Propeller	/
			Frame Vibrations	/
			Poor Center of Gravity	/
			Long Mounting Screws	X
			Level	X
			Environment	/
		Life Span		/
		Failed Bearing		/
		Infant Mortality		/
I: if Four motors or less else II	ESC Failure	Surge of Current		
		Manufacturing Defect		/
		Infant Mortality		
I: if Four motors or less else II	Propeller Failure	Contact with Equipment		X
		Improper Mounting		X
		Damage from Contact		X
I	Flight Computer Failure	Infant Mortality		
		Manufacturing Defect		/
		Life Span		/
		Environment		/
		Surge of Current		

The provide stability fault tree table, part of the flight functionality, is shown in Table 5. Frame failure is a criticality value of I, as any large change in frame structural support will induce flight failure. A propeller component failure in the form of a wrong propeller direction is a criticality of III, since the air vehicle will not takeoff and requires little time to fix. All other component failure modes can range in criticality from I-III. The level of criticality is largely dependent on the operator’s familiarity with the system, the ability to recognize irregularities, and the level of the error. An example of this is a center of gravity imbalance, if the air vehicle takeoffs, an experience operator will recognize and issue and land the air vehicle immediately. Although if the level of center of gravity issue is high or the operator in inexperienced, the air vehicle will take off and immediately crash. Many of these issues can be mitigated by pre-flight checklists.

Table 5. Flight: Provide Stability Fault Tree Table

Criticality	Component	Failure Level 1	Checklist Item
I	Frame Failure	Over Flexibility	X
		Crack Propagation	/
		Loose Fasteners	X
I-III	Center of Gravity	Baseline	X
		Payload Modularity	X
		Frame Level	X
		Shift in Flight	
III	Propeller	Wrong Prop Direction	X
I-III	Motor Mount	Poor Mounting	X
I-III	Flight Computer	Poor Gain Tuning	/
I-III	ESC	Wrong Mode	X
I-III	Payload	Excess Weight	X
I-III	N/A	Environment	/

The launch fault tree table, part of the flight functionality, is shown in Table 6. Operator failures within the table benefit from a well-trained operator on the representative system and a checklist. Training combined with pre-flight checklists enables the operator to identify irregularities in the system and component, preventing criticality level I failures. Environmental effects and assembly errors can be mitigated by checklists and training but require operator experience. Component level errors and auto takeoff are attributed to failures within components and software.

Table 6. Flight: Launch Fault Tree Table

Criticality	Component	Failure Level 1	Checklist Item
I-III	Operator	Error in Assembly	/
		Collision	
		Setup	X
		Flight Error	
I-III	Various	Component Error	
I-III	Flight Computer	Auto Takeoff Error	
I-III	N/A	Environment	/

The recover and reuse fault tree table, part of the flight functionality, is shown in Table 7. The criticality of failures are all level I since the if they occur the mission is ended, as the aircraft is no longer airborne and/or is unable to be reused. These failures are acceptable if the operator has completed the mission to satisfaction, or if the mission requires termination due to a threat. Emphasis in recover and reuse is the prevention of betrayal. The system shall not reveal the operator's location or provide intelligence to an adversary.

Table 7. Flight: Recover and Reuse Fault Tree Table

Criticality	Component	Failure Level 1	Checklist Item
I	Various: Destructive Crash	Battery Depletion	X
		Collision	
		Ditch	/
		Environment	
I	Operator	Operational Decision	
		Ground Effects	/
I	Frame	Frame Failure	/
I	Flight Computer	Flight Comp Failure	/
I	Sensor	Sensor Failure	/
I	Landing Gear	Landing Gear Failure	/
I	Various	No Spares	/

The pack and store fault tree table, part of the transport functionality, is shown in Table 8. Transporting the SUAS at an appropriate weight to the field is critical to use the system.

Damaged components due to transport can be replaced in most cases with a dedicated spares kit but in extreme conditions the vehicle may be unrepairable. System design should allocate weight and space for required spares, if possible. The SUAS should be packaged in a manner that allows for deployment in a timely manner based on mission, preventing system betrayal to the user.

Table 8. Transport: Pack and Store Fault Tree Table

Criticality	Component	Failure Level 1	Checklist Item
I	Rucksack/SUAS	Unable to Breakdown	X
		Unable to Configure	X
		Excess Weight	X
I-III	Various	Damaged Components	
II	Various	Fail to Deploy in Time	X
I-III	Various	Damaged Support Equipment	
II	Various	Inability for Spares	X

The monitor fault tree table, part of the power functionality, is shown in Table 9. Monitoring the battery information is a critical piece of information for the operator in determining mission duration. Dependent on system architecture, the battery information can be collected by the sensor and/or flight computer. This information is then passed through transmitters on the SUAS to the receiver on the GCS for the user to view. Monitoring the battery levels is level II criticality since the mission can continue at a degraded state without the information. In this case more risk is placed on operator awareness to know the endurance limitations of the system.

Table 9. Power: Monitor Fault Tree Table

Criticality	Component	Failure Level 1	Checklist Item
II: If redundant or failsafes	Transmitter/ Receiver	Out of Range	/
		Signal Noise	
		Wrong pairing	X
		Faulty	/
II: If redundant or failsafes	Flight Computer	Faulty Wiring	/
		Bad Data	
		Incorrect Wiring	/
II: If redundant or failsafes	Sensor	Faulty Wiring	/
		Bad Data	
		Incorrect Wiring	/
I	Battery	Depleted	/

The distribute fault tree table, part of the power functionality, is shown in Table 10. The SUAS must provide power to enable critical functions. If the battery is depleted the mission will end, and in most cases will induce a fatal crash of the SUAS. A wiring and circuit fault can range in criticality. This criticality is dependent on the operator recognizing the issue and mitigating it as soon as possible. Pre-flight checklists are focused at mitigating these two failures while the vehicle is on the ground before flight. Once airborne, these failures are more likely to induce level I or II criticality.

Table 10. Power: Distribute Fault Tree Table

Criticality	Component	Failure Level 1	Checklist Item
I	Battery	Depleted	X
I-III	Wiring	Faulty	
		Incorrect Wiring	/
		Disconnected Wire	X
		Cut Wire	/
I-III	Circuits	BEC Failure	/
		ESC Failure	/
		PDU Failure	/

The regulate fault tree table, part of the power functionality, is shown in Table 11. Critical components must receive the correct voltage and current from the power supply to perform their functions. Redundancy for BEC and ESCs can mitigate the criticality of the failure but at the cost of system weight and complexity. In turn, to maximize endurance, BEC and ESC are usually single points of failure resulting in motor, flight computer, or sensor issues. Battery and grounding component failures will cause an unrecoverable system failure.

Table 11. Power: Regulate Fault Tree Table

Criticality	**Component**	**Failure Level 1**	**Checklist Item**
III: if redundant else I	BEC/ESC	Bad Soldering	/
		Burst Current	
		High Current	X
		Infant Mortality	
		Manufacture Error	
I	Battery	Depletion	/
I	Various	Grounding Issue	X

The store fault tree table, part of the power functionality, is shown in Table 12. Storing power is performed by a battery attached to the vehicle’s frame. If the air vehicle is unable to store power the mission will end. Increased risks for lithium polymer battery failure include punctured battery, depletion past 80% life, overcharge/undercharge, to many charge cycles, and poor wiring connection. The operator must pay attention to securing the battery to the frame via storage bay, Velcro, fasteners, etc. All failures can be mitigated by checklist items.

Table 12. Power: Store Fault Tree Table

Criticality	Component	Failure Level 1	Checklist Item
I	Battery	Depleted	/
		Punctured	/
		Overcharge	X
		End of Life	X
		Poor Connection	X
		Undercharge	X
I	Battery + Frame	Unsecure	X

The observe environment fault tree table, part of the surveillance functionality, is shown in Table 13. The SUAS must observe the environment to satisfy the ISR mission. Any fault that prohibits the sensor on the SUAS from working eliminates the usefulness for the operator. These failures can be attributed to the sensor itself, power to the sensor, the environment, or the configuration of the sensor. A sensor gimbal allows the operator to independently control the camera from the air vehicle. If the gimbal fails, the sensor will still can observe the environment but requires the air vehicle to get in the correct position.

Table 13. Surveillance: Observe Environment Fault Tree Table

Criticality	Component	Failure Level 1	Checklist Item
I	Sensor Defect	Infant Mortality	
		Manufacture Defect	
		Wiring	/
I	Sensor Environment	Lens Fog	
		Wrong Sensor	X
		Altitude	
		Poor Look Angle	
		Interference	/
I	Sensor Configuration	Lens Focus	/
		Data Rate	/
		Obstructed View	X
II	Gimbal	BEC Failure	/
		Servo Failure	/
		Lock	/
		Wiring Issue	/

The transmit and receive fault tree table, part of the surveillance functionality, is shown in Table 14. To give the operator an enhanced visual perspective the imagery must be transmitted from onboard sensor to the GCS. Transmitter and receiver errors occur when there is information being transferred, the air vehicle is out of range, or there are component level failures. The antennas must be paired correctly together at the same frequency and place in correct orientation. Body masking from the air vehicle and the environment can impact the antenna and the quality of transmission. If the sensor architecture is dependent on a BEC for a stepdown of voltage, then it must perform to allow transmission. The operator must ensure the sensor is properly connected to the transmitter or output source.

Table 14. Surveillance: Transmit and Receive Fault Tree Table

Criticality	Component	Failure Level 1	Checklist Item
I	Transmitter / Receiver	Out of Range	/
		Transmit Error	
		Low Bandwidth	/
		Receive Error	
II/III	Antenna	Masking	/
		Wrong Antenna	X
		Broken Antenna	/
I	BEC	BEC Failure	/
II/III	Sensor Config	Poor Connection	/
I	GCS	Power Issue	/
II/III	N/A	Interference	/

The human interface fault tree table, part of the surveillance functionality, is shown in Table 15. For surveillance to be successful the operator must be able to receive the sensor feed from the SUAS; this is done through the GCS. The GCS can fail by either hardware or software issues. In most cases a software issue will only degrade functionality of this system, assuming all pre-deployment checklist items are completed. While hardware failures like loss of power, broken screen, or weather damage will render surveillance capability inoperable. Training is important to the human interface function, since wrong inputs to the GCS can reduce the functionality of the system. Training time and functionality should be balanced with GCS complexity to ensure the system is simple enough to perform required tasks but also robust enough to allow for operator decision making.

Table 15. Surveillance: Human Interface Fault Tree Table

Criticality	Component	Failure Level 1	Checklist Item
II	Software GCS	No User Input	X
		Bad Update	X
		Glitch	
I	Hardware GCS	No Power	X
		Broken Screen	X
		Weather Damage	/
II	Operator	Improper Command	
		Complexity	X

The sensor control fault tree table, part of the control functionality, is shown in Table 16. Control of the sensor is important to detect and track items of interest from the SUAS. The gimbal controls and stabilizes movement of the sensor independent of the air vehicle. A gimbal failure degrades functionality and places more stress on the operator to maneuver the air vehicle to capture the desired information. Transmission of control is done through the GCS. If a failure occurs the air vehicle can still be positioned via remote control to capture information. The sensor and its components must be in working condition for successful control. If the lens is fogged or improperly connected, no level of control will mitigate this failure. In addition, the sensor and its power must be functioning properly for control the be effective. Pre-flight checklist largely mitigates these potential failures.

Table 16. Control: Sensor Control Fault Tree Table

Criticality	Component	Failure Level 1	Checklist Item
II	Gimbal	BEC Failure	/
		Lock	/
		Wiring Issue	/
		Transmit/Receive	/
		Servo Failure	/
II	GCS	Software Issue	/
		Hardware Issue	/
		Transmit/Receive	/
		Operator Issue	/
		Processing Issue	/
I-III	Lens	Poor Lens Connection	X
		Lens Fog	/
I	Power/Battery	GCS Power Failure	/
		Payload Power	/
I	Sensor	Poor Connection	X
		Infant Mortality	
		Manufacture Defect	

The flight control fault tree table, part of the control functionality, is shown in Table 17. This fault tree table assumes there are two control nodes within the SUAS system. The first node is the remote-control node consisting of a transmitter, controlled by the operator, and a receiver on the air vehicle. The second node is the autopilot node consisting of a transmitter, controlled by the GCS, and a receiver on the air vehicle. In this configuration one node can fail and system performance is only degraded. For example, if the autopilot fails, the operator now must control the air vehicle manually without preprogramed commands. This degrades the operator's situational awareness and puts them at a higher level of risk. The hub of all control on the air vehicle is the flight computer. It processes commands from both the remote control and GCS. If the flight computer fails, the system is no longer controlled, and a failsafe will be activated.

Table 17. Control: Flight Control Fault Tree Table

Criticality	**Component**	**Failure Level 1**	**Failure Level 2**	**Checklist Item**
II: If system has both autopilot and RC else I	Remote Control Components	Transmitter	Frequency	X
			Antenna Position	/
			Depleted Power	/
			Wrong Input	
			Low Signal	/
			Software Issue	/
			Manufacture Defect	
		Receiver	Antenna Issue	/
			Payload Interaction	X
			Wiring Issue	/
			Range	/
			Manufacture Defect	
			Not Paired	X
II: If system has both autopilot and RC else I	Autopilot Components	Transmitter	Manufacture Defect	
			Orientation Issue	/
			Poor Link w/GCS	/
			Poor Pair w/Receiver	X
			Wiring Issue	/
		Receiver	Antenna Issue	/
			Range	/
			Wiring Issue	/
			Manufacture Defect	
			Payload Interaction	X
I for all except gain tuning II	Flight Computer	Software Issue		/
		Motor Wiring		/
		Infant Mortality		
		Gain tuning		/
		Excess Vibrations		/

The failsafe fault tree table, part of the control functionality, is shown in Table 18. Failsafes are operator programmed flight modes that activate when link is lost between the GCS and/or the remote control. Flight modes include but are not limited to return to base, hover, self-destruct, or land. A failure of a failsafe is defined as the air vehicle performing a flight mode that is unexpected or not commanded. This can occur by incorrect programming of failsafes by the operator including the wrong return to base location, wrong failsafe, or unprogrammed failsafe. Additionally, the air vehicle may be unable to complete the command due to an object within its path or a recovery issue. Finally, the flight computer may think there is a failsafe command when there is not, type I error or the flight computer does not perform a failsafe when it is commanded, type II error.

Table 18. Control: Failsafe Fault Tree Table

Criticality	**Component**	**Failure Level 1**	**Checklist Item**
I-III	Operator/GCS	Unprogrammed	X
		Wrong Failsafe	X
		Wrong RTB	X
I or III	Air Vehicle	Object in Failsafe path	/
		Hard Landing	
I or II	Flight Computer	Type I Error	
		Type II Error	

The guidance fault tree table, part of the control functionality, is shown in Table 19. Guidance is required for the autopilot to function correctly. With a dual control mode in the system architecture a guidance failure only degrades the performance of the SUAS, since the air vehicle can still be controlled by the remote control. The GPS enables positioning for the air vehicle and provides location information via the GCS to the operator. GPS can be degraded by conditions including a GPS denial environment, urban canyons, power lines, or large metal objects. The air vehicle can also mask the GPS signal depending on the frequency and power of signals emanating from the platform, placement of antennas, and electromagnetic interference from the selected sensor or components. The Initial Flight checklist is focused on mitigating these failures.

Table 19. Control: Guidance Fault Tree Table

Criticality	Component	Failure Level 1	Checklist Item
II	GPS	Environment Masking	/
		Poor Connection	X
		Manufacturing Defect	
II	Transmitter/ Receiver	Range	/
II	Air Vehicle	Frame Masking	X
II	Sensor	Jamming GPS	X

The provide status fault tree table, part of the control functionality, is shown in Table 20. The flight computer provides flight information to the GCS including altitude, speed, flight mode, heading, pitch, GPS, signal strength. These data categories are important to monitor the performance of the air vehicle for mission execution and irregularities. The air vehicle can still perform without this information but at a higher burden on the operator to identify performance issues. Issues can arise from the GCS software of hardware, flight computer, or operator error with the GCS interface.

Table 20. Control: Provide Status Fault Tree Table

Criticality	Component	Failure Level 1	Failure Level 2	Checklist Item
II	GCS	Display	Broken Screen	X
			Power	X
			Hidden Data	/
		Software Issue		/
II	Flight Computer	Wiring Telemetry Issue		/
		No GPS Data		/
		Transmitter/Receiver Issue		/
II	Operator	Data not Configured		X
		Obscured Data		/

Reliability Analysis

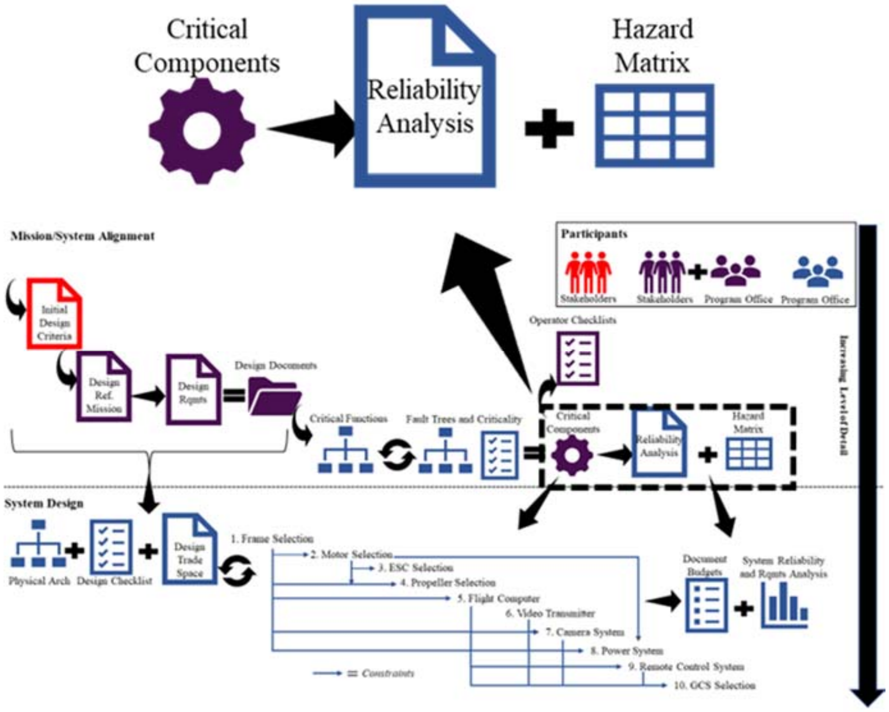


Figure 18. Critical Components and Reliability Analysis Process

Probability of failure for SUAS components were researched. Limited information exists on failures of critical SUAS components due to rapid advancement of components, diversity of components, and relatively low costs. Components that induce Category I event failure include motors, propellers, flight computer, ESC, BEC, transmitter, receiver, sensor, battery, frame, and GCS. Table 21 provides a summary of failure rates for these components that were researched and documented from online sources.

Failure rates are in failures per hour and are grouped based on components. Average failure rates are displayed for common component categories. For example, the average failure rate from the data collected for flight computers is $4.46 * 10^{-3}$ failures per hour. All like component failure rates are used for average failure, except the receiver system which is in bold text under the part column. This failure rate of 0.37 failures/hr was excluded since the failure would be observed on a majority of missions, therefore is not an acceptable part and would be replaced with a more reliable system.

Failures for components are assumed to be past the infant mortality phase and occur within the constant failure rate zone of the bathtub curve. At a constant failure rate, the components are in normal life of the bathtub curve and have had burn-in performed to remove early life errors. Figure 19 shows the bathtub curve for electronics. These failure rates can be applied to a representative multirotor system for a system level reliability and mean time to failure. This is performed in the System Design section of the SUAS product process.

Table 21. Failure Rates for Category I Components

Part	Failure rate/hr	Average	Condition	Comment	Source
Flight Computer	1.50E-02	4.46E-03	Field	Pixhawk 1-quote from 3DR Chris Anderson	(Thompson & Anderson, 2016)
Flight Computer	1.57E-03		Research		(Reimann et al., 2013)
Flight Computer	1.25E-04		Research	Based on sub components: Gyro Accel and filter, low reliability	(Pashchuk, Salnyk, & Volochiy, 2017)
Flight Computer	4.94E-05		Research	Based on sub components: Gyro Accel and filter, high reliability	(Pashchuk et al., 2017)
Flight Computer	1.00E-02		Research	Common electronics	(Breunig et al., n.d.; Stockwell & Schulman, 2016)
Flight Computer	2.00E-05		Lab		(O'Reilly, 2017)
Motor	1.00E-04	1.59E-03	Lab	After infant mortality	(O'Reilly, 2017)
Motor	1.00E-04		Lab		("Phantom 1 MTBF," 2016)
Motor	5.00E-03		Observed	Crowd source data collect	(Moore, 2018)
Motor	2.20E-03		Research		(Reimann et al., 2013)
Motor	5.56E-04		Research		(Wang, Mao, & Wei, 2018)
Propeller	8.33E-04	1.81E-02	Research		(Wang et al., 2018)
Propeller	3.40E-03		Research		(Reimann et al., 2013)
Propeller	5.00E-02		SME	FOD Contact	(Kevorkian, 2016)
Rotor (motor+prop)	4.00E-02		Research	Combined Motor and Propeller subsystem	(Aslansefat, Marques, Mendonça, & Barata, 2017)
Frame	5.00E-04	1.57E-03	Research		(Wang et al., 2018)
Frame	2.07E-04		Research		(Abdallah, Kouta, Sarraf, Gaber, & Wack, 2018)
Frame	4.00E-03		SME	Crack Propagation	(Kevorkian, 2016)
Batteries	2.00E-05	4.77E-03	Lab		(O'Reilly, 2017)
Batteries	1.40E-03		Research		(Reimann et al., 2013)
Batteries	5.00E-04		Research		(Wang et al., 2018)
Batteries	8.76E-06		Research		(Abdallah et al., 2018)
Batteries	1.00E-02		SME		(Kevorkian, 2016)
ESC	2.00E-04	1.26E-02	Research		(Reimann et al., 2013)
ESC	2.50E-02		SME		(Kevorkian, 2016)
BEC	1.10E-03	1.77E-03	Research		(Reimann et al., 2013)
BEC	6.67E-04		Research		(Wang et al., 2018)
Receiver	2.60E-03	1.16E-03	Research	Entire radio system, outlier	(Reimann et al., 2013)
Receiver	7.14E-04		Research		(Wang et al., 2018)
Receiver	1.53E-04		Research	With interference from NPRD-2016	(Abdallah et al., 2018)
Receiver System	*3.70E-01*		SME	Entire radio system, **outlier**	(Kevorkian, 2016)

Part	Failure rate/hr	Average	Condition	Comment	Source
Blackfly S Camera	6.32E-07	1.03E-05	Mobile environment	5 hr Burn In @50C	("Blackfly S Color 1.3 MP USB3 Vision (ON Semi PYTHON 1300)," 2018)
Camera	2.00E-05		Lab		(O'Reilly, 2017)
GCS	8.55E-04	1.93E-03	Representative Environment	1 yr life at 4 missions a week at 1.5 hr missions, 2.4% Failure per year, Panasonic Toughbook	(Panasonic, 2009)
GCS	3.00E-03		Representative Environment	1 yr life at 14 missions a week at 1.5 hr missions, 2.4% Failure per year, Panasonic Toughbook	(Panasonic, 2009)

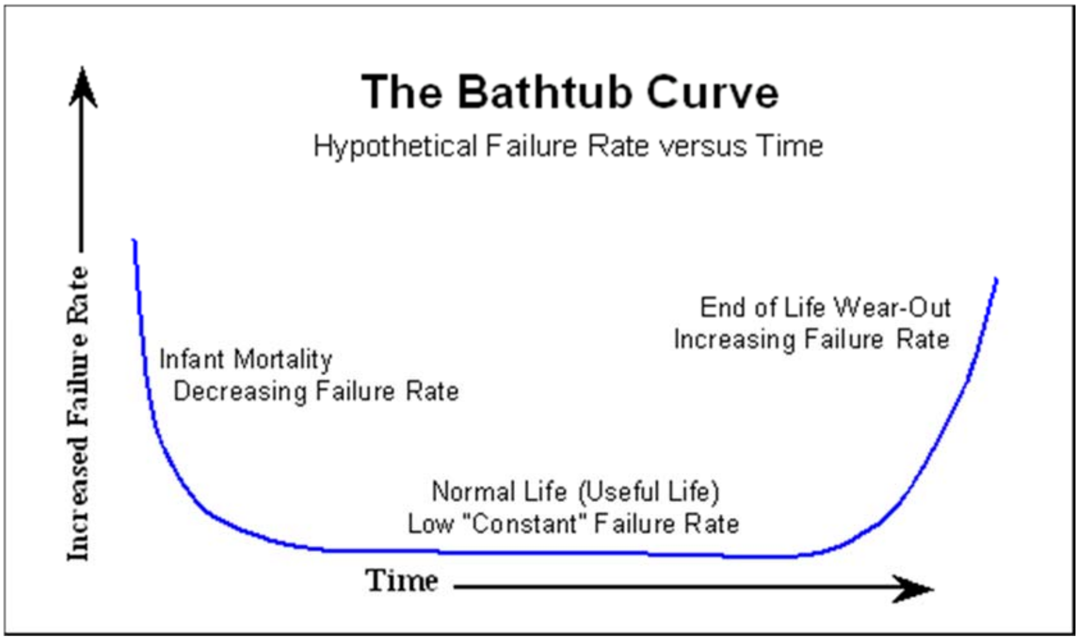
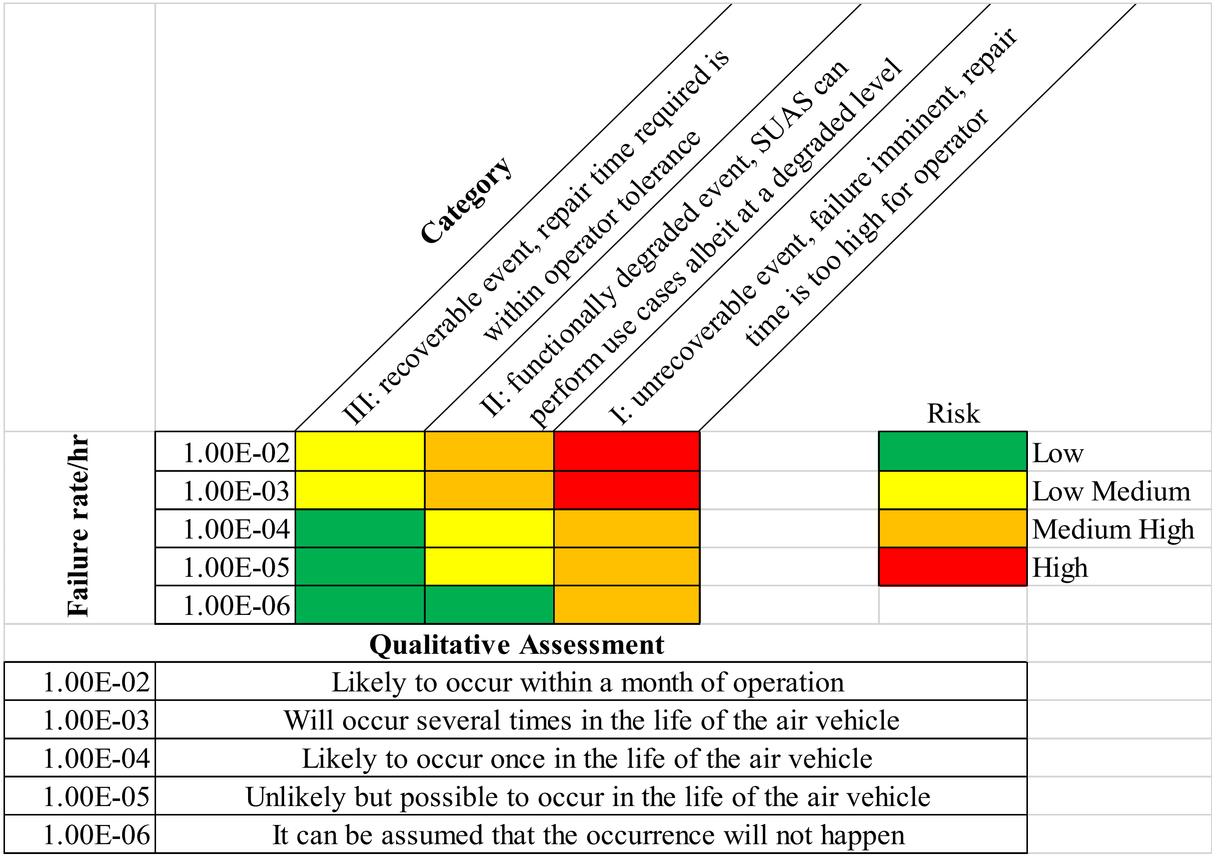


Figure 19. Bathtub Failure Rates for Electronics (Wilkins, 2002)

With failure rates and categories of failures defined, a hazard/reliability matrix can be defined to show the impact to the overall system if a specific component fails. The matrix takes the failure rate for a given component and the category/impact of failure and then defines the level of risk to the system. Risk focus areas are mitigating components that induce high and medium-high risk areas. Figure 20 shows the hazard/reliability Matrix with operational definitions for categories, failure rates, and risks. Figure 21, then places the category I components into the matrix aligned with average researched failure rates.



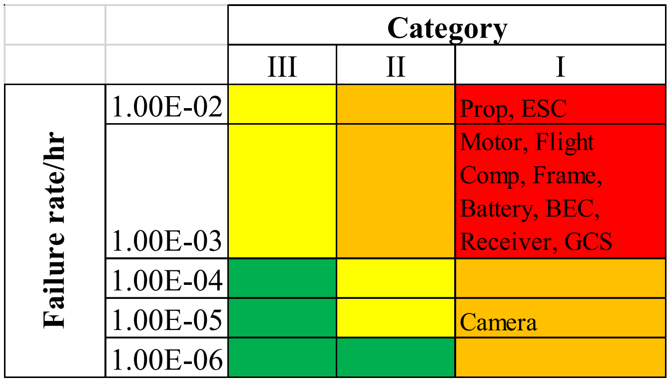
Category

Failure rate/hr	III: recoverable event, repair time required is within operator tolerance	II: functionally degraded event, SUAS can perform use cases albeit at a degraded level	I: unrecoverable event, failure imminent, repair time is too high for operator
1.00E-02	🟨	🟧	🟥
1.00E-03	🟨	🟧	🟥
1.00E-04	🟩	🟨	🟧
1.00E-05	🟩	🟨	🟧
1.00E-06	🟩	🟩	🟧

Risk	
🟩	Low
🟨	Low Medium
🟧	Medium High
🟥	High

	Qualitative Assessment
1.00E-02	Likely to occur within a month of operation
1.00E-03	Will occur several times in the life of the air vehicle
1.00E-04	Likely to occur once in the life of the air vehicle
1.00E-05	Unlikely but possible to occur in the life of the air vehicle
1.00E-06	It can be assumed that the occurrence will not happen

Figure 20. Hazard/Reliability Matrix



		Category		
		III	II	I
Failure rate/hr	1.00E-02	🟨	🟧	🟥 Prop, ESC
	1.00E-03	🟨	🟧	🟥 Motor, Flight Comp, Frame, Battery, BEC, Receiver, GCS
	1.00E-04	🟩	🟨	🟧
	1.00E-05	🟩	🟨	🟧 Camera
	1.00E-06	🟩	🟩	🟧

Figure 21. Hazard/Reliability Matrix with Critical Parts

Generate Checklists

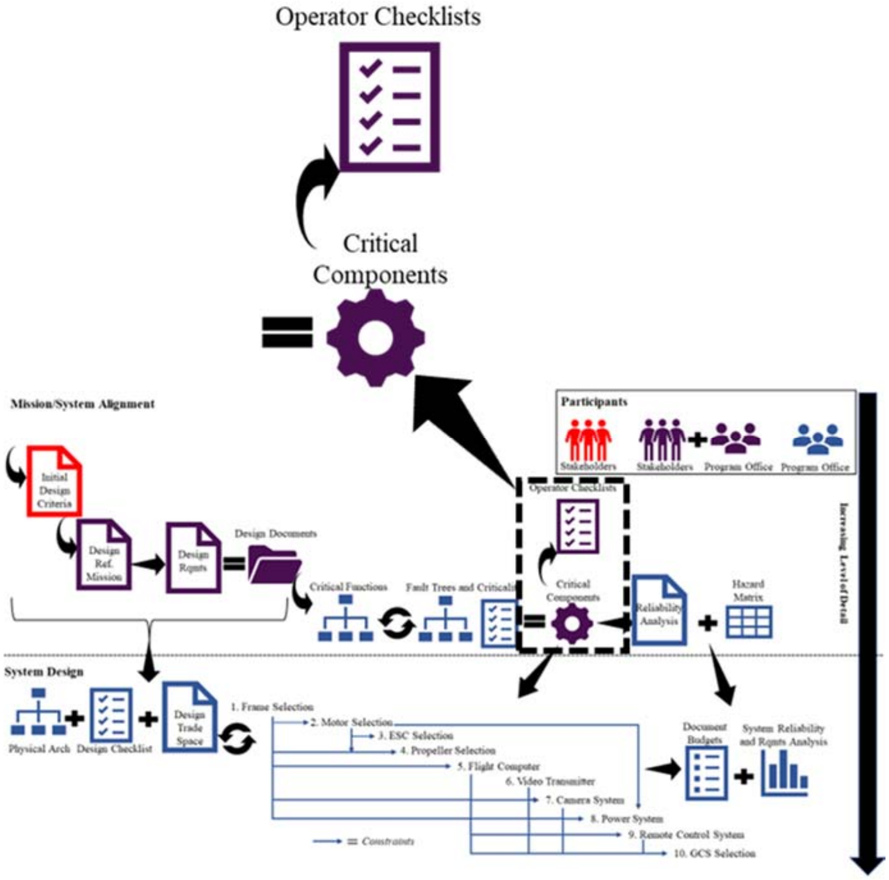


Figure 22. Generate Operator Checklist Process

Four checklists are generated from inputs from the fault tree diagrams and identification of critical components. Checklist are designed to mitigate risks to the system before operational flights. Each checklist rule is attributed to SUAS component and category. Additionally, benefits to each checklist rule are listed that detail which failures are mitigated. The first checklist is the pre-flight checklist, meant to be performed before each mission. This checklist is designed to be a low time commitment inspection that the operator can perform, mitigating X checklist items generated in the fault tree tables. Examples within this checklist include visual inspection of components for damage, securing of fasteners and components, center of gravity, proper wiring, and propeller clearance. The pre-flight checklist, shown in Table 22, should be performed on scene and once the SUAS is assembled to ensure failures were not induced from transportation.

Table 22. Pre-Flight Checklist

Component	Category	Checklist Rules	Benefits
Motor	Attachment	Ensure motors are properly attached to frame, secure all fasteners. Ensure fasteners are not touching motor coils.	Prevents motor detachment and overheating in flight and ensures stable flight
Motor	Wiring	Ensure motor are wired properly, connected to ESCs and flight computer. Ensure wires are secured and in good condition.	Prevents motor power failure in flight
Motor	Leveling	Ensure motors are level to frame.	Prevents overheating, enables stable flight
Motor	Defect Check	Ensure motor spins freely without resistance. Listen for any rubbing. Inspect coils and magnets for any damage.	Motor is properly functioning for stable flight
Propeller	Attachment	Ensure propellers are properly attached to motors and have the correct direction of rotation.	Prevents propeller detachment and ensure stable flight
Propeller	Defect Check	Ensure there are no defects in the propellers, minor nicks are ok. Inspect for delamination and cracks.	Prevent propeller failure in flight
Propeller	Size	Ensure propellers are the correct size for the motors.	Prevents motor overheating and degraded flight
Propeller	Contact	Ensure all propellers are clear of wires and components. 1/4" clearance is desired for frame flex. Secure potential contact items.	Prevents cut wires or destroyed components
Frame	Stiffness/Secure	Check for loose fasteners, loose arms, and overall frame stiffness. Place weight on the frame and listen for any creaking sounds to inspect for frame cracks. Tighten fasteners and components if required.	Enables stable flight and reduces probability of induced crash
Frame	Leveling	Ensure frame is level ground.	Promotes stable takeoff
Frame	Landing Gear	Ensure landing gear are stable and solid with required weight. If landing gear retracts, cycle through procedure to ensure functionality.	Prevents landing failure
Wiring	Connections	Ensure all wires are connected into flight computer and required components (motors, ESC, battery, payload). Check for any improper wiring. Check battery connection polarity.	Ensures communication and power are distributed across vehicle safely.
ESC	Defect Check	Check ESC for loose soldering or poor connections.	Prevents ESC and flight failure
Battery	Charge	Ensure battery is the correct cell count, capacity, and is fully charged.	Prevents shortened endurance and flight failures
Battery	Damage	Ensure battery is free from punctures or frayed connections.	Prevents in flight battery failure

Component	**Category**	**Checklist Rules**	**Benefits**
Battery	Secure	Ensure battery is secure to the frame and wires are free from contact.	Prevents CG shift in flight or loss of battery
Frame	Center of Gravity	Hold the air frame along rotation axis and ensure aircraft is balanced. If unbalance shift battery, payload, or components.	Promotes stable flight and maximum endurance
Payload/Sensor	Secure	Ensure sensor and components (lens) are properly connected to frame. Field of view of payload should not be blocked by frame. Cabling should be plugged in a secure.	Enables proper functionality of sensor for mission
Payload/Sensor	Lens	Ensure lens is connected to camera and is not cracked or fogged.	Enables proper functionality of sensor for mission
Flight Computer	Defect Check	Ensure proper power supply from battery, secure to frame, and secure cabling.	Proper functionality for mission
Receiver	Antenna	Ensure antenna is correct for receiver is clear of propeller and plugged in before powering. If dual antennas position one in horizontal frame and one in vertical frame.	Proper placement ensures maximum control range
BEC	Defect Check	Check incoming cabling for defects and inspect BEC for any damage.	Promotes proper voltage for all critical components
Environment	Envelope	Ensure the current and forecasted weather is within the performance envelope for the configured air vehicle. Document wind speed, gust speed, precipitation, temperature, and humidity levels.	Promotes expected flight performance. Provides data for environmental impacts for flight analysis
Environment	Flight Path	Evaluate surroundings for planned flight path. Check for obstacles within path. Identify power lines, metal buildings, or large objects which can interfere with signals.	Mitigates command and control loss

Next is the pre-deployment checklist, this checklist occurs before deployment to the mission location due to the larger time commitment. The pre-deployment checklist is shown in Table 23. The checklist ensures the SUAS is performing its designed functionality while on the ground in a stable environment allowing for simplified troubleshooting from the operator. The checklist provides possible failure modes for unsuccessful checks for operator troubleshooting. Examples within the checklist include initial component check, range check, flight computer calibration, system power check, and GCS mode check.

Table 23. Pre-Deployment Checklists

Component	Category	Checklist Rules	Possible Failures	Benefits
Multiple	Initial Function Check	Plug in all batteries to the aircraft. Ensure no smoking wires, burning smells, or odd noises. If these exist immediately unplug and troubleshoot.	Wiring issue, wrong batteries, damaged battery, depleted battery, poor grounding.	Confirms correct wiring and power to subsystems
RC Transmitter	Distance check	Ensure the RC receiver on the aircraft receives command from the transmitter at minimum of 100 yards on the ground.	Sensor jamming RC controls, wrong receiver/transmitter pair, low transmitter battery, damage receiver/transmitter, receiver masking, environmental effects, poor wiring	Prevents signal loss in the air
GPS	Lock	Ensure GPS has satellite lock for more than 30 seconds and is stable. Check for Satellite count (min 6) and HDOP values (1-2 m standard).	Sensor jamming, poor wiring, bad GPS unit, environmental effect, no power, faulty flight computer, GPS masking	Establishes GPS connection and established no interference w/payload
Flight Computer	IMU/compass calibration	Calibrate IMU/compass within flight computer.	Software issue, poor user calibration	Correct calibration for flight.
RC Transmitter/GCS	Mode Check	Toggle flight modes on flight computer and confirm modes on GCS software i.e. position hold, altitude hold etc.	Flight computer issue, software issue, transmitter issue	Establishes correct flight controls for the RC system
Sensor	Function check	Establish connection with sensor and ensure data is being transferred to GCS. Evaluate quality of data and any changes required to sensor.	Poor GCS/sensor power, poor connection with GCS (software, transmitter), poor sensor connection, low bandwidth, too high of data rate from sensor, lens issue, poor antenna position.	Confirms good data flow from sensor
Sensor	Frequency Test	Power up sensor, transmitter, and receiver to transmit video. Ensure air vehicle is a short distance from GCS. Cover transmitter and receiver antenna and ensure no degradation in video.	Wrong frequency pairing between transmitter and receiver.	Ensure proper video feed
Sensor	Movement	Command movement of the sensor through GCS ensure functionality and confirm data.	Gimbal issue, power issue, GCS issue, wiring issue	Confirms performance of sensor and gimbal

Component	Category	Checklist Rules	Possible Failures	Benefits
Motor	Function check	Ensure the correct motor is commanded from flight computer. Listen for odd sounds or movement.	Motor defect, wiring issue, failed ESC, wrong ESC mode, wrong propeller direction or attachment, poor motor attachment	Confirms motors are functioning correctly for stable flight
Propeller	Balancing	Ensure each propeller and backups are balanced using a propeller balancer (standard propellers) or a scale (foldable propellers).	Manufacturing defect, damaged propeller	Prevents unstable flight
GCS	Function check	Ensure video, battery data, GPS, and flight data are displayed on GCS. Ensure GCS receives information at 100-yard range.	Hardware issue, software issue, transmit issue, power issue, setting issue	Confirms all data is provided to operator
Battery	Power Check	Ensure batteries are fully charged, establish cut off voltage for flight. Test with voltage monitor or GCS. 3-3.2 V/cell is minimum cut of voltage.	Batteries not fully charged, charger issue, wrong battery	Confirms full endurance flight capability
GCS	Gain Tuning	Ensure gain tunnning is correct for selected configuration or set at established defaults.	Software update/reset, configuration control	Promotes stable flight for selected payloads
ESC	Configuration	Confirm the correct configuration for the ESC for flight profile. Calibrate ESCs.	Mode changed by user, configuration change, software update	Promotes stable flight
Multiple	Spares	Confirm all required spares are packaged, configured, and in working condition.		Mitigates component failures

The largest time commitment checklist is the initial flight checklist, shown in Table 24. This checklist focusses on performing required functions while the SUAS is airborne in a controlled manner. The initial flight checklist allows a stable environment for performance issues to be revealed and mitigated. If possible, the checklist should be performed by the operator with the aid of the system developer, allowing the operator to gain experience with the handling and control of SUAS. Tests include a range test, flight control mode, gain tuning, sensor transmit, takeoff and landing. The initial flight checklist should be performed when any aircraft modification is made to the system including new motors, new sensors, shift in center of gravity, etc. Even if system is in a baseline configuration there should be an established schedule to perform the checklist based on flight hours. This ensures the SUAS is still performing as expected and rules out induced errors from the operational environment, transport, or operator handling. This checklist also includes a possible failure column for operator troubleshooting.

Table 24. Initial Flight Checklists

Component	Category	Checklist Rules	Possible Failures	Benefits
Multiple	Cyber Vulnerability	Ensure data transmitted including imagery, telemetry, and command is secure. Use close networks and secured networks if possible. Implement failsafes if data has been compromised.	Loss of data from cyber breach put special operators at risk.	Prevents data loss and ensures mission data is secure.
Multiple	Takeoff	Slowly spin up motors for takeoff, listen for any irregularities. Ensure the air vehicle is not directly overhead of anyone. Place aircraft in hover position were the operator can visually see and note performance of the air vehicle.	Center of gravity, motors un-leveled, propeller contact, excess weight, depleted battery, motor failure	Detect poor performance before airborne or on mission. Ensure safety of participants and perform flight inspection.
Multiple	Manual Hover	Place the air vehicle into hover via RC control, document any drifting, cyclical, or vibrating behavior. Document throttle percentage at hover, hover should be at 50% throttle or less.	Gain tuning unbalanced in GCS/flight computer, environment impacts, center of gravity issue, motor/prop issue	Allows stable position to evaluate control issues. Land air vehicle and make changes to gains.
Multiple	Mode Check	While in hover place air vehicle into desired modes including altitude and position hold. Document any drifting, cyclical, or vibrating behavior. If the vehicle is making large in air adjustments, switch to RC and land immediately.	Gain tuning unbalanced in GCS/flight computer, environment impacts, center of gravity issue, motor/prop issue, GPS issue	Allows stable position to evaluate control issues. Land air vehicle and make changes to gains.

Component	Category	Checklist Rules	Possible Failures	Benefits
Transmitter/ Receiver	Range Check	Place air vehicle at desired operating altitude and move vehicle away from transmitter gradually. Document signal strength for both RC and GCS.	On board EMI, body masking, antenna issue, environmental masking, power issue, software issue	Establishes approximate flight range
RC	Responsiveness	Control the air vehicle manually and ensure all input movement is correct i.e. yaw input controls, etc. Operator should perform desired and required movement to achieve comfort with the system and document any limitations and alter gain tuning for desired improvements.	Gain tuning unbalanced, excess weight, low battery, software issue, improper wiring, center of gravity issue	Establishes correct flight controls for the operator
GCS/ Flight Computer	Mission Follow	Plan a mission within the GCS and transmit to air vehicle, include loiter points. Document air vehicle performance and any deviations from the mission. Document GPS performance and transmitter/receiver strength.	GPS issue, environment, range, transmitter/receiver issue, software issue	Confirms desired mission performance
Sensor	Performance	Confirm sensor performance while in flight, ensure data is transferred to GCS. Check focus levels at representative altitude, data bandwidth, and frames per second.	Lens issue, environment, transmit/receive issue, software issue, GCS issue	Confirms sensor performance is appropriate for mission
Gimbal	Performance	Operator induces sensor movement for a desired target point. Document performance issues: target out of view, gimbal lock, transition time, etc.	Servo issue, transmit/receive issue, flight computer issue, software issue, BEC issue, environment	Confirms gimbal performance is appropriate for mission
Software	Performance	Operator sends required tracking commands or target detect commands for the sensor. Operator ensures the air vehicle follows commands and provides feedback to GCS.	GCS configuration, software update, hardware issue, sensor issue, lens issue, environment	Ensures software and human interface is functioning for mission
Multiple	Landing	Safely land the air vehicle via RC. Evaluate for any propeller wash, hard landing, and stability.	Propeller wash, high weight, configuration issue, center of gravity	Confirms air vehicle can handle load and land safely

Component	Category	Checklist Rules	Possible Failures	Benefits
Multiple	Configuration	Document time required to unpack, assemble, and deploy air vehicle. Then document time to store vehicle for transit.	Broken components, missing parts, missing tools, frame stiffness issue	Representative time for mission deployment established

The final checklist is a spare checklist. This checklist details the required spare components for the operator to pack to mitigate critical component failures. Spares should be pre-configured for ease of integration into the system. For example, the spare flight computer has the same gain tuning parameters as the onboard flight computer, motors have burn-in test complete with representative propellers, transmitters and receivers are paired, etc. The spare list is focused on replacement parts for components which induce category I events if they fail. Spares should always be packed with the system if room and weight exist in the pack. The spare checklist is shown in Table 25.

Table 25. Spares Checklist

Component	Number of Spares	Notes
Propeller	1 for each motor	if quad 4, if hex 6
Motor	1 min, 2 desired	Burn in completed and preconfigured for assembly. Correct connections.
Flight Computer	1 fully configured	Correct flight parameters and required cabling
GPS	1	Complete with wiring harness
ESC	2	Correctly configured, initial inspection completed
BEC	design dependent, min 1	Correct step-down voltage, complete with wiring
Landing Gear Replacement Kit	1 desired	Replacement material, connectors, and fasteners.
Transmitter/ Receiver	1 pair for RC, 1 pair for GCS, 1 for video	Correct frequency and antennas with cabling
Arm Replacement Kit	1 desired	Replacement material, connectors, and fasteners.
Backup sensor	1	Fully configured for air vehicle integration and GCS integration. Does not have to be same as primary sensor.

Component	Number of Spares	Notes
Battery Main	1 min	Fully charged
Battery GCS	1 min	Fully Charged
Battery Connectors	1 min	Correct connector type
Battery Payload	1 min	Fully charged
Tools	Complete set	Required tools for tightening fasteners and assembling components, knife, wire strippers, vice grips, scissors
Others	kit	Velcro, tape, super glue, fasteners, zip ties

System Design

Define Physical Architecture

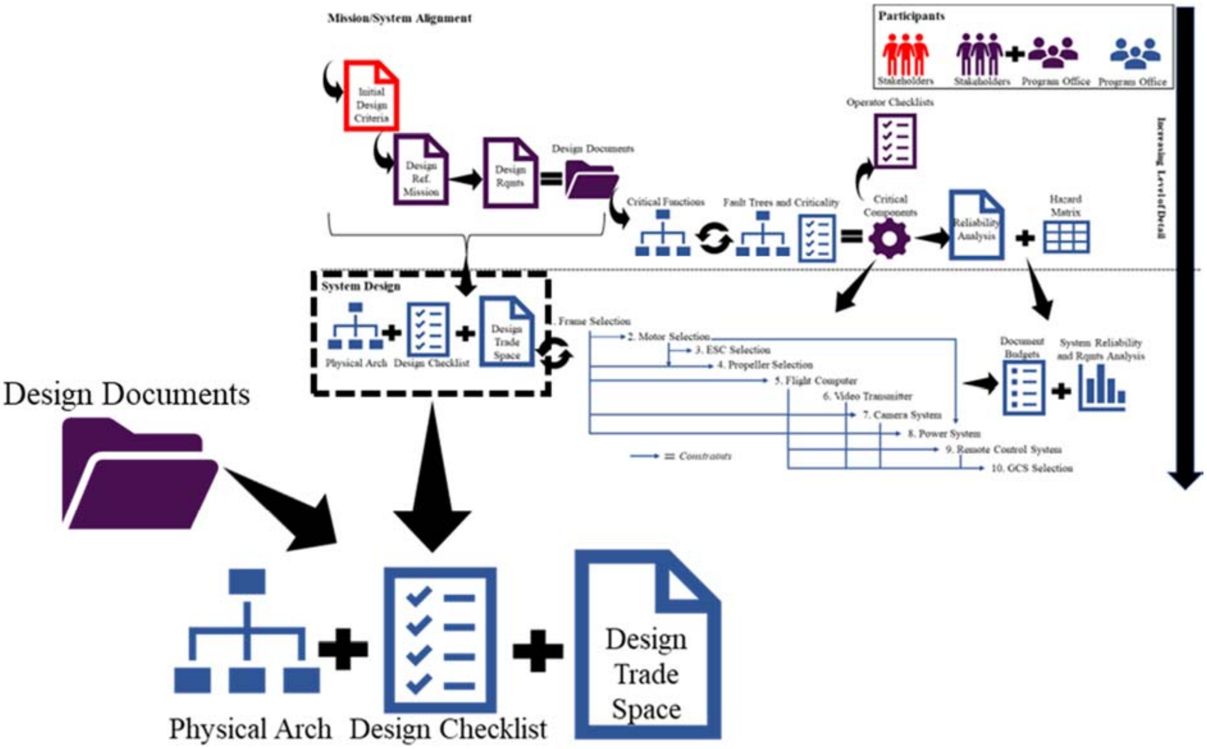


Figure 23. Physical Architecture Process

The second section of the product development process is to define the physical architecture of the systems. It is important to take and balance inputs from the previous steps focusing on initial design criteria, requirements, and mitigating reliability risks to the overall system. A designcChecklist was built from the author's experience in the AFIT SUAS design sequence and online drone design forums. References for the online drone design forums are listed in Appendix B. These sources were utilized for not only design rules but the ISR SUAS design itself.

The design checklist provides a ruleset with benefits, as physical architectures are built. The checklist starts at the system level providing input on multirotor type, material selection, frame size and then moves to rules for integrating components. Then integration of the appropriate motor and propeller combination based on frame type and weight is discussed. Design rules are established for motor size, weight, efficiency, power, torque, and KV value. Next, electronic components are discussed with and the importance of balancing a power budget for the SUAS. The power budget impacts battery selection including parameters of capacity, cell count, and discharge rating. With all components selected, weight budget is assimilated for endurance and packing weight calculations. The checklist is shown in Table 26.

Table 26. Multirotor Design Checklist

Component	**Category**	**Checklist Rules**	**Benefits**	**Popular Brand/ Type**
Motor	Number	If packing requirement and endurance can be met, design for redundancy i.e. 6 motors. If not design for 4 motors.	Increases overall system reliability and carry weight.	T-motor, Multistar, KDE, Arris
Sensors	Type/size	Consider sensors to perform mission, record weight, power requirements and designs impacts. Investigate the required components to transmit signals to the selected GCS interface.	Meet sensor requirements, focus on trades for endurance, modularity, user interface, and power.	FLIR, Go-Pro, Sony, Runcam (FPV), Foxeer (FPV)
Flight Computer	Type	Select flight computers capable of autonomous and controlled flight. Investigate how electronic components interface with the computer and if the sensor requires	Defines interfaces and helps establish wiring diagrams. Establishes power	Pixhawk: 1,2,4 (open source), Piccolo

Component	Category	Checklist Rules	Benefits	Popular Brand/ Type
		an interface. The flight computer should be centered in the frame design since it is the control hub.	budget and control nodes.	(closed Source),
Frame	Type/size	Choose an air frame which supports the number of motors selected and packing requirement. Frame must carry all required components and weight.	Frame must fit the number of motors and projected design weight.	Tarot, Foxtech, Matrix
Frame	Material	Select frame which has a high stiffness with capability to be packaged based on mission requirements.	Higher stiffness mitigates control failure in flight. Material needs to fold multiple times for packing.	Carbon Fiber, Aluminum
Propeller	Size	Determine propeller diameter based on frame size, ensure room on frame for payload. Maximize propeller size if possible. Consider thrust, motor efficiency, and heating.	Mitigates propeller and component failure from strikes.	KDE, T-Motor, Tiger, Foxtech
Propeller	Material	Determine propeller material type and design which yields best performance for design. Material choices are carbon fiber or plastic.	Design and material choice paired with motor type can yield increased efficiency.	
Propeller	Configuration	Consider folding propellers and quick disconnect propellers, evaluate performance differences between traditional propellers.	Increases packaging and decrease user set up time.	
Motor	Sizing	Determine motor size based on propeller size, consider the most important design factor for mission: Weight, Efficiency, Power, or Torque. These trades balance payload weight and endurance. Evaluate thrust test of motor with correct propeller size and reputation of motor brand. Seek out motor testing data with candidate propellers.	Maximize endurance for a given design, select a reliable brand.	T-motor, Multistar, KDE, Arris
Motor	Weight	Lighter motors have a better response to input but are generally less reliable. Heavier motors pair well with larger propellers but have a slower response rate.	Balance between weight trades for endurance and maximizing propeller size and thrust ratings.	
Motor	Efficiency	Choose a motor that is most efficient through the range of operations. Efficiency is measured in grams/Watt. Brushless motors are 85-90% efficient while brush motors are 75-80% efficient.	Maximize endurance, determine battery size required.	

Component	Category	Checklist Rules	Benefits	Popular Brand/ Type
Motor	Power	Ensure a power to weight ratio of minimum 2:1 with a goal of 3:1 for maximizing endurance. Weight is total weight of air vehicle with payload and batteries. Power is the max thrust of all motors with propellers.	Ensures correct power draw for battery and ESC design. Ensures hover around 50% throttle position to meet endurance.	
Motor	Torque	Higher torque allows for quicker changes in speed and easier user tuning.	Torque is a low design consideration since the air vehicle is not acrobatic.	
Motor	KV	Pick appropriate KV motors for propeller size. Lower KV motors pair with larger propellers and higher KV motors pair with smaller propellers. Ensure propeller size is not at the edge of motor design space.	Promotes better motor propeller efficiency, benefiting endurance and payload weight.	
ESC	Sizing/type	Once motors are selected pick ESCs which can handle amp draw for motors. Always step up a size in ESCs, if motors are drawing 25A choose 30A. Frame and design considerations can dictate 4-in-1 ESC or ESCs for each motor. Ensure peak current, cell size, programming, and weight of ESC meet design. Evaluate ESCs on brand reputation.	ESCs are critical to preventing motor failure. Design margin should be built into ESCs for flight reliability.	Castle Talon, KDE
BEC	Sizing/type	Flight computer, sensors, and other electronics which require voltages differing from that of the battery will require BECs. Multiple components can run off the same BEC if they have similar voltage ranges. Evaluate BECs on the voltage range and brand reputation.	BECs are critical for components that require voltage levels different than the battery (most likely 5V). If the BEC fails so does the component.	
Wiring	Gage Check and Connectors	Ensuring wiring and battery connectors are proper size for current demands.	Ensures reliable power distribution	Deans connectors for low current, XT family for medium to high
Video Transmitter/ Receiver	Range/quality/ type	Ensure video transmitter choice interfaces with GCS, meets range and quality demands. Ensure onboard transmitter fits within weight budget.	Ensures video system meets requirements	TBS Ground Station, Insight SE
Transmitters/ Receiver	Signal Budget	Ensure the signals for RC, GCS, and video are at different frequencies so all systems function properly	Prevents conflicting signals and all systems transmit	Futaba (RC), Frsky (RC), Turnigy (RC), 3DR (telem)

Component	Category	Checklist Rules	Benefits	Popular Brand/ Type
Multiple	Power Budget	Document power demand for electronic components and evaluate against proposed battery design/choices.	Establishes battery options and theoretical range	
Battery	Size/Number/ Cell count	Select batteries which can meet power demands, and endurance requirements. Select mah, cell count, and number of batteries.	Establishes system weight and aids in endurance calculations	Multistar
Multiple	Weight Budget	Add all components weight and determine if selected frame is appropriate. Determine projected endurance and evaluate against requirements.	Established endurance envelope, and packing weight	

The top level of the physical architecture is defined by a block diagram shown in Figure 24. The block diagram displays systems, components, and sub components. The architecture shows there are two modes of control, one through the GCS and the other through a RC controller. The next level of detail is displayed though an internal block diagram, that reveals both the physical, data, and power connections between components. The system is broken down into three sub-systems. Flight control is responsible for performing controlled flight of the SUAS. Payload system is responsible for the functionality of the on-board sensor. The GCS is responsible for sending command signals from the operator to the SUAS and receiving information from both the flight control and payload subsystems. The internal block diagram is shown in Figure 25.

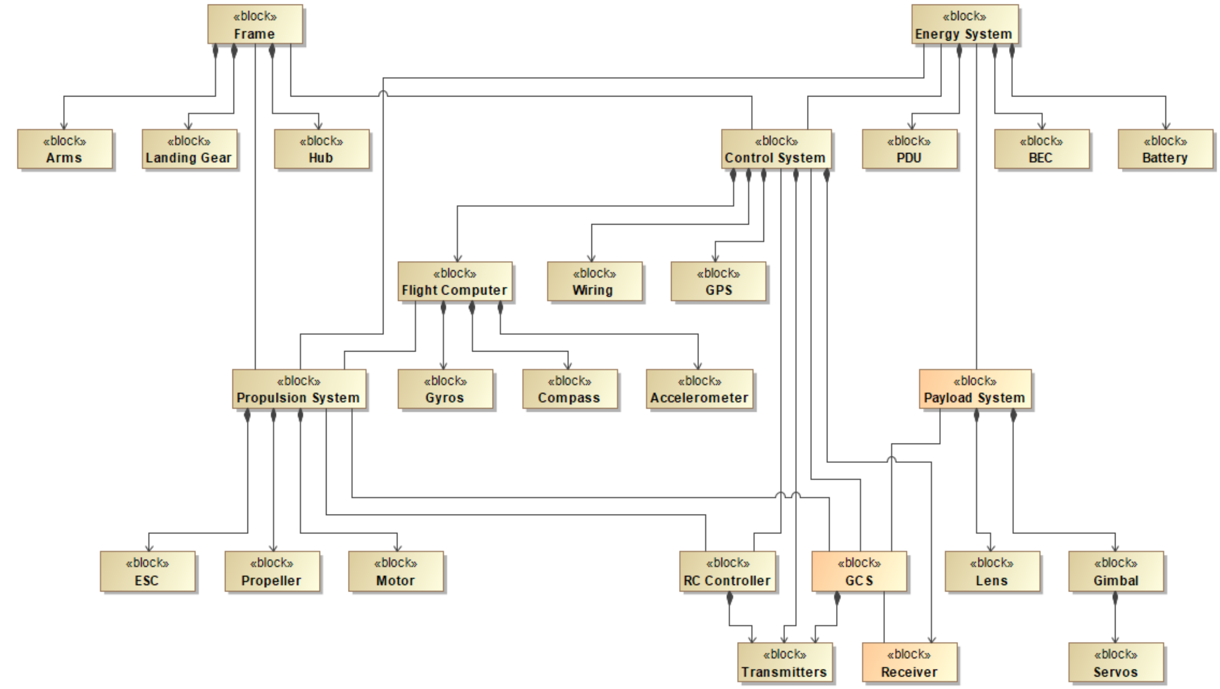


Figure 24. SUAS Physical Architecture

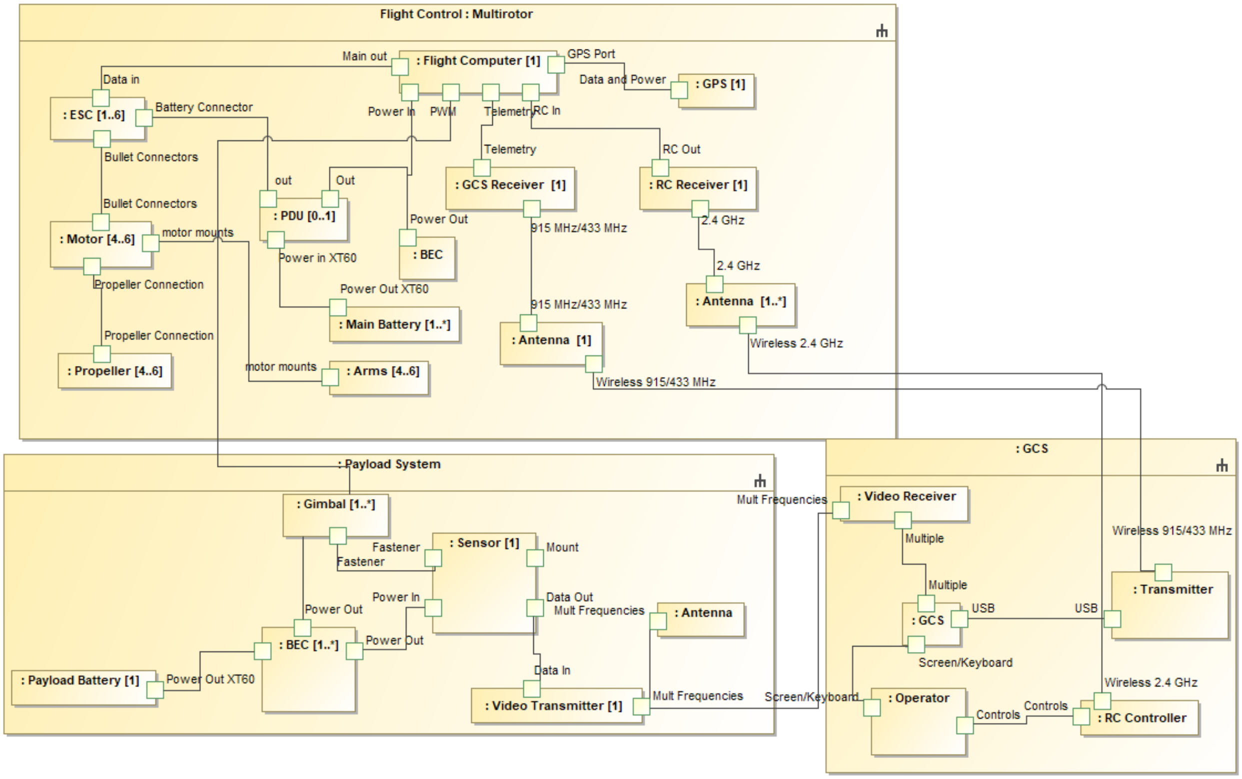


Figure 25. SUAS Internal Block Diagram

The physical architecture diagrams aid in developing design trades within the system. Design trades can be architectural, configuration, or component based. Architectural trades change the overall design of the SUAS system. An example would be implementing six motors versus four motors, driving a change of frame for a quad rotor to hexa rotor. Architecture trades allocate changes to the entire system. In the case of moving from a quad to hexa rotor changes the entire componentry of the system due to a larger frame. It also changes the layout of where components are placed and configured on the SUAS. Due to this trickle-down effect architectural trades must be considered first in the design process.

Configuration trades affect the number of components and/or the placement of components. An example of this is implementing a secondary battery designated for the payload system. This trade affects the wiring and powering configuration of the entire system. It also dictates if additional components are required for implementation, for example structural platforms, BEC, and PDUs. Since configuration trades change the layout, connections, and components within the SUAS, they must be considered second.

Finally, there are component trades. Within component trades there are two levels, simple trades and complex trade. Simple trades are component swaps without impacts on the systems architecture and limited impact on configuration. Changing to a more reliable motor with a similar KV rating would be an example of this, since the new motor can be integrated without impacts to the rest of the architecture and configuration. Complex component trades drive changes to the system architecture or have a major impact on configuration. In the case of the ISR mission, complex component trades involve selection of a sensor and the ability to transmit the sensor data. An example of this is changing from an analog video transmission system to a digital system. Digital transmission requires a change of transmitter and receiver pair, hardware and software video interface with GCS, camera and wiring changes.

Each design trade has a cost and benefit to the system. Cost and benefits are scoped and evaluated against system requirements. By balancing these trades against prioritized requirements, informed design decisions can be made for the benefit of the system. An analysis of example design trades against the established ISR mission is detailed in Table 27. Example components for commercial SUAS are listed within table for reference.

Table 27. SUAS Design Trade Space

Trade	**Benefits**	**Costs**	**Example**	**Type**
6 Motors	Motor redundancy, system can accept 1-2 motor loss, larger lift, bigger payload	Endurance, size, weight	Tarot 680 (hex) vs. Tarot 650 (quad)	Architecture
Frame PDU	Less parts/space/weight	Soldering, more wiring, exposed to elements	Tarot 650 Sport	Architecture
Sensor Gimbal	Range of video, decreased control burden on air vehicle, stable video	Complexity, weight, size, space, endurance	Yuneec Cgo3 4k	Configuration
Payload Battery	Endurance, Closed payload system for troubleshooting	Weight, space, set-up time	6S 10000 mah primary battery, 3S 850 mah payload	Configuration
BEC Power Regulator, opposed to ESC	Higher power reliability, less heating	Higher part count, weight, space	CASTLE-CSE010000400	Configuration
4 in one ESC	Less parts, less wiring, combines PDU and ESC, protected from crash	Cooling, hard to replace component if it fails, single point of failure, poor reliability for high energy	AIKON AK32 35A BLHELI_32	Configuration
Dedicated PDU	Less wiring, dedicated wiring hub	Soldering can be failure point	REALACC Matek Mini Power Distribution Board	Configuration
GCS Laptop	Better troubleshooting, robust user control, processing power	Weight, space, set-up time	Panasonic Toughbook	Configuration
GCS Tablet/phone	Simplified interface, lightweight, space, portability	Troubleshooting, user options	iPad mini	Configuration
GCS Open Source	User editability, rapid updates, security	Requires in depth knowledge of software	QGroundControl	Configuration

Trade	**Benefits**	**Costs**	**Example**	**Type**
GCS Closed Source	Stable baseline, simple interface	Limited to make changes, restricts component use, DoD security concerns		Configuration
Retractable Landing Gear	Increase video field of view	Weight, complexity	Tarot 650 Sport servo retractable landing gear	Simple Component
Plastic Propellers	Dampening vibrations due to material flex	Efficiency loss due to material flex, durability	Aerostar Composite Propeller 15x5.5 Grey (CW/CCW)	Simple Component
Carbon Fiber	Rigid to prevent flex, durability	Require balancing, prone to cracking from crash	KDE-CF155-DP	Simple Component
Folding Propellers	Storage size, store system with propellers mounted (reduce setup time), leading and lagging creates balancing effect, noise	Sensitive to fastener tension to mitigate flex, manufacturing to balance is difficult	KDE-CF155-DP	Simple Component
Traditional Propellers	Data availability, proven designs	Misbalancing of propeller in horizontal position, excess vibration, increase motor stress, storage	Dynam 15x5.5 Carbon Fiber Propellers for Multirotor (CW and CCW)	Simple Component
Triple Blade Propellers	Increased thrust for smaller propeller size	Endurance, efficiency	KDE-CF155-TP	Simple Component
FPV sensor	Weight, size, live video	Range, video quality	Runcam Eagle 2	Complex Component
HD sensor	Video quality, video storage	Latency, weight, size, possible RF interference, power	FLIR Duo, GoPro	Complex Component
Analog Video Transmission	Light components, low latency. Simple design will not freeze.	Poor video quality, low frame rate, no encryption	TBS Ground Station, 2.4 Ghz, Yagi antenna	Complex Component
Digital Video Transmission	Higher image quality	Image processing/ compression, latency, few out of box solutions	Amimon Connex LR	Complex Component

Frame Selection

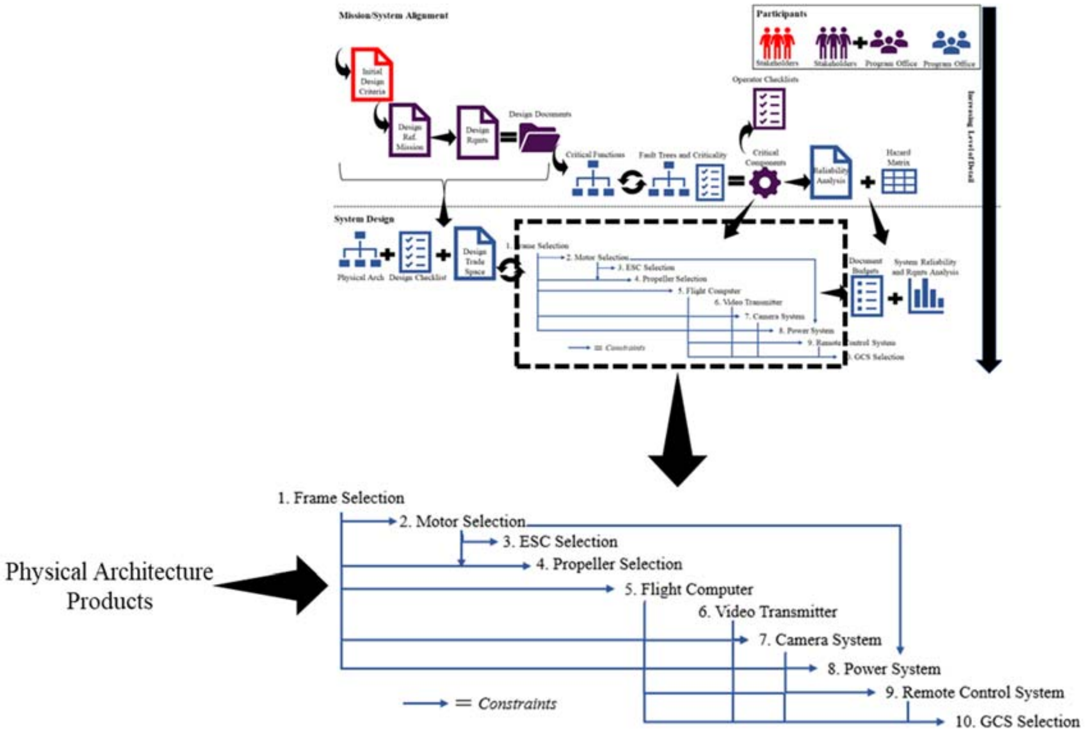


Figure 26. Component Selection Process

Designing the system is performed by progressing through the design trade space, evaluating decisions against the design checklist, and evaluating component selections against requirements. The first trade space area to evaluate is architectural decisions, based on frame selection. The frame affects the following requirements: endurance, transport, set up time, and number of operators required for set up. Following the design trade space, Table 27, the first trade is the number of motors. Research revealed current commercially available hexarotors are unable to meet the transport and endurance requirements established in Table 2. In turn, the design must be based on a quadrotor architecture. Commercially available quadrotor architectures were investigated. The candidate quadrotor architectures are presented in Table 28. These candidate architectures show either recommended componentry or proven builds by the manufacture, providing realistic endurance values. Frames were discriminated based on component integration space, endurance, and ease of transport.

Name	**Foxtech Hover 1**	**Foxtech F1000 Pro**	**Tarot Peeper**	**Tarot 650**	**Matrix-I**
Take-Off Weight	1400 g (battery excluded, as configured)	1900g	1565 g	476g, 1700g (total)	2177 g
Frame Material	Carbon Fiber	Carbon Fiber	Carbon Fiber hub, aluminum arms	Carbon Fiber	Carbon fiber and aluminum arms
Frame Type	Quad	Quad	Quad	Quad	Quad
Folded Dimensions	285 mm x 285 mm x 175 mm, Foldable arms	Detachable Arms with configured ESC, Motor, and propeller dimension of arm 310 mm. Quick disconnect.	Foldable arms to 750 mm, pre-assembled motors and esc	Foldable arms to 650 mm and landing gear. Air vehcle folds flat.	Foldable arms to 780 mm x 295 mm (w) x 110 mm (h)
Unfolded Dimensions	640 mm x 640 mm x 280 mm	560 mm X 160 mm (tall)	440 mm X 210 mm X 258 mm (tall)	650 mm X 650 mm X 170 mm	
Flight time	55 mins (as configured)	60 min	45-60 min	45 min	40-42 min
Motors	T-Motor MN3508	T-Motor U8 Pro, brushless	4008 Brushless Motor TK2955	T-motor Antigravity 4004	U5 T-Motor
KV	380	100	330	300	
Prop	Foxtech 15522 Folding Propeller	Foxtech Supreme 28"	TL 2948 17.5" Folding Props	T-motor 15x5 Carbon Fiber	15"
ESC	Hobbywing X rotor 40 A	T-motor Flame 60 A	40 A ESC	T-motor 25A 2s-6s Simonk ESC	40 A
Landing Gear	Foldable Aluminum	Carbon Fiber, detachable		Foldable carbon fiber	Static carbon fiber
GPS	Pixhawk	DJI A3			
Batteries	10000 mah 6s Li-ion	(2) Li-ion 12500 mah	Lipo 10000 mah, 6S		22000 mah 6s battery
Camera	HD 10 X zoom FH310Z or W (250g)	Multiple, exchangeable			Hero 4/ 3 Gimbal or 600TVL Camera
Gimbal	3 Axis				
GCS	Ipad Mini	Ipad			
RC Control/ Receiver	Futaba 14SG Radion Controller, Taranis X9D Plus RC	DJI Lightbridge/Futaba 14 SG		FrSky D8R-XP Receiver	Futaba EZUHF

Name	**Foxtech Hover 1**	**Foxtech F1000 Pro**	**Tarot Peeper**	**Tarot 650**	**Matrix-I**
Flight Computer	Pixhawk	DJI A3/DJI N3		3DR Pixhawk	Naza V2 Flight Controller
Environment		Rain Proof			
Feasibility	Possible design requires control redundancy. Room for components.	Too large/heavy to transport	Possible design, large folded dimension, low clearance for gimbal integration	Too large for transport, low endurance	Low endurance

Table 28. Quadrotor Frame Options

The frame selected was Foxtech Hover 1with a configured endurance of 55 minutes, room for additional components, small folding dimensions for transport. It was the only frame to meet the discrimination criteria. Table 29 shows more detailed specifications of the frame. The selected frame provides a take-off weight as configured, this weight includes 4 motors, 4 ESCs, 4 propellers, frame, landing gear, and wiring. This configuration provides a baseline for more reliable component swaps as progress is made in the design. Additionally, the frame selected does not include an integrated PDU. Exposure to weather elements and transport risk preclude PDU integration for the ISR mission.

Table 29. Quadrotor Frame Options (Foxtech, 2018; glassfox, 2017)

Name	Foxtech Hover 1
Take-Off Weight	1400 g (battery excluded, as configured)
All Up Weight	2300 g
Frame Material	Carbon Fiber
Frame Type	Quad
Frame Weight	596 g
Folded Dimensions	11.22 in x 11.22 in x 6.89 in, Foldable arms
Unfolded Dimensions	25.20 in x 25.20 in x 11.02 in
Flight time	55 mins (as configured)
Motors	T-Motor MN3508
Motor Weight	82 g
KV	380
Prop	Foxtech 15522 Folding Propeller
ESC	Hobbywing X rotor 40 A
Landing Gear	Foldable Aluminum
Battery	6S3P Lithium Ion 9500 mah
Battery Weight	900 g
Camera	FH310 Z 1080P w/3 axis gimbal
Camera System Weight	368 g

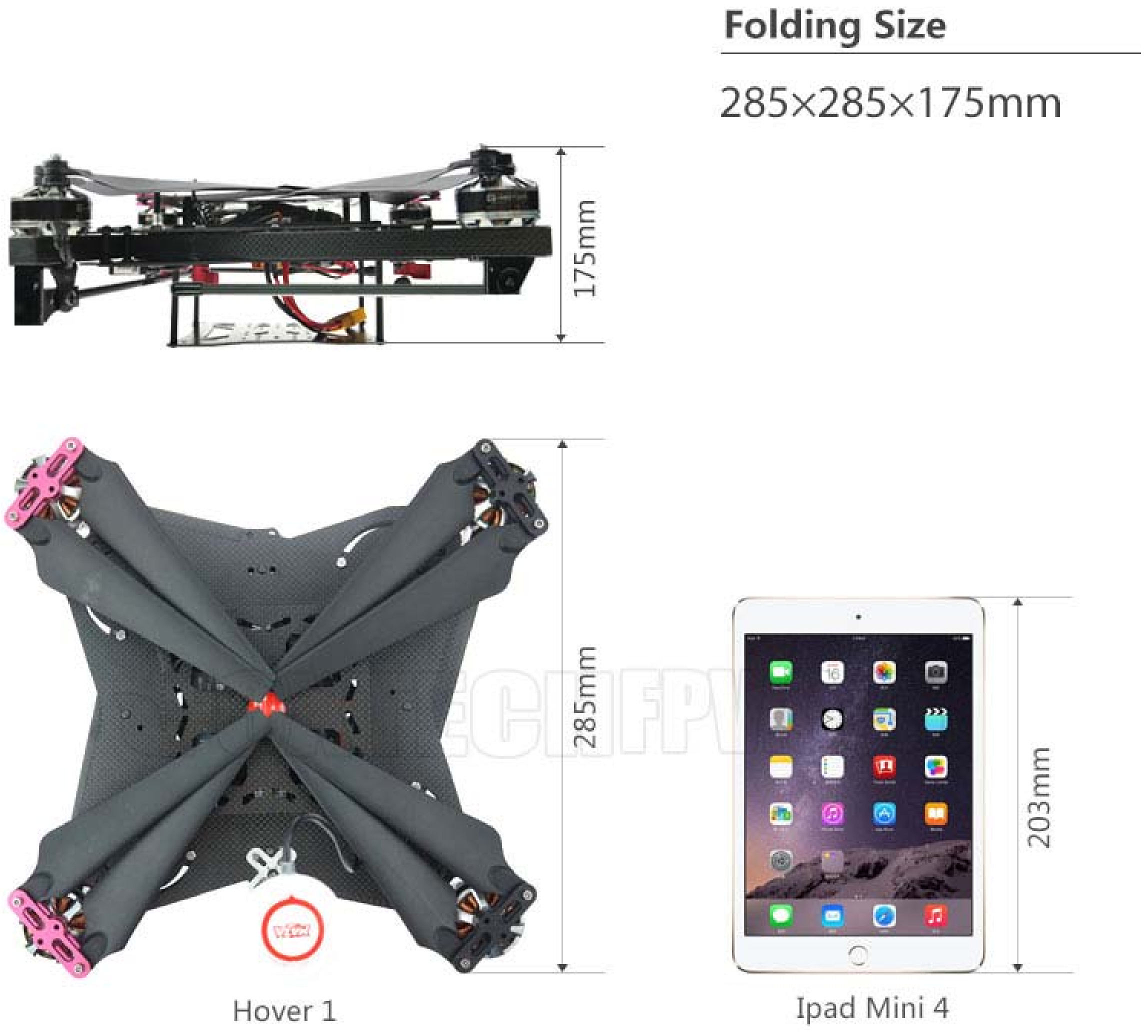


Figure 27. Foxtech Hover 1 Folded Dimensions (Foxtech, 2018)

Figure 28. Foxtech Hover 1 Unfolded Dimensions (Foxtech, 2018)

Evaluating the frame against the design check list for type/size category reveals the frame can support required components and meets the packaging requirement of fitting in a ruck sack of 22" X 14" X 9". It currently contributes 1.4 kg to the allocated 5 kg system weight. The material category for the frame is carbon fiber with aluminum legs which supports a high level of frame stiffness supporting controlled flight. Setup time for the frame, as configured, is 150 seconds by one operator; this includes deploying four arms, four landing gear, connecting a GPS, connecting a battery, and connecting a camera system (N, 2016). This setup time is within the 5-minute requirement objective and promotes operator design criteria of simplicity and prevention of betrayal. Landing gear are static which increases system reliability by eliminating a landing gear retraction servo. The landing gear are relatively small and are acceptable being within the proposed cameras field of view. Integration of a gimbal will be investigated to mitigate the impact of the landing gear on imagery.

Motor Selection

The next design point considered is motor selection. The Foxtech Hover 1 base configuration uses T-Motor MN3508 at 380 KV paired with 15” folding propellers. T-motors are a trusted brand and a quality motor selection, per online sources. Per T-motors website a 15” propeller at 50% on a 6 cell (6S) battery has power demand of 80 W, thrust of 820 g, and an efficiency of 10.26 g/W. With a thrust of 820 g/motor the total lift capability of the air vehicle is 3.28 kg at 50% throttle. All up-base configuration weight is 2.3 kg, therefore a 50 % hover is achievable. The power to weight ratio must be checked for the max thrust of the motors. At 100% throttle four motors produce 7.52 kg of thrust, dividing by air vehicle all up weight gives a ratio of 3.27. This meets the goal design checklist criteria of a power to weight ratio of 3. In fact, there is trade space with this value. A smaller 14” propeller could be used leveraging a higher efficiency albeit at the cost of thrust. With a 14” propeller 2.84 kg of thrust is produced at 50%, and the max thrust produced is 6.92 kg. Dividing this thrust by air vehicle all up weight gives a thrust to weight ratio of 3. If slightly more thrust and efficiency are required out of motor in order to handle additional weight or endurance, the T-Motor Antigravity 4006-380 are a design option. Paired with a 15” propeller the motor produces 805 g of thrust at 74.4 W with a 10.82 efficiency. Max thrust produced is 8.9 kg, giving a power to weight ratio of 3.87. Both motor’s recommend motor or bearing change after 60 flight hours (T-Motor, 2017, 2018a).

Figure 29. T-Motor MN3508 380 KV (T-Motor, 2018b)

Figure 30. T-Motor Antigravity 4006 KV380 (T-Motor, 2018a)

ESC Selection

With the motors selected, ESCs are selected and sized. The ESC design trade is either an ESC for each motor or a 4-in-one ESC. For the selected ISR mission single ESCs promote the operator's design criteria of simplicity. As previously stated, the number of parts the operator must interact with to operate or repair the system should be low and intuitive. Time is the operator's most valuable resource. While an ESC for every motor is four more parts than a 4-in-one ESC, the repair and troubleshooting are less time consuming. If a 4-in-one ESC fails all motors fails. In a 4-in-one ESC failure, the fault is not isolated, therefore the operator is unable to discern the cause of the failure. The failure may be the flight computer, battery, wiring, or ESC. Additionally, the 4-in-one ESC is often located in the center of the air frame for center of gravity purposes, this makes it more difficult to access, troubleshoot, and repair. Single ESCs are placed within the frame at the arm junction points, allowing for user accessibility. A quick inspection on a single ESC will reveal if a failure has occurred, as black burnt electronics will be visible. Design recommendations from AFIT's ANT Lab staff is to use ESCs for each motor for all multirotor designs. Their experience has revealed single ESCs are more reliable in handling current demands for multirotors greater than 1 kg.

Sizing for ESCs are based on current rating. Current rating is set at two levels, continuous and burst. The current the ESC will experience is based on the maximum current the motor will experience. These values can be determined by motor specification provided by the supplier. If the data is not provided by the supplier, the max current for the motor is determined by dividing the motor rated watts by battery voltage. For the ISR mission the SUAS is most likely using 6S or 4S lithium polymer or lithium ion batteries to achieve the required flight endurance. The S rating of the battery is the number of cells, each cell carries 3.7 volts. Therefore, a 6S battery carries a voltage of 22.2 V and a 4S 14.8 V.

For the two motor solutions selected the maximum amperage is provided by the suppler. Suppliers often test maximum amperage at motor efficiencies less than 100%, down to 80% efficiency. For a conservative design the assumed efficiency of tested by T-motor is 80%, a factor of 1.25 will be applied to the maximum amperage. MN3508 motor has a list maximum 14A, with a factor of 1.25 this raises to 17.5A (T-Motor, 2018b). The Antigravity 4006-380 has a maximum of 16A, with a factor of 1.25 this raised to 20A (T-Motor, 2018a). In turn, the design requires an ESC rated greater than 20A. A 25A Castle Talon ESC handling up to 6S battery is a good choice. This ESC comes with an 8A BEC for handling any servos required in the build, an example would be a gimbal. It provides a user manual for install, operation, and ESC mode programming (Castle Creations, 2013).

Figure 31. Castle Creations Talon 25 AMP ESC, 6S/25V with 8 AMP BEC (Castle Creations, 2018)

Propeller Selection

The next design decision is the selection of propellers. Sizing for the propeller is based on frame and motor limitations. The current frame unfolded diameter is 640 mm and can handle up to a 17” propeller. Both selected motors are specified at 15” with the MN3508 operating at 70°C and Antigravity 4006-380 46°C. The temperature was recorded on the surface of the motor in 100% throttle for 10 minutes. 70°C is a high operating temperature for brushless motors and operating at this level increases the probability failure. For a conservative design a 14” propeller should be paired with the MN3508 motors. The Antigravity motors allow for maximum 16” propeller but the operating temperature stated is HOT. In turn, the largest propellers safe for these motors are a 15.5” propellers, with a projected maximum temperature of 63°C.

In the case of the ISR mission, transportability is a critical function. The SUAS system must fit within the rucksack dimension in order to be transported to the deployment location. To achieve this the selected platform must be folded and stowed in the operator’s rucksack. To decrease deployment time folding propellers are preferred. The folding capability allows the propellers to be transported in an installed configuration on the frame. Folding propellers can induce frame vibrations and require proper torqueing of attachment points, this is a required preflight checklist step.

Material is also an important selection step. Current multirotor options are either plastic or carbon fiber. Carbon fiber frames are more rigid and providing more control and are more efficient than plastic. Brittleness from ground impacts is mitigated by carrying spares. A trusted brand of folding propeller is KDE. The KDE-CF155-DP is a 15.5” x 5.3 pitch propeller which meets the design criteria. The two bladed variant was selected over the three bladed variant since the design is for a small payload only, resulting in a low thrust requirement. KDE propellers are dynamically-balanced matched pairs and must be kept in set, meaning if one blade tip is damaged the entire propeller pair must be replaced. Selection of the KDE propellers eliminates the MN3508 possibility from the trade space due to overheating concerns from a large propeller.

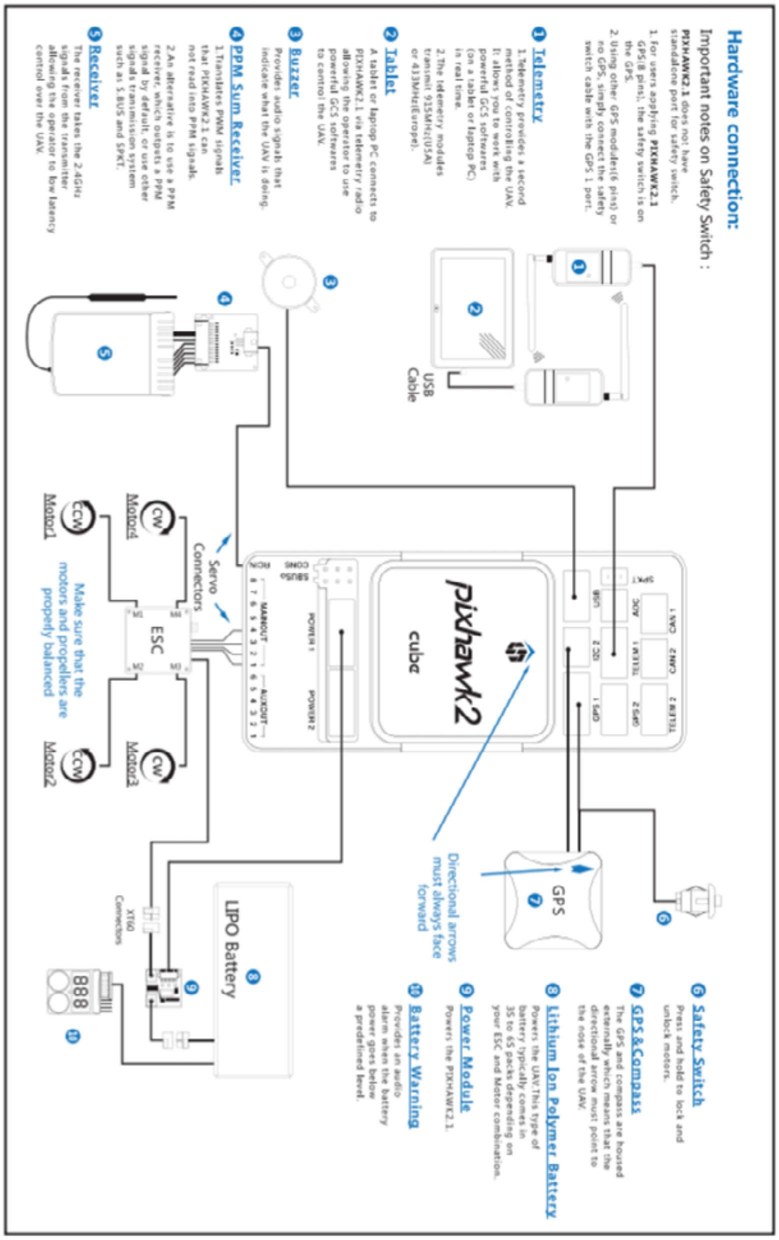
Figure 32. KDE-CF155-DP 15.5” x 5.3 Propeller (KDE Direct, 2018)

Flight Computer Selection

With the frame and the propulsion system established, the brain of the SUAS can be selected. The flight computer controls the functionality of the drone and bounds the user interfaces. In the ISR mission, the flight computer must handle dual control modes, programable flight and controlled flight. The main trade in for flight computers is open source software versus closed source. Top flight computers for open source are the Pixhawk family, and they include flight computers for various applications that run on the same software. User forums, documentation, software updates, troubleshooting guides are available to anyone for free at ardupilot.org.

The top-flight computers for closed source flight computers are built by DJI. Functionality of these computers are limited to what is provided in the device and software. DJI does provide the simplest out of the box solution, since the customer base is the general public with little to no drone experience. The DJI computers interface most reliably with DJI cameras and therefore limit design trade space. Recently the DoD has banned DJI drones and components over security concerns, citing "increased awareness of cyber vulnerabilities associated with DJI products (Newman, 2017)." Due to these security concerns the Pixhawk was selected as the flight computer for the ISR mission.

The current proven Pixhawk flight computer is the Pixhawk 2 Cube built by ProfiCNC. The Pixhawk 2 has a triple redundant isolated inertial measurement unit (IMU) system including accelerometers, gyroscopes, magnetometers, and barometers. It is also designed for operational conditions with enhanced drop and shock resistance. The Pixhawk 2 interfaces with Mission Planner or Qgroundcontrol mission planning software and telemetry information is transmitted either 915MHz or 433Mhz. Mission planning software can be run through a tablet, phone, or laptop. Included with the Pixhawk 2 is all required connection cabling, XT60 Battery Power module connector, micro USB cable, frame mounting pad, arming buzzer, and mounting screws. Figure 33 details the wiring diagram for the Pixhawk 2.



Hardware connection:

Important notes on Safety Switch :

PIXHAWK2.1 does not have standalone port for safety switch.

1. For users applying **PIXHAWK2.1** GPS(8 pins), the safety switch is on the GPS.
2. Using other GPS modules(6 pins) or no GPS, simply connect the safety switch cable with the GPS 1 port.

❶ **Telemetry**

1.Telemetry provides a second method of controlling the UAV. It allows you to work with powerful GCS softwares (on a tablet or laptop PC) in real time.

2.The telemetry modules transmit 915MHz(USA) or 433MHz(Europe).

❷ **Tablet**

A tablet or laptop PC connects to PIXHAWK2.1 via telemetry radio allowing the operator to use powerful GCS softwares to control the UAV.

❸ **Buzzer**

Provides audio signals that indicate what the UAV is doing.

❹ **PPM Sum Receiver**

1.Translates PWM signals that PIXHAWK2.1 can not read into PPM signals.

2.An alternative is to use a PPM receiver, which outputs a PPM signal by default, or use other signals transmission system such as S.BUS and SPKT.

❺ **Receiver**

The receiver takes the 2.4GHz signals from the transmitter allowing the operator to low latency control over the UAV.

❻ **Safety Switch**

Press and hold to lock and unlock motors.

❼ **GPS&Compass**

The GPS and compass are housed externally which means that the directional arrow must point to the nose of the UAV.

❽ **Lithium Ion Polymer Battery**

Powers the UAV.This type of battery typically comes in 3S to 6S packs depending on your ESC and Motor combination.

❾ **Power Module**

Powers the PIXHAWK2.1.

❿ **Battery Warning**

Provides an audio alarm when the battery power goes below a predefined level.

Figure 33. Wiring Diagram Pixhawk 2 Cube (Hex, 2018)

Select Video Transmission System

The two most common transmission frequencies for video are 2.4 GHz and 5.8 GHz. 2.4 GHz provides the longest range and best penetrating frequency for video transmission. This frequency is also the most popular for remote control transmitters therefore, deconfliction between the two must occur to achieve reliable vehicle performance. With 2.4GHz being the main frequency for remote control, 5.8 GHz is the most popular frequency to gather first person video from the drone. At this frequency video latency is adequate but range and obstacle interference become a concern. Companies are experimenting with different frequencies; FPV Blue released a digital video system in 2017 which transmits at 1.2GHz, promoting a range of 7 km with less than 50 ms latency at 720p video (FPV Blue, 2018). This system is still in beta development but shows future promise in image quality and range for live video systems. In addition to frequency, antenna types, antenna directionality, and transmitter power can affect the range of the transmission. For the ISR mission the 5.8GHz is the selected video frequency due to maturity of the technology and commercial availability.

The next design trade to consider is digital transmission versus analog. Analog transmission has benefits of direct signal, low latency, and large component market. Disadvantages to analog include low image quality, signal interference, low frame rate, and lack of encryption. Digital transmission provides high image quality at the cost of latency due to signal conversion. While A low latency rate is important for racing drones due to rapid position and speed changes, it is deemphasized in favor of image quality in aerial photography drones. The ISR mission requirements align closely with aerial photography, therefore a digital system is preferred over analog.

A current out of the box digital transmission solution at the 5.8 GHz frequency for over 1-mile range is the Amimon Connex LR Receiver paired with the Connex Mini Transmitter. The system offers a directional range up to 3 km or 1.8 miles with HDMI out video. Video formats range from 1080p to 576p at less than 1 msec latency. The receiver system is easily backpack portable at 660 grams and dimensions of 7.9 in X 7.9 in X 2 in. Power for the receiver is provided by a 3S-6S lithium polymer battery through a provided XT90 or XT60 connector. For maximum range a tripod is required for the receiver where the main lobe of the system's five antennas spread 70° horizontally and 25° vertically. It is important to position the flight of the SUAS within this spread to achieve maximum range.

The system provides the following information to be displayed on the GCS: video strength, distance, video resolution, selected frequency, bandwidth, home location arrow. Additional telemetry information such as height, yaw, ground speed, flight mode, number of GPS, and aircraft battery charge may be displayed when the transmitter is connected to flight computer. The Connex system is compatible with the Pixhawk family of flight computers. Both the transmitter and receiver can be updated with required firmware provided by Amimcon. Additional specifications, performance parameters, and installation instruction can be found in the Connex LR Manual (Amimon, 2018).

Figure 34. Amimon Connex LR Receiver and Connex Mini Transmitter (getfpv.com, 2018a, 2018b)

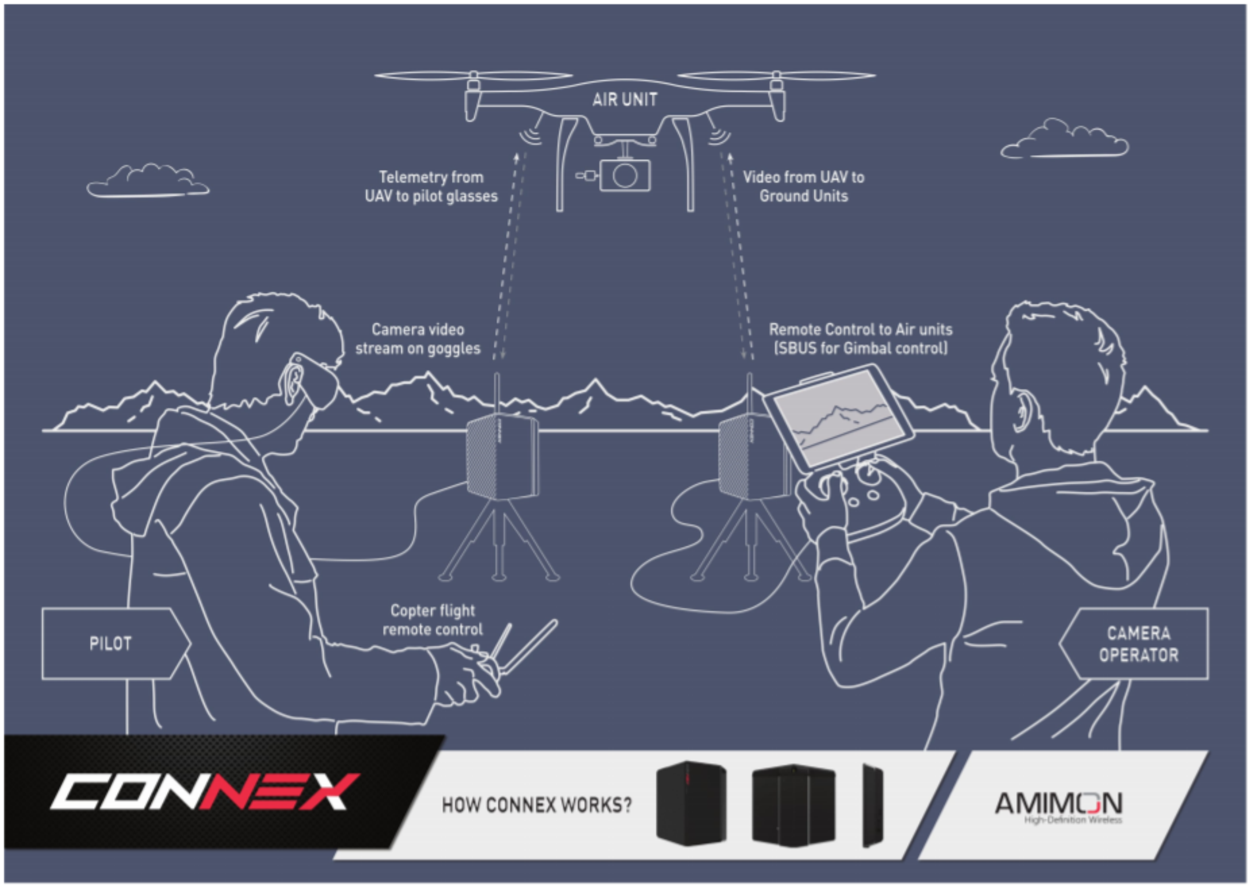


Figure 35. Concept of Operations Connex LR Video Receiver (Amimon, 2018)

Camera System Selection

The first design decision for the camera system is to incorporate a gimbal system. A gimbal provides user-controlled range independent of the air vehicle enabling stable image viewing. The selection of a gimbal comes at the cost of weight, power, and complexity, affecting requirements of endurance, user set time, and number of operators. Gimbals add from 100-300 g of payload and consume approximately 200-350mA, this can reduce endurance by up to 5 minutes in the established endurance model, Table 33.

In the transportation of the SUAS, the gimbal is required to be separate for the air vehicle, due to rucksack space limitation. This attachment process for the gimbal, prior to launch, can add 1-2 minutes of operator install time. The addition of the gimbal can also complicate the control structure of the SUAS in flight; if the flight is being controlled by remote control, gimbal operation may require a second operator due to task saturation. For an ISR mission to be successful some sort of intelligence must be gained by the operational user, a gimbal stabilizes the data provided by a camera maximizing the quality of the intelligence. The cost to the systems requirements from a gimbal is within the acceptable trade space, therefore a gimbal is recommended for better ISR capability.

The second design decision is to incorporate a HD camera or a First-Person View (FPV) camera. Since the selected video transmitter is digital and HD capability a HD camera is selected for the design, promoting better image quality. The recommended camera system for the Foxtech Hover 1 frame is the FH310Z 1080p HD 10X Optical Zoom Camera with 3-Axis control. The gimbal system is designed to match the Hover 1 frame and mounts easily on the lower platform. The camera can display live day time video up 1080p, when paired with the Connex system. Additionally, the camera can record video while in flight through a 32 GB SD card slot. Camera functionality of zoom, move, and mode control can be integrated into the flight control transmitter for operator remote control. Mode controls include photo shoot, video recording start/stop, and live feed selections. The system demands static current of 240mA at 12V or 320mA at 12V. All up-system weight is 370g with the camera weight 110g and the gimbal weighing 260g. Figure 36 shows the FH310Z camera with gimbal system and Figure 37 shows the camera system mounted on the Hover 1 platform.

Figure 36. FH310Z Camera with Gimbal System (Foxtech, 2017)

Figure 37. FH310Z Camera with Gimbal System Mounted on Foxtech Hover 1 Platform (Foxtech, 2017)

Power System Selection

Trades for the power system include battery chemistry type, cell count, and inclusion of a payload battery. Proven battery chemical technology for SUAS include lithium polymer or lithium ion. Lithium polymer batteries have become popular due to high C rating or discharge capability. Lithium polymer batteries with medium capacity, 8,000 mah to 10,000 mah, have a C rating ranging from 10 to 30 C, while similar lithium ion batteries possess C ratings of 3C to 5C. The C rating on the battery determines how much amperage can be safely drawn by the motors. This max safe current draw per motor is determined by multiplying the rated battery capacity by the C rating and dividing by the number of motors. This value is then compared to the motors current draw at 100% throttle for design viability.

The selected Antigravity motors provide data for a 16” propeller with the maximum current draw at 100% throttle of 17.5A (T-Motor, 2018a). With four motors, the required current for the propulsion system is 70A. A lithium ion battery with a 9,000 mah capacity and 5C rating can provide a total of 45A. Since this value is less than the required 70A, lithium ion batteries are not a viable design. Conversely, a 9,000 mah lithium polymer battery with a 10C rating provides 90A meeting the design requirements. Therefore, a lithium polymer battery is selected for the ISR mission.

Cell count is described in series and parallel for batteries. Cells in series add 3.7 volts for each cell to the overall battery voltage. For example, a 6S or 6 series cell has a voltage of 22.2 and a 4S has a voltage 14.8. Higher battery voltage allows for lower current draw, less voltage sag, and higher response in motors. These performance improvements come at the cost of added battery weight, which may reduce endurance. For mission reliability purposes the lower current draw keeps the battery cooler battery during flight, promoting maximum life for the battery.

From a user control perspective 6S batteries enable a more responsive multirotor due to lower voltage sag under load, enabling the motors to change RPM more rapidly (Liang, 2018). For the ISR mission responsiveness is important to prevent enemy detecting and for taking evasive maneuvers to ditch the air vehicle. For these reasons a 6S battery is desired.

The final design point for the power system is for a payload battery. Payload batteries allow the operator to independently test and troubleshoot the payload system prior to flight without effecting endurance time. Of course, an added payload battery adds weight for both the air vehicle and the operator to transport to the deployment location.

In flight, the payload battery does add another failure point to the system, if the payload battery fails the functionality of surveillance is not upheld. Although the criticality of this failure is reduced, in most cases, from a category I to a category III. The operator will be able to recover the aircraft, isolate the fault to the payload system, and replace the defective component with a spare within a short period of time. Conversely, if the system only contained a primary battery and this component failed the air vehicle will no longer perform the function of flight, and the mission would terminate. These risk mitigations for both preflight and in-flight show that use of a payload battery is warranted if the threshold requirement value of endurance can be meet.

From the above discussion the system will include two batteries, primary for flight and secondary for payload. The primary battery will be a 6S lithium polymer. Current ratings for the battery selected is based on endurance calculation aimed at achieving the threshold requirement at 45 minutes of flight with the associated all up weight for the air vehicle. A current trusted brand for multirotors recommend by the ANT Lab staff and online drone blogs is Multistar batteries. This brand experiences low level of failures in flight and provides nominal flight performance. A Multistar High Capacity 10000mAh 6S 10C Multi-Rotor Lipo Pack XT90 at a weight of 1189g provides a projected flight time of 48 minutes per endurance calculations performed in Table 33.

Figure 38. 10000mAh 6S 10C Multi-Rotor Lipo Pack XT90 (Amazon, 2018)

Flight Remote Controller Selection

The transmitter of the remote controller is what the operator uses to send commanded input to the air vehicle. The receiver on board the air vehicle receives the commands from the operator and sends the commands to the flight computer to perform the actions. Important aspects to consider for the remote controller pair is range, ease of use, functionality, and durability.

A leading brand for flight controllers and revivers is Futaba. Remote control forums and user reviews place trust in Futaba for reliability, range, and build quality. The Futaba T14SG is considered on one of the most reliable transmitters on the market ("Which Is The Best Quadcopter Transmitter?," 2018). It includes 14 channel control or 14 functions commands which can be sent to the aircraft. This is useful for the operator to control the flight of the air vehicle and to control the camera system when the flight of the air vehicle is being controlled by the autopilot. User reviews and groups describe the maximum range of the 2.4Ghz transmitter at 4.5 km or 2.8 miles. This range is evaluated at a clear line of sight and is reduced to under a mile with obstacle interference. The Futaba T14SG transmitter can contain up to 30 models, meaning 30 different SUAS or configurations can be flown with the same transmitter. The transmitter also has the ability to receive telemetry, battery, and link data to a 1.75 X 3 in backlit LCD screen, providing critical information to the operator. Another benefit of this transmitter is that it can be paired with any Futaba 2.4Ghz receiver, further increasing the systems modularity (Futaba, 2018). With any remote-control system, it is important for the operator to train and become familiar with the controller's function and feel, to mitigate any potential user induced error into the system.

Figure 39. Futaba T14SG transmitter (Futaba, 2018)

GCS Selection

With the selected flight computer as a Pixhawk 2, the GCS software is bounded to open source options. Popular software includes Mission Planner, APM Planner 2, MAV Proxy, QGroundControl, and UgCS. The only software which is compatible with all platforms to include Windows, Mac OS X, Linux, Andriod and iOS is QGroundControl (ArduPilot Dev Team, 2016). This maximizes platform flexibility and minimizes the amount of software operational users must be familiar with. Key interface features of QGroundControl are mission planning for autonomous flight, flight map display of vehicle and tracking information, video streaming with instrument displays, and support for multiple vehicles. Software downloads and complete user guide is available online at https://docs.qgroundcontrol.com/en/.

The next step for the GCS for the ISR mission is selecting the appropriate hardware. Options for hardware are laptop, tablet, phone, or a combination of devices. To meet the mission planning time objective of 10 minutes a laptop is preferred. The laptop configuration allows the operator to plan and view routes on a larger screen, input commands with a touchpad and keyboard, and access more features of the software. Once the air vehicle is set up and routes are planned, a phone configuration is desired for mission viewing and any route deviation. A phone can be mounted on the flight transmitter, enabling the operator to view mission progress and video feed through the phone while controlling the air vehicle. A two GCS system allows one operator to focus on flight and another operator to focus on surveillance, mitigating risk for each function. Since two operators for operations is a threshold requirement, this is an acceptable trade. A Panasonic Toughbook is an excellent option for handling a rugged deployed environment for a primary GCS handling drops, humidity, high temperature, and vibrations. Packing weight for the Toughbook is 4.2 lbs at 10.7” x 13.6” x 1.2”.

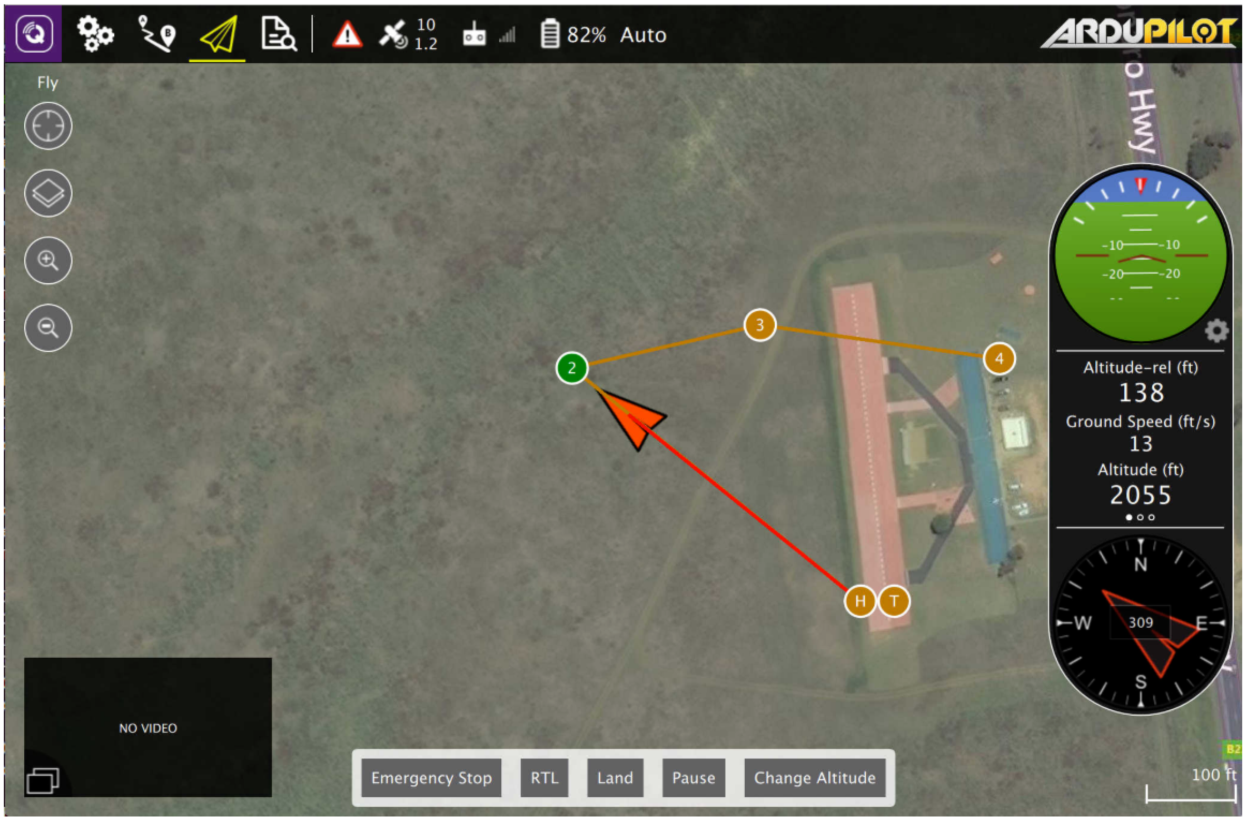


Figure 40. QGroundControl User Interface (“QGroundControl User Guide,” 2018)

Budget Allocation

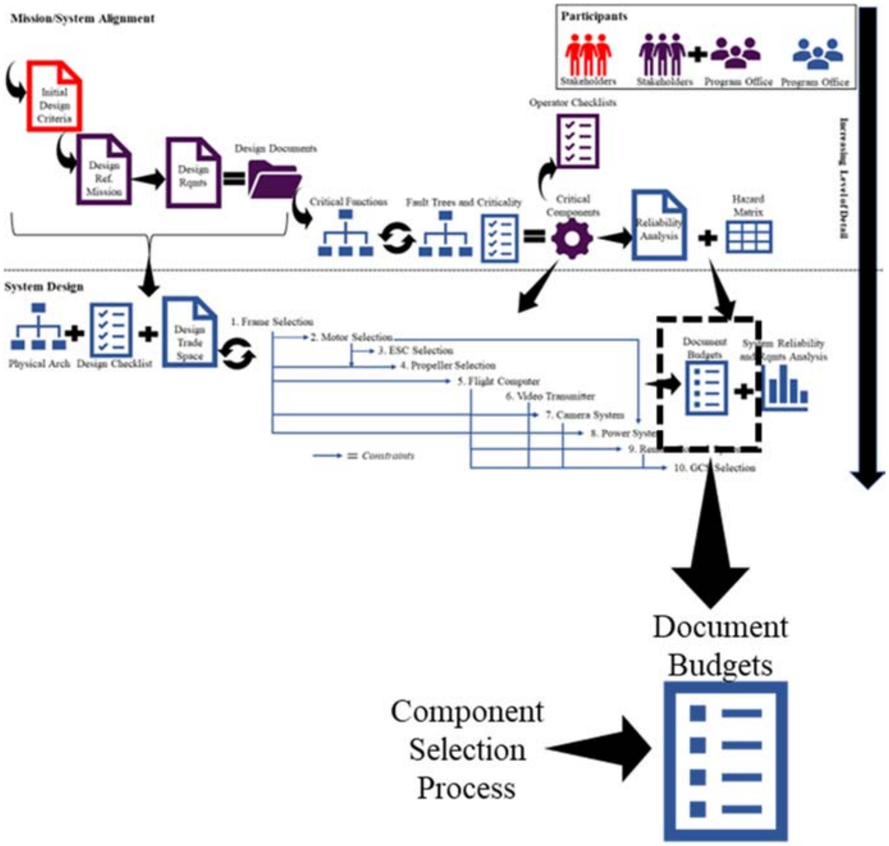


Figure 41. Budget Allocation Process

Once all components are selected for the ISR mission the budgets for frequency, weight, and power must be allocated. The frequency budget ensures the telemetry, command and control, and video signals are within their own band, preventing harmful system interactions. Table 30 shows the signal frequency for the selected components. All systems are in separate frequency bands and the system is projected to perform nominally.

Table 30. Frequency Budget

System	Component	Frequency
Flight Telemetry	3DR Telemetry Radio Transmitter/ Receiver	915MHz or 433Mhz
Video Transmitter	Connex LR System	5.8GHz
Remote Control Transmitter	Futaba 14SG Transmitter and Receiver	2.4GHz Frequency Hopping

The next budget to perform is the weight allocation for both the air vehicle and additional components. The weight of the air vehicle is important since the threshold requirement is 5 kg and is also a critical piece of information for endurance calculations. The additional components weight, used for ground support, provide the total system weight. Components not previously mentioned for the air vehicle include HERE+ GPS, Pixhawk 2 Power Module (5V), 850mAh 3S lithium polymer payload battery, and additional wiring. Combined with the previous air vehicle components this provides an all up weight of approximate 3 kg. Components not previously mentioned for the additional components include a tripod transmitter mounting and 5200mAh 4S lithium polymer for transmitter power. Additional component weight is approximately 5.2 kg bringing the complete system weight to 8.3 kg. Table 31 details the componentry weight for the ISR SUAS. Included in the table is the system cost and air vehicle cost, where air vehicle cost include all components except GCS, RC transmitter, Video receiver, and tripod.

Table 31. Weight Budget with Cost

Component	**Air Vehicle Weight (g)**	**Pack Weight (g)**	**Cost ($)**
Hover 1 Frame	596		1400
4X Antigravity MN4006 Motors w/wiring	272		300
4X KDE-CF155-DP 15.5" Folding Propellers	58.8		156
4X KDE-DPA-ML Propeller Adapters	56		80
4X Castle Talon 25 AMP ESC w/wiring	71.6		180
Pixhawk 2 Cube	39		250
Pixhawk 2 Power Module	24		Incl w/Comp
Here GPS	49		95
Connex LR Video Receiver		660	1750
Connex Mini Transmitter	60		650
Telemetry Transmitter/ Receiver	15	15	25
Camera	108		Incl w/Frame
Gimbal	260		Incl w/Frame
850mAh 3S Lipo Payload	83		10
10A 6S Lipo	1189		120
Other Wiring	100		25
Tripod		1180	100
5.2 A 4S Lipo		430	50
Futaba R7008SB Receiver	10.9		165
Futaba 14SG Transmitter		980	650
Panasonic Toughbook		1905	1450
Sum	**2992.3**	**5170**	$7,456
Air Vehicle Only Cost (less GCS, RC Transmitter, and Video Receiver)			$3,456

The last budget is performed on the power system. The power system is divided into two sections depending on their power source. The budget evaluates all components that demand power, less the motors. The control section, powered by the main battery, powers the Pixhawk 2, Futaba receiver, and telemetry receiver. The video section, powered by the payload battery, includes the gimbal, camera, and Connex Mini transmitter. Power draw values obtained from the product specifications are provided in Table 32, along with required power levels. The control system power level is managed by a 5V Pixhawk 2 power module and the video system is managed by direct voltage from the 3S payload battery at 11.1V.

Table 32. Power Budget

Component	**Power Draw (mA)**	**Power (V)**
Pixhawk 2	280	4.8 to 5.4
Connex Mini Transmitter	400	8 to 26
Gimbal + Camera	280	11 to 12
Futaba Receiver	75	3.7 to 7.4
Telemetry Transmitter	25	3.7 to 6
Sum Control	**380**	
Sum Video	**680**	
Sum	**1060**	

Hover Endurance Calculation

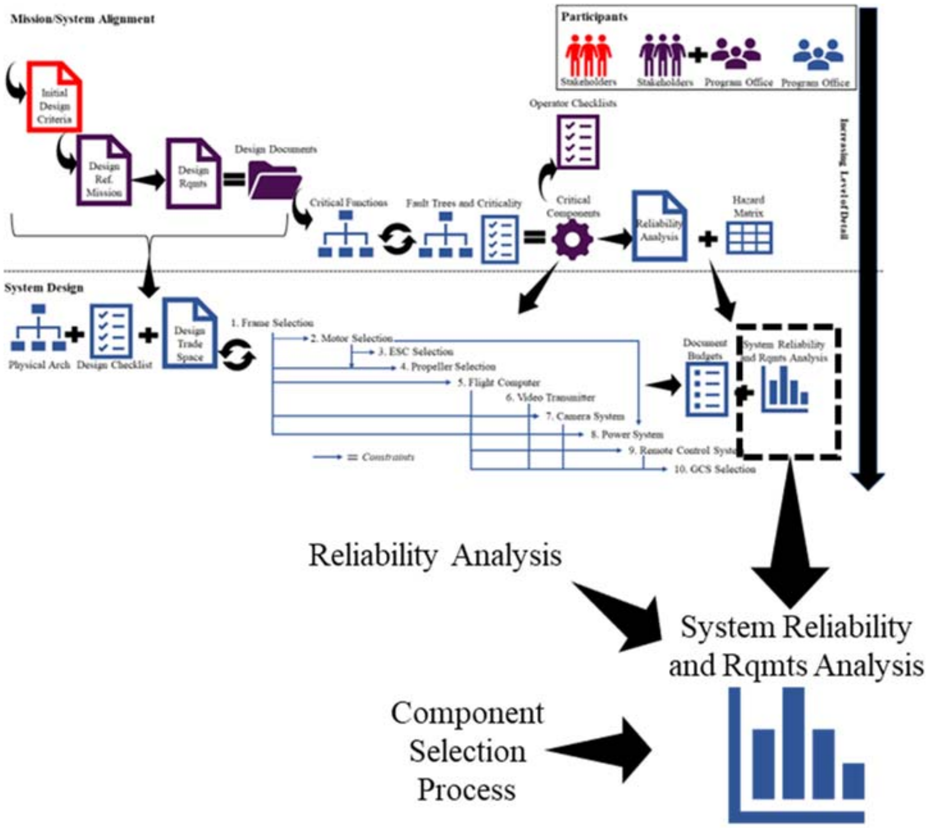


Figure 42. System Reliability and Requirement Analysis

With the power demand and all up weight determined for the air vehicle the hover endurance can be calculated. Using the propeller momentum theory, the theoretical time in hover can be calculated for the system (Phillips, 2004). The power required per propeller ideal is calculated using Equation 2. The propeller efficiency is set at 90% and air density is calculated at sea level and 20 °C.

$$Pii = 2A_p\rho * \frac{\left(\sqrt{\frac{mg}{2A_p\rho n}} * \left(\frac{1}{0.98}\right)\right)^3}{\eta_p} \qquad (1)$$

$$where\ \rho = 1.204\frac{kg}{m^3}, g = 9.81\frac{m}{s^2}, A_p = \pi * \left(\frac{diameter\ of\ propeller}{2}\right)^2, n = \#\ of\ props,$$

$$m = all\ up\ mass\ of\ vehicle, \eta_p = prop\ efficiency$$

The ideal power per propeller fails to incorporate inefficiencies in electric motors, to account for this Equation 3 is used. For a brushless motor 85% efficiency is standard. The current per motor is calculated using Equation 4 based on the volts per cell, number of cells, and efficiency of the battery. The total current of the system is calculated by the current per motor multiplied by number of motors plus additional current required for the system, this is shown in Equation 5. The ISR SUAS has four motors and has an additional current requirement on the main battery of 0.38A for control systems, seen in Table 32.

Finally, the time in hover is calculated by accounting for the battery capacity, percent usable battery capacity and the efficiency of the battery. For the developed SUAS, the battery capacity is 10000 mah, a usable percentage of 85%, and an efficiency of 90%. Equation 6 shows this calculation. Table 33 shows the parameters and calculated information for the ISR SUAS hover time. The table shows a projected hover time of 48 minutes. This is a theoretical value and requires real world testing to determine the operational endurance incorporating factors such as humidity, temperature, wind, transitional lift, and system losses.

$$Pi = \frac{Pii}{\eta_m}, where\ \eta_m = motor\ efficiency \tag{2}$$

$$I_{i=} \frac{Pi}{V_C\, n_c}, where\ V_C = \frac{volts}{cell}\ and\ n_c = \#\ of\ cells \tag{3}$$

$$I_t = I_i * n + aux\ current, where\ n = \#of\ motors \tag{4}$$

$$t_h = \frac{c_b * f_u * \eta_b}{I_t} * \left(60\,\frac{min}{hr}\right), where\ c_b = battery\ capacity, f_u = \%\ usable\ capacity,\ \eta_b = efficiency\ of\ battery \tag{5}$$

Table 33. Endurance Calculations

mass w/o primary battery and motors[kg]	1.531
gravity[m/sec^2]	9.81
air density[kg/m^3]	1.204
prop diameter[in]	15.5
prop diameter[m]	0.3937
prop efficiency	0.9
motor efficiency	0.85
number battery cells	6
rated battery capacity [Ah]	10
battery voltage[volts]	22.2
battery mass [kg]	1.189
nbatteries	1
battery efficiency	0.9
f_usable	0.85
total usable batt capacity [A hr]	7.65
nmotor	4
motor mass[g]	68
aux_current[A]	0.38
battery C rating	10

Area P[m^2]	0.12
Total mass[kg]	2.99
total mass lbs	6.58
P_prop_ideal, Pii[W]	43.34
P_prop_reqd, Pi[W]	50.99
I_motor_reqd, Ii[A]	2.30
I_total, It[A]	9.57
t_endurance, th[min]	**47.98**

Max safe Amp draw [A]	100
per motor [A]	25

System Reliability

Using the component reliabilities researched in Table 21, a theoretical system reliability can be determined. The components researched support either flight or surveillance functions. If either of these functions fail while the SUAS is performed a mission, a total system failure has occurred. Components that enable flight for the ISR SUAS are a flight computer, 4 motors, frame, a primary battery, 4 ESCs, a BEC, a telemetry transmitter/receiver pair, a remote-control transmitter/receiver pair, and GCS.

All components except the transmitter/receiver pairs are in series configuration, meaning if one component fails in the chain the function of flight fails. Since the SUAS can be controlled by either autopilot or remote-control modes, this configuration allows one mode to fail and the system will still perform the function of flight. This leads to a parallel configuration for the transmitter/receiver pairs.

Equation 7-9 show the calculations for system reliability for series and parallel systems respectively. Figure 43 shows the average reliability for the flight system of 0.8656, R1. Each component or component group displays its respective failure rate, λ, and reliability, R. Propeller failures are attributed to FOD contact in the environment, if this failure is mitigated by a clear operational environment the flight system reliability increased to 0.933, R2. The surveillance function has just three component types, a camera, payload battery and a video transmitter/receiver pair. The gimbal system is ignored in this analysis, its failure does not promote a critical category I failure. In other words, the surveillance function still occurs when the gimbal fails, this is a type II failure category. Figure 44 shows the reliability diagram for the surveillance system. For the SUAS system reliability the flight system reliability and surveillance system reliability are multiplied together. This creates two average system reliabilities, with propellers is 0.8615 and without is 0.9286. The resulting system MTTF is, per Equation 10, are 6.86 hrs with propeller failure and 13.63 hrs without propellers failures.

For a point of comparison, the MTBF for a car can be evaluated. MTBF is used as the criteria since a car can be repaired and put back into servable condition. A car has three critical subsystems that must function for the car to drive and transport people. These subsystems are the power train, tires, and brakes. Each subsystem has an associated MTBF based on a driving profile, these MTBFs are then added for a system MTBF, per Equation 11. The power train has a 1500 hrs MTBF for 90,000 miles at 60 mph, the tires have 1000 hrs MTBF for 60,000 miles at 60 mph, and the brakes have a 666 hrs for 40,000 miles. These subsystem MTBF result in a car MTBF of 315 hrs (Hamby, 2003). Reliability for a given operating time completed or conditional reliability can be computed using Equation 12. For a 1.5 hrs operating period, equivalent to two SUAS missions, the SUAS reliability is 89.58% while the car reliability over the same period is 99.52%. The SUAS reliability is determined without propeller failures.

$$R_{series} = R_1 * R_2 * R_3 \ldots \tag{6}$$

$$R_{parallel} = 1 - [(1 - R_1) * (1 - R_2) * (1 - R_3) \ldots] \tag{7}$$

$$R_{system} = R_{series} * R_{parallel} \tag{8}$$

$$MTTF = \frac{1}{\sum \lambda_{series} + \frac{2\lambda_{Parallel}}{3}} \tag{9}$$

$$\frac{1}{MTBF_s} = \frac{1}{MTBF_a} + \frac{1}{MTBF_b} + \frac{1}{MTBF_c} \tag{10}$$

$$R = e^{-\frac{t}{MTBF}} \tag{11}$$

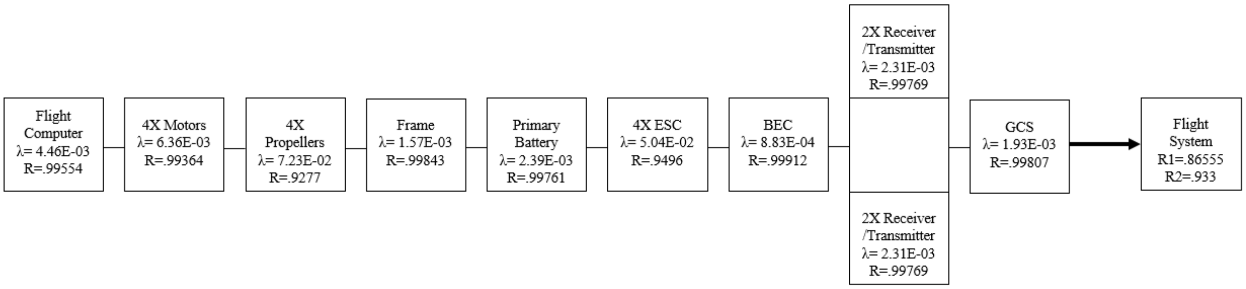


Figure 43. Reliability Block Diagram, Flight System

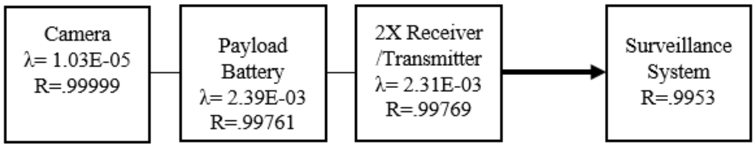


Figure 44. Reliability Block Diagram, Surveillance System

Requirements Analysis

Table 34 details the projected performance of the selected ISR SUAS for each requirement. Setup time, ISR-1, which has a threshold value of 10 min is met by the ISR SUAS with a projected time of 6 minutes. This time includes 150 seconds for air vehicle setup from a backpack, 60 seconds for video receiver setup on tripod, 60 seconds for primary and secondary battery, 60 seconds for remote control system setup, and 30 seconds for GPS initialization. This time is projected for one operator setting up the system, the time may be reduced with and additional operator.

ISR-2, mission planning time, objective is projected to be met using QGroundControl as the GCS software and a laptop as the GCS hardware. QGroundControl is a user-friendly interface for mission and route planning but does require operator training for efficient use. A laptop as a primary GCS enables quicker functionality for mission planning opposed to a tablet or phone. As previously mentioned, the system can be set up by one operator but is recommended to have two operators set up to reduce set up time. With two operators, one operator can set up the video system while the other sets up the air vehicle, reducing the set-up time to the objective value of 5 minutes.

ISR-4, deployment range, is limited by the video system. The selected LR Connex 5.8GHz video receiver has a max directional range of 1.8 miles with a clear line of sight. The remote control and 433Mhz Pixhawk 2 Autopilot have ranges greater than 1.8 miles. Signal condition can impact this range and requires system level testing to prove out the SUAS range.

ISR-5, resolution, has a threshold value of 30 pixels/m^2 to identify and track a moving vehicle. With the selected FH310Z 1080p HD camera a 30 pixels/m^2 can be met from 0-395 m without the aid of the 10x zoom function of the camera, using the zoom function will only increase this pixel density. Equation 13 was used to calculate the pixel length in meters for both the x and y direction (“DIY Drones,” 2013). Pixel density is determined by finding the number of pixels in $1m^2$ or taking 1/P and multiplied for both x and y values.

ISR-6, ensures the vehicle can hover over the target for 10 minutes. Hover over target is enabled in the ISR SUAS by using either position or altitude hold flight modes while controlling in remote control or autopilot flight. Since the air vehicle has a theoretical hover 48 minutes, the vehicle has time to transverse to the max range.

$$\frac{\theta\left(\frac{2\pi}{360}°\right)r}{N_x\,g} = P \tag{12}$$

$N_{x,y} \; = number\ of\ pixels\ in\ x\ or\ y$

$\theta = lens\ field\ of\ view\ (FOV)\ in\ degrees,$

$r = altitude\ in\ meters\ above\ ground,$

$g = effectice\ pixel\ cover\ for\ distortion, 90\%\ used,$

$P = length\ in\ meters\ for\ each\ pixel\ of\ the\ camera$

Table 34. Requirement Analysis for ISR Mission

Rqmt	**Description**	**Objective**	**Threshold**	**Priority Level**	**Projected**
ISR-1	Setup of system from unpacking to ready for launch shall be	5 min	10 min	2	150 Sec for AV, 60 sec for video system, 60 sec for battery system, 60 sec RC control, 30 sec for GPS: 6 minutes total
ISR-2	Mission planning time from coordinates provided to operator to ready for launch	5 min	10 min	3	Depends on mission complexity, 5 minutes is projected using a laptop with Qgroundcontrol.
ISR-3	Operators required for setup	1	2	5	1 min, 2 ideal to buy down set up time
ISR-4	System shall have a range from deployment location of	2 mile	1 mile	11	1.8 miles in LOS conditions
ISR-5	System shall provide resolution for tracking a vehicle		30 pixels/m^2	7	Camera more than covers requirement. Has 30 pixels/m^2 at 395 m without using 10x zoom function.

Rqmt	Description	Objective	Threshold	Priority Level	Projected
ISR-6	System shall loiter over the target and provide 10 minutes video of target for	100% of time	85% of time	8	Deconflicted A/V signals, selected high quality video transmitter, air vehicle can be placed in position hold. Hover endurance is 48 minutes.
ISR-7	System shall transmit geo-location		15 ft	17	HERE GPS integrated, works with GLONASS, BeiDou, Galileo. Advertised within 8 ft 50% of time.
ISR-8	System shall require dedicated operators for control and operations	1	2	6	System can operate in 1-2 operator configurations with dual GCS control. Flight modes are rc control or autopilot control modes.
ISR-9	Operator shall be able to identify ground targets while controlling vehicle		X	10	Vehicle can be used in autopilot and operator can control camera zoom for video. GCS software for phone can display live video.
ISR-10	System shall display near real time imagery to the operator(s)	2 sec delay	5 sec delay	12	1 msec latency advertised by Connex with LOS, 30 FPS. Observed latency 30-46 msec.
ISR-11	Operators required recovery, landing, and retrieval of the system	0	1	18	1 to recover system, 0 to destroy system via autopilot.
ISR-12	Endurance of the system while performing video shall be	60 minutes	45 minutes	9	48 minutes at hover
ISR-13	System shall perform "return launch" if communication is lost with operator		X	15	Failsafes are programable by using in Qgroundcontrol. If lost link occurs for X amount of time the system will enter return to launch if programed.

Rqmt	Description	Objective	Threshold	Priority Level	Projected
ISR-14	System shall indicate to operator if GPS is lost and allow for manual recovery mode		X	14	HERE GPS and Qgroundcontrol provide information to operator on GPS status including number of satellites and HDOP, allowing air vehicle to enter failsafe or operator to command via remote control.
ISR-15	System shall provide status of battery to operator		X	13	Battery information can be routed through Pixhawk 2 and sent via telemetry data to GCS
ISR-16	System altitude shall be greater than 100 ft except at launch and recovery		X	19	Radio Control and autopilot all projected to work at greater than 100 ft
ISR-17	System shall have the capability swapping in a night capable camera of 0.001 LUX or better	X		16	.05 Lux, traditional color camera. Can handle twighlight conditions only.
ISR-18	System shall have a low noise profile of 50 db or lower at minimum safe flight altitude		X	4	15.5" foldable propellers minimize sound profile. Sound testing required to confirm.
ISR-19	Air vehicle shall weigh less than 5kg and be packable in 2 standard ruck sack 22" X 14" X 9"		X	1	A/V 3kg, support equipment 5 kg. All projected to fit within dimensions

V. Results and Conclusion

The preceding thesis outlines a tailored system engineering product development process for designing a SUAS for a given operational mission. Design constraints and the process support rapid development of low-cost aircraft with systematic reduction of failure mechanisms. The process was limited to Group I SUAS made from commercial components.

The three contributions of this research are: a process to support Small Unmanned Aerial Systems (SUAS) design, tools to support the design process, and tools to support risk assessment and reduction for both design and operations. The product development process allows DoD program offices to own the technical baseline of an SUAS design, promoting better system understanding, responsiveness to operator needs, and complete understanding of the drone marketplace. This is a repeatable process for a given operational mission, documented in a user-friendly pictorial and demonstrated using an exemplar SUAS design for an Intelligence, Surveillance, and Reconnaissance (ISR) mission set. Tools supporting risk assessment and reduction include operator checklists, fault tree diagrams, failure criteria, critical component definition, critical component reliabilities, and system reliability.

This chapter discusses how the (3) investigative questions were addressed from Chapter I, using the information from the ISR design exemplar in Chapter IV. In addition, recommendations in support of implementing the product development process in DoD program offices are provided. Lastly, topics for further research for expanding and refining the product development process are discussed.

First Investigative Question

What systems engineering methods are appropriate for a tailored rapid SUAS design process?

The defined SUAS product development process mirrors the Initial DoD System Engineering Process model displayed in Chapter III. The process pictorial is displayed in Figure 11. The first step is the requirements analysis. In this step focus is placed on first establishing design needs and operational conditions from the operational user. This is a conversation, and if possible, face to face meeting between the design team and the operational user. This communication is paramount in identifying assumptions and clarifying needs. These needs are translated into specific, measurable, attainable, realistic, and time bound design requirements for standard to evaluate the future design against.

The second step is functional analysis and allocation. This step is first performed by translating the design reference into a use case diagram. The use case diagram maps specific functions the system must perform to provide use to the actors of the system. At another level of detail is the functional allocation which displays and helps identify critical functions of the system when evaluated against requirements. The final level of detail for the functional allocation is perform through a fault tree analysis. The fault tree analysis investigates all the ways critical componentry can fail on the SUAS for the given use cases for the system. Fault trees aid in developing operator checklists to mitigated pre-flight system risks promoting a reliable in-flight system. Operator checklists are an engineering product and discussed in further detail in the second investigative question.

The next step in the system engineering process model is the design synthesis, which is informed by decisions completed in the previous two steps. System design starts with the establishment of a physical architecture, aimed at meeting requirements and critical functions of the SUAS. By diagraming the physical architecture into a top-level view and integrated view (internal block diagram), the system design can view critical interfaces, information flow, and component dependencies. This information aids in the physical component selection process, as design decisions can be processed through based on impact to other components and system performance. Componentry selection for the SUAS flows from components that constraint the system architecture from most to least. Frames are selected first since they define the physical architecture for the system, while the ground control station (GCS) is selected last due to a low impact physical impact to the air vehicle.

With the design established, the final step of the system engineering process is system analysis and control. System analysis is completed with inputs from all previous steps and ensures the design is feasible in meeting the desired functions and requirements of the system. In the case of the ISR exemplar, engineering calculations were performed for SUAS hover endurance, system reliability, reliability for a mission, and pixel density. All other requirements were evaluated based on input from online drone blogs, Autonomous Navigation Technology (ANT) Lab Staff, and/or the authors experience.

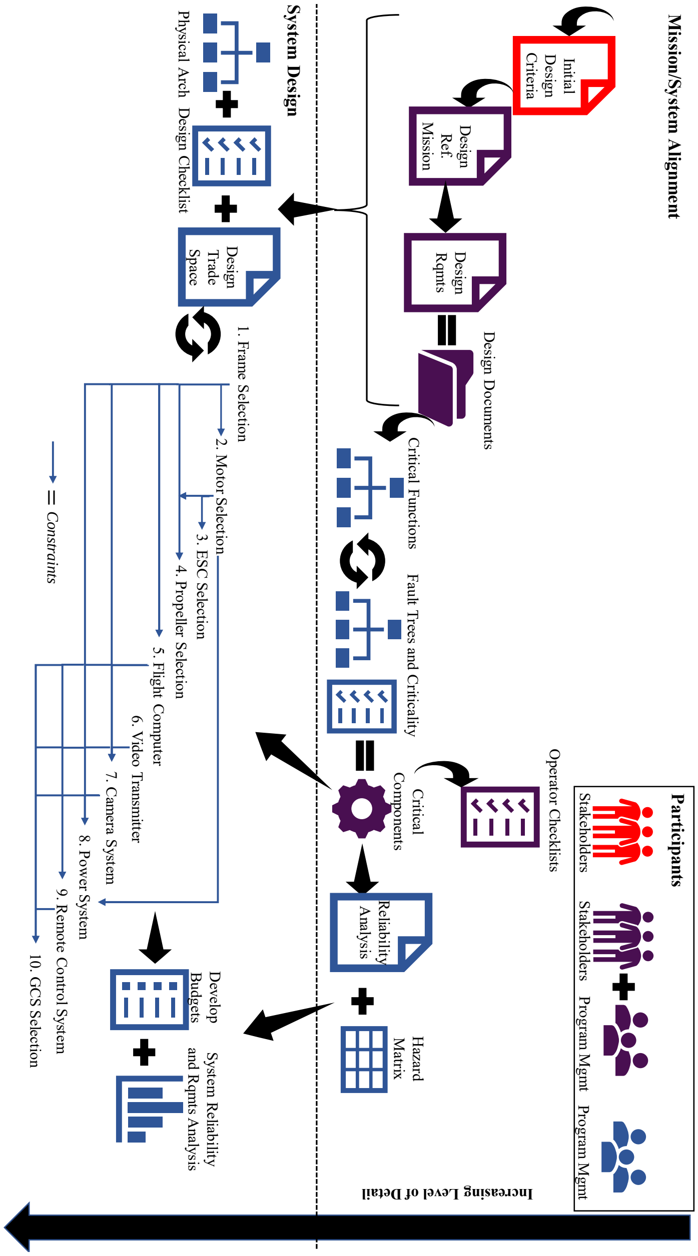


Figure 11. SUAS Product Development Process

Second Investigative Question

What baseline design tools and heuristics are required to support decisions for vehicle performance, trades, reliability, assessment and follow-on designs?

Engineering products that aid in decision making for are built into the SUAS product design process. The first product is general and displays current researched critical component failure rates. It provides program offices data on how often failures occur for flight computers, motors, propellers, frames, batteries, electronic speed controllers, battery elimination circuits, signal receivers, cameras, and GCS. This data provide combined with the physical architecture of the SUAS enables a reliability analysis for the system. The system specific reliability analysis provides the failure rate for the overall system. These calculations are tailorable to system reliability for a given time and MTTF, providing valuable information on projected system life and maintenance cycles.

The second product that promotes system reliability and performance are operator checklists. These checklists are developed from fault tree diagrams aimed at mitigating pre-flight errors that may be induced by the operator, environment, or transportation. Checklists provide operators short repeatable rules that provide common troubleshooting advice, aligned with specific components. Checklists are aligned with specific points in the SUAS lifecycle pre-flight, pre-deployment, and initial flight, aimed to mitigate specific risks for common situations. For the SUAS design team, checklists allow the majority of non-component risk to be mitigated for the system. In turn, system risk is distilled down to component failure rates aligned with the physical architecture. This provides the most accurate level of system reliability. Finally, a spares checklist is included to mitigate critical component errors that occur in the deployment location. The decision to incorporate spare kit comes at the cost of transportation of the system in the form of weight and space.

Another valuable product to the program office is the critical component hazard/reliability matrix. This matrix displays the failure rates of SUAS components against the impact category to the system. The matrix is then color coded based on these two factors provided a high, medium, or low system risk. The hazard matrix provides program office decision makers a visual depiction of what components are contributing the most risk to the system. This ranking of critical components informs investment for critical components in the form of testing, funding, and research. This process mitigates system design risk while executing shortened development timelines.

In the system design phase, the design checklist and design trade space products provide a valuable roadmap for designer decisions. The design checklist is built for a multirotor design and provides critical design information for component sizing, selection, pairing, configuration, and analysis. The design trade space evaluates common trades for multirotor SUAS highlighting the impacts to established requirements. Additionally, the trade space identifies at what level in the architecture the trades occurs. This provides the knowledge to decision makers on when to evaluate trade's in the design process, and the proposed trades impact on mission requirements. Using both of these products while building the SUAS design, provides a stable approach to evaluate requirements.

The final engineering product is the component selection exemplar for the ISR mission. The process reveals the order to select components for the ISR mission and how each component constrains other components. Each time a component is selected the design trade space is narrowed, this enables designer to focus decision and shorten design cycles. The component selection process is mission dependent and based on the preference of the design team. In the case of the ISR mission, components were selected in order of architecture impact.

Third Investigative Question

What SUAS components are critical to mission success and can reliability rates be found, documented, and analyzed for these components?

Critical components were determined to be components whose failure induce unrecoverable events. Unrecoverable events mean the SUAS can no longer be flow with system failure imminent. In addition, repair time for the system to regain critical functionality is too high for the operator to accept. In the case of the ISR mission, critical functions are flight, transport, provide power, surveillance, and be controlled. The components that must work to uphold these functions were determined to be the flight computer, motors, propellers, frame, battery system, ESCs, BECs, receivers/transmitters, camera, and GCS.

It is possible to determine an estimate of system reliability. From a physical architecture standpoint all components are in series configuration, except receivers/transmitters pairs, meaning if one component type fails the system enters an unrecoverable event. Receiver/transmitters pairs are in parallel configuration due to implementation of due control mode; one via remote control and one via autopilot control. This allows one control system to fail and still permit controlled flight.

Limited work has been performed on documenting failure rates for critical SUAS components. It is the author's belief that this is due to the rapid technology advancement of the commercial drone market. Components are produced for short periods of time making reliability testing minimally beneficial to industry and academia, since new components will improve upon reliability. Future research is recommended on when it is worth investment in generating failure rate data for a given platform, based on the proposed design life of the system.

Table 21 in Chapter 4 reveals the researched failure rates for critical components. Failure rates were found in various testing conditions including operational, research/theoretical, lab, or subject matter input. The table was validated by the AFITs ANT Lab staff as realistic values for commercially available components. One value was determined to be an outlier for the receiver system at a failure rate of 0.37 failure per hour. It was determined either the product or operating environment was suboptimal and was not included in future calculations.

Component group failure rates were average and used as the component failure rate for system reliability calculations performed for the ISR system. Failures for components were assumed to be past the infant mortality rate and occur within the constant failure rate zone of the bathtub curve. At a constant failure rate, the components are in normal life of the bathtub curve and burn-in was performed to remove early life errors.

Recommendations

The DoD can benefit from implementing mission specific SUASs for tactical and operation mission sets. SUASs remove mission demand for larger UAS assets, freeing up flight hours for strategic level operation. Additionally, the DoD can leverage the expanding commercial drone market for technology, integration, and documentation for rapid custom SUAS builds. The outlined SUAS product development process offers a simple roadmap to build such SUASs using system engineering methods.

While the process is a roadmap to build SUASs; the process needs a plan to support operational implementation. A recommendation is to implement the product development process at the DoD SUAS training center, USAF 371st Special Operations Combat Training Squadron (SOCTS) Detachment 1. SOCTS is at a critical point in SUAS development cycles where training emergent technology occurs, and feedback is immediately provided. It is a center of excellence for SUAS expertise in the DoD. By incorporating the product development process at this location operator feedback on requirements, design, and checklists can be immediately garnered, shortening development timelines.

The initial system design of SUAS easily transitions to follow on platform developmental testing by the operational customer. This implementation would require acquisition personnel from various DoD service branches to ensure proper process documentation and management, along with investigation and implementation of future drone technology. With program office involvement on location, liaisons are available for documenting emergent operation needs and justifying future project funding. By implementing this process with actual on-site stakeholders of the system, not only will the product improve over time but so will the product development process itself.

An additional recommendation is for the DoD to invest in a reliability database for implemented critical components on deployed SUAS designs. This would allow the DoD and program offices to justify investment in critical componentry with high failure rates, promoting more reliable system designs. A component reliability database also informs future designs and architecture decisions for a given mission. Finally, deployed systems life, maintenance schedule, and reliability can be tracked, impacting future programmatic decision for sustainment or new platform development.

Further Research

Implement SUAS product development process for all mission sets. This thesis focuses on building a product architecture around an ISR mission set. Further research would be required to see if the process and the engineering products of the process change for other SUAS mission sets outlined by United States Air Force SUAS Flight Plan: 2016-2036. This research would involve running through SUAS product development process for each mission set, documenting any required deviation from the process, and capture all engineering products including for further design implications. This research would aid in validation or invalidation of the SUAS product development process**.**

In depth reliability analysis of critical components. This thesis performed an initial reliability analysis of critical components, based on current document research. For a more robust reliability analysis research is required on determining quantitively which component brands and components have the highest reliability. Life and operational testing would be useful on top drone industry brands for motors, ESCs, flight computers, BECs, frames, receiver/transmitters, and sensors. Furthermore, the SUAS designer community would benefit from common test standards to ensure a stable reliability baseline for critical components. The goal of reliability testing for the DoD would to possess a trusted manufacture list to choose SUAS design components from based on empirical evidence. This would aid in mitigation of early component life failures promoting a more predictable system reliability and life estimation.

Failure mode testing for commercially fabricated drones. Failure rates of critical components were used to determine the system reliability of the SUAS in this thesis. An alternate way to determine system reliability is done by determining the probably of failure modes occurring. This analysis was left unperformed due to a lack of data on specific failures within the SUAS. This research would require flight a series of commercially fabricated drone platforms, documenting when failures occur, and investigate the root cause of the failure. This would provide failure information at level lower than the component level. For example, root cause analysis post SUAS flight failure may reveal the failure was attributed to motor over heating opposed simply motor failure. This testing would provide information on what failures are most common, allowing designer to not only implement material solutions but also operational, training, and architecture solutions. It would also provide information on what platforms/designs excel in specific mission, narrowing the trade space for future platform/mission pairing.

Lifecycle modeling for mission specific SUAS. Future investigation is required to determine the useful life of mission specific SUAS. Useful life for a SUAS is dependent on how long the design mission remains the same and how long the requirements the SUAS was designed to are stable. In addition, program office personnel must balance system maintenance cost versus the cost of building a new system with potential upgraded capabilities. Timelines of new system testing, training, and deployment must also be considered in lifecycle analysis. Recommendations are required for the optimal SUAS deployment life considering all these factors. Product line turnover rates of the commercial drone industry would provide valuable starting point for research.

Appendix A. SUAS Fault Tree Diagrams

Flight Function Fault Tree Diagrams

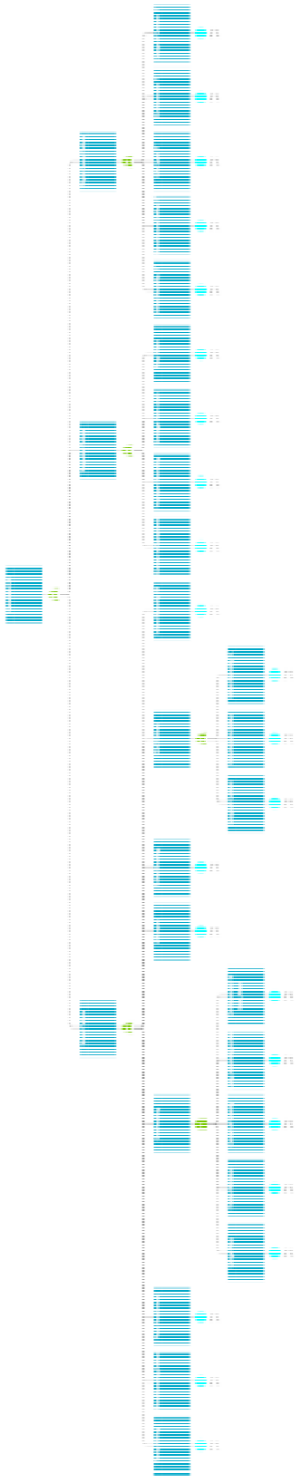


Figure 45. Generate Lift Fault Tree Diagram: Full View

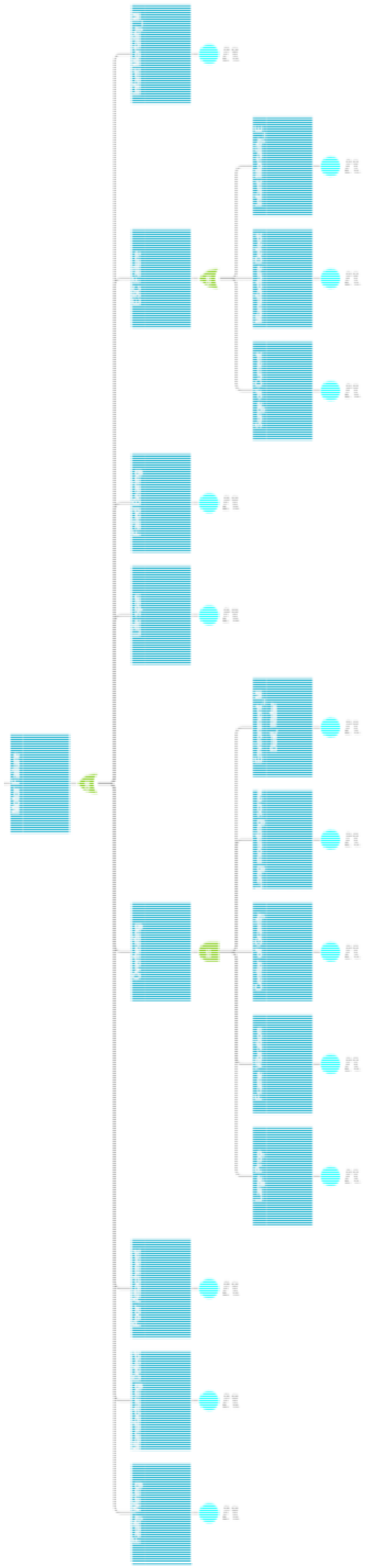


Figure 46. Generate Lift Fault Tree Diagram: Motor Failure

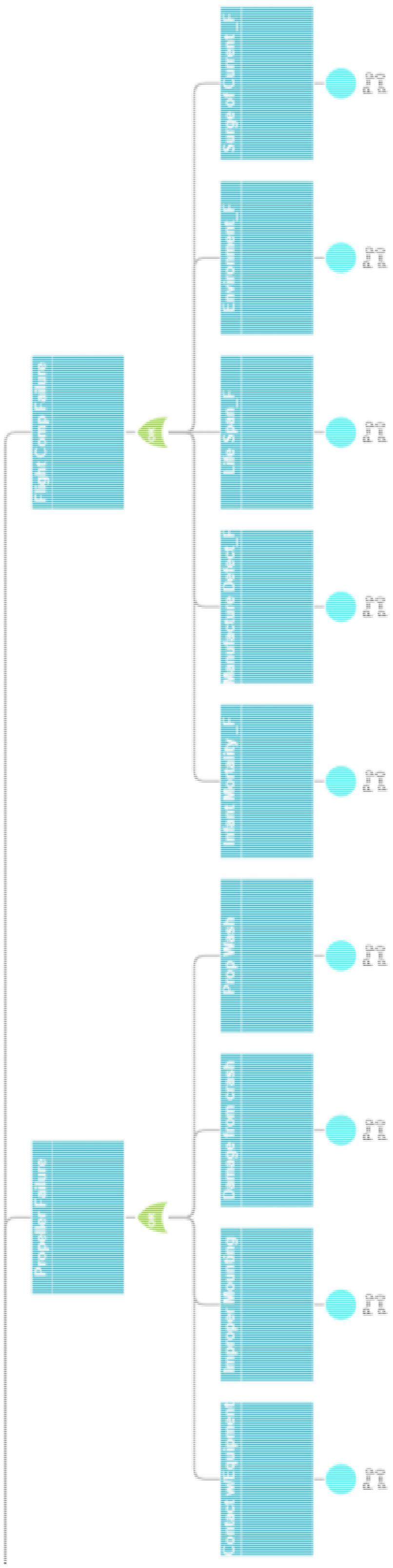


Figure 47. Generate Lift Fault Tree Diagram: Propeller and Flight Computer Failure

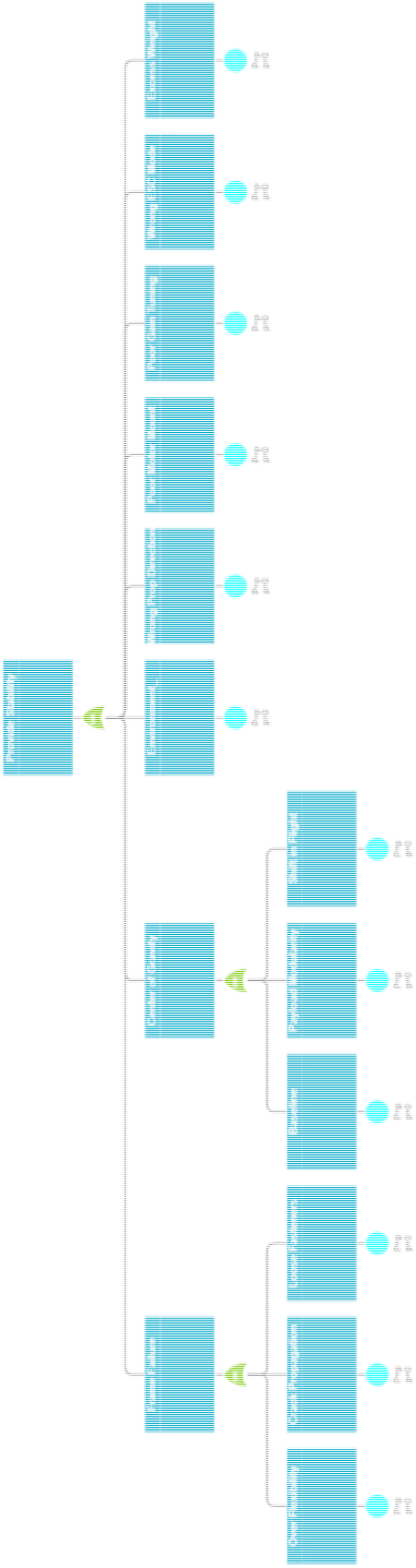


Figure 48. Provide Stability Fault Tree Diagram

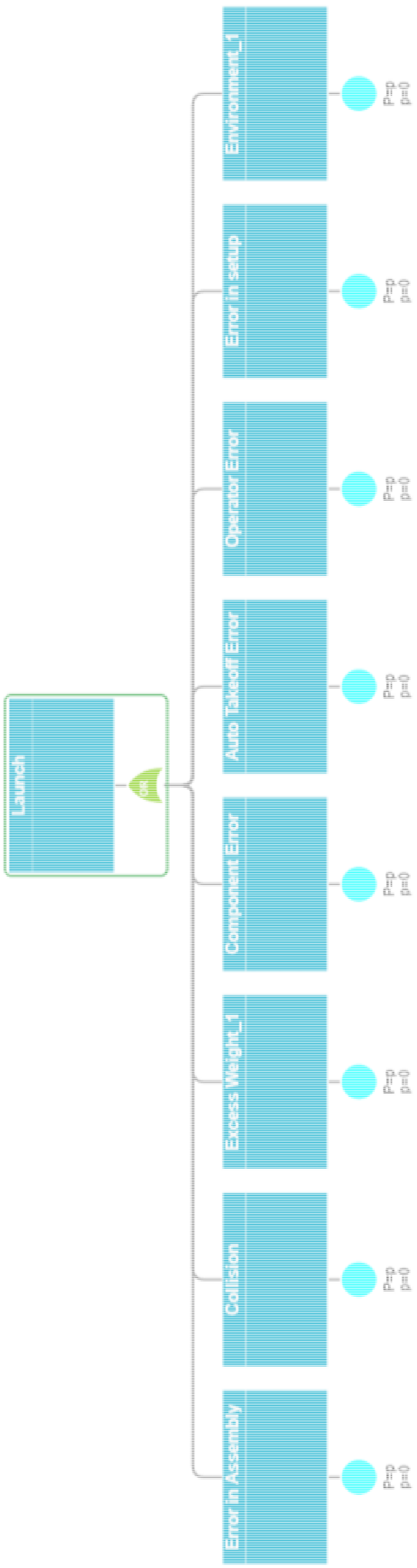


Figure 49. Launch Fault Tree Diagram

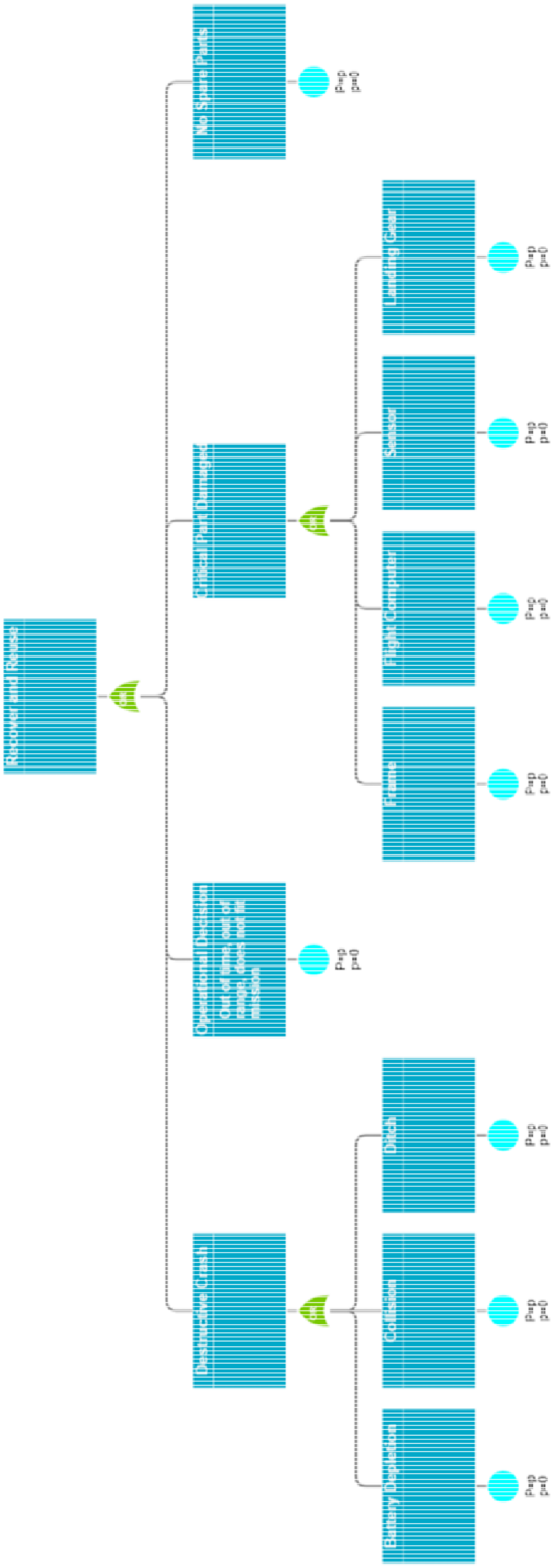


Figure 50. Recover and Reuse Fault Tree Diagram

Transport Function Fault Tree Diagram

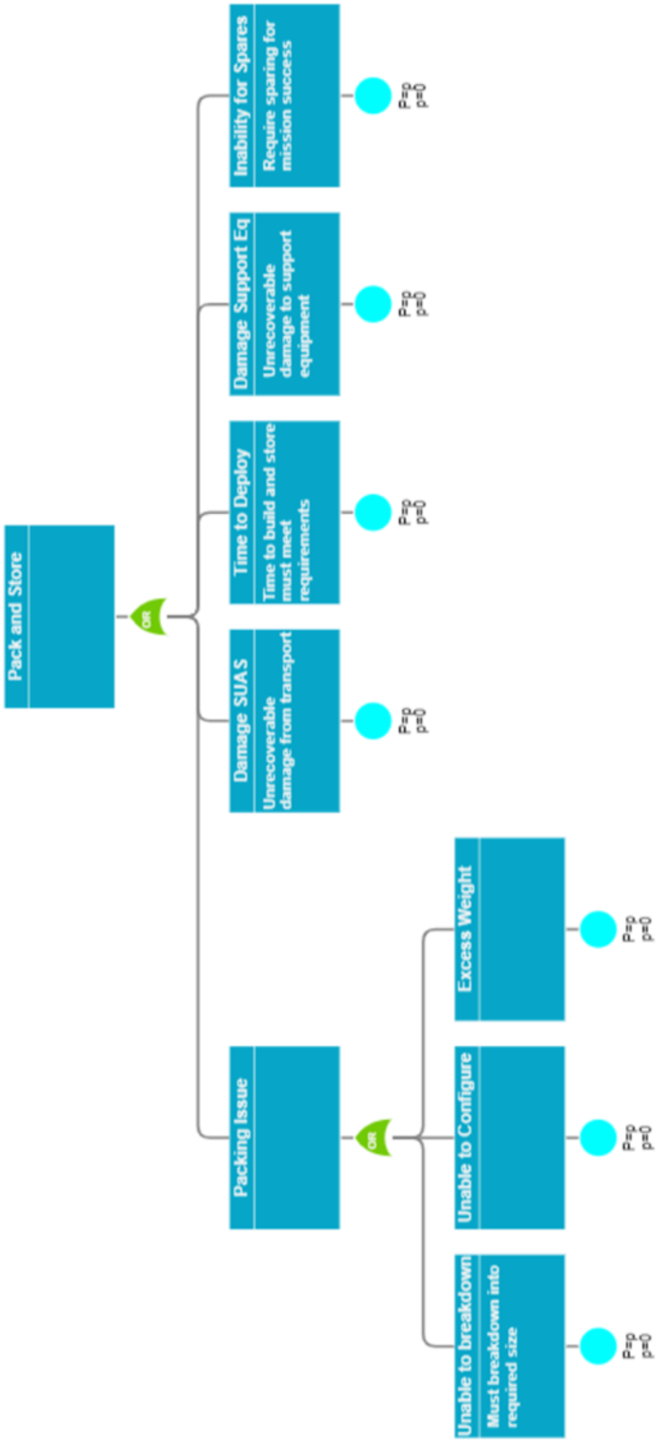


Figure 51. Pack and Store Fault Tree Diagram

Power Function Fault Tree Diagrams

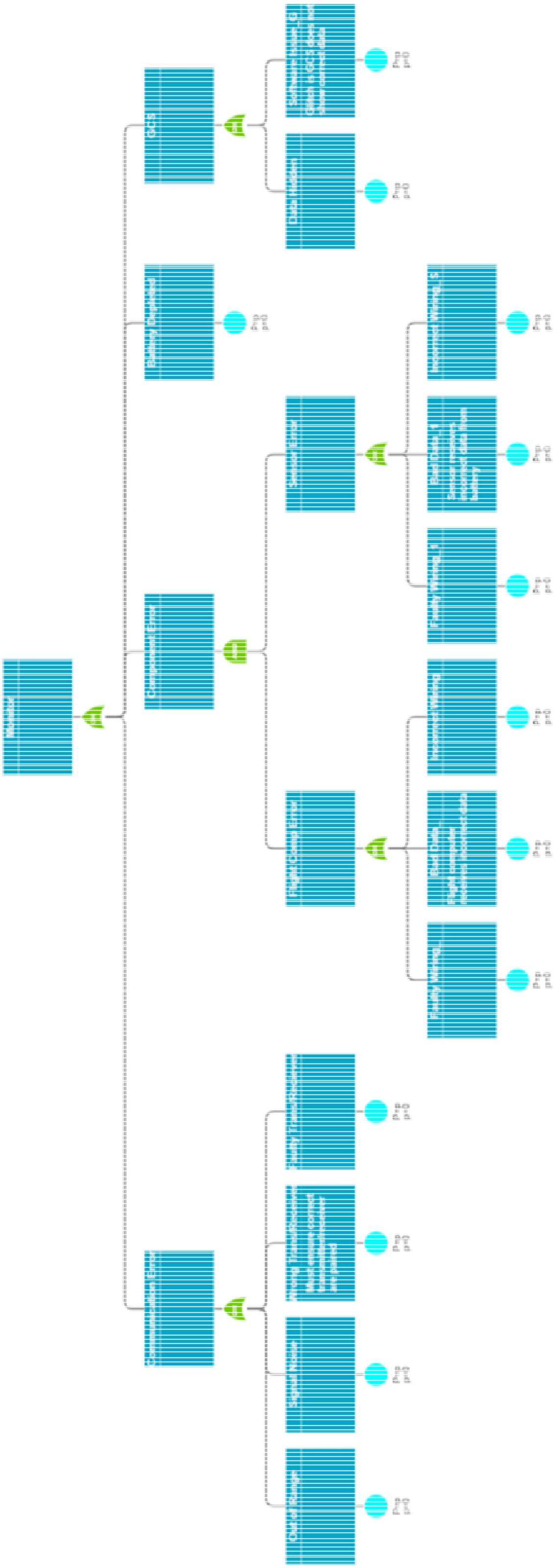


Figure 52. Monitor Fault Tree Diagram

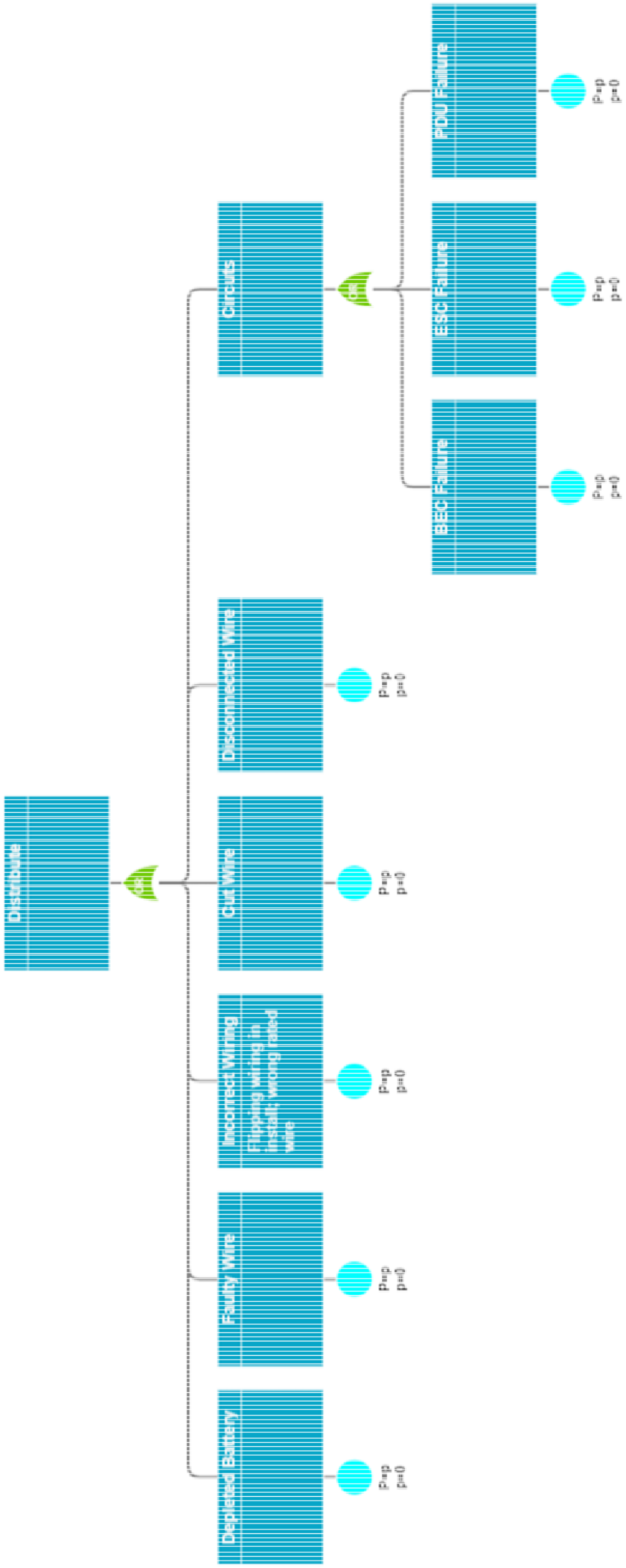


Figure 53. Distribute Fault Tree Diagram

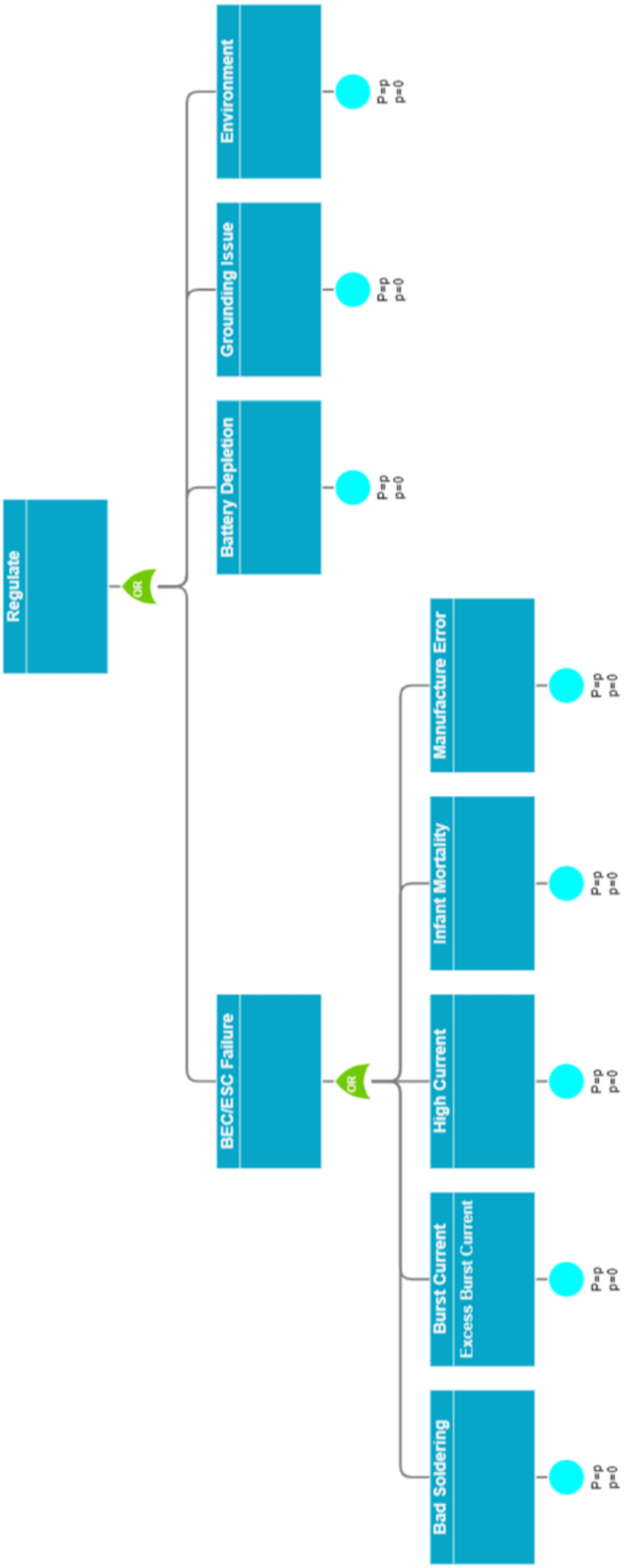


Figure 54. Regulate Fault Tree Diagram

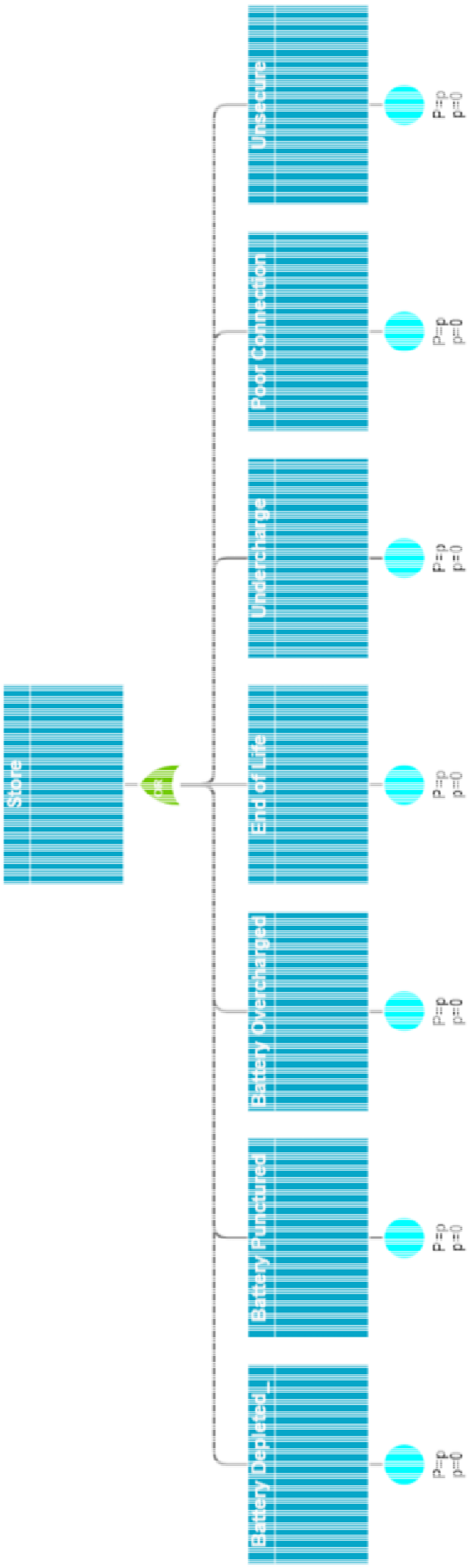


Figure 55. Store Fault Tree Diagram

Surveillance Function Fault Tree Diagrams

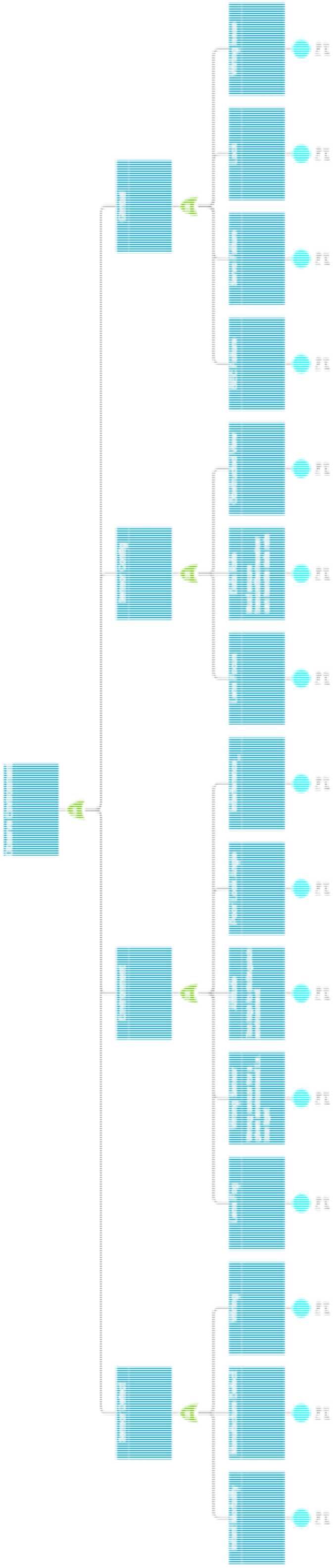


Figure 56. Observe Environment Fault Tree Diagram: Full View

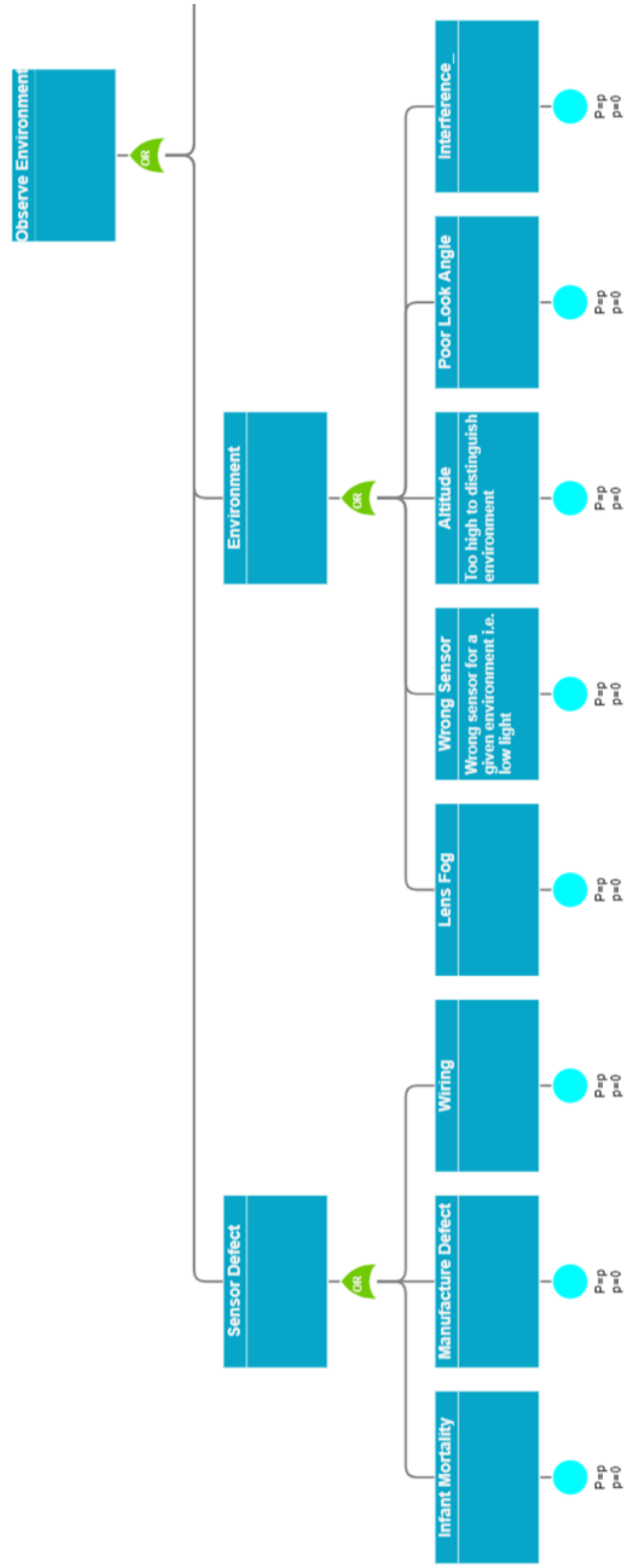


Figure 57. Observe Environment Fault Tree Diagram: Sensor Defect and Environment Failures

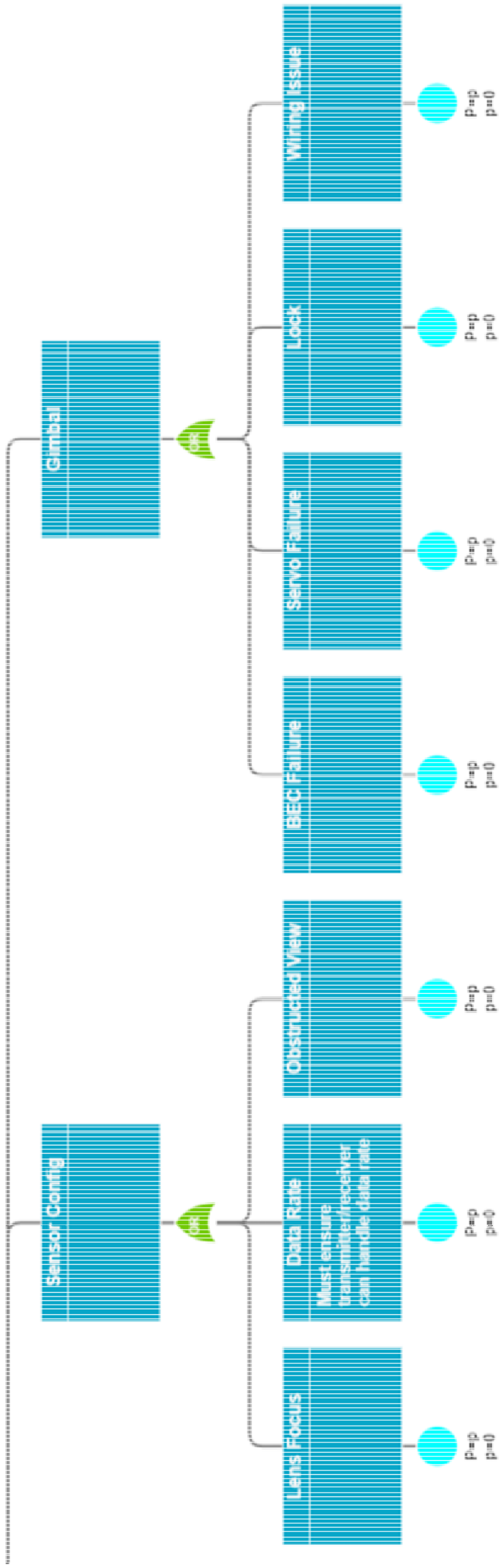


Figure 58. Observe Environment Fault Tree Diagram: Sensor Configuration and Gimbal Failures

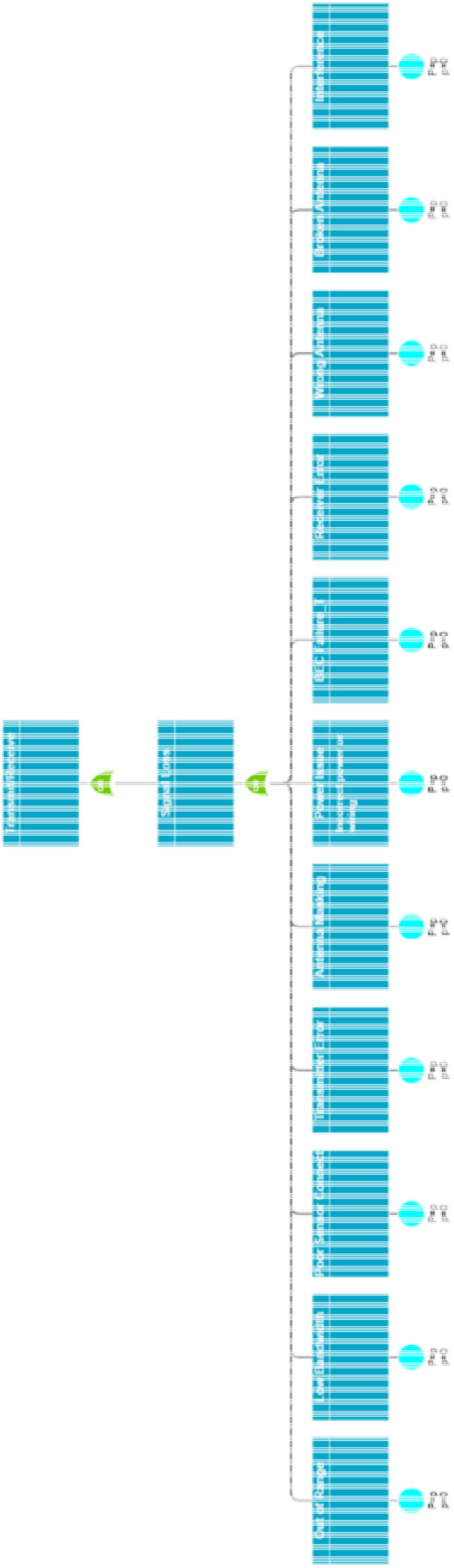


Figure 59. Transmit and Receive Fault Tree Diagram

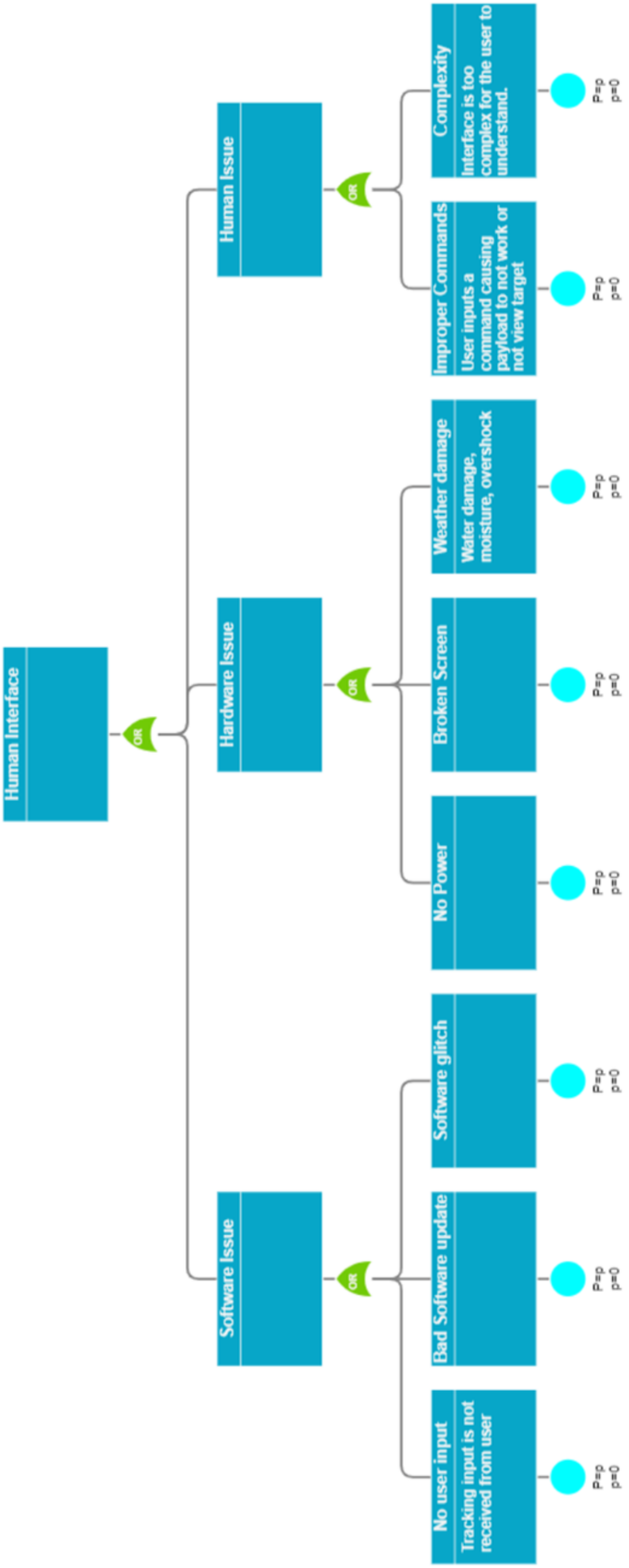


Figure 60. Human Interface Fault Tree Diagram

Control Function Fault Tree Diagrams

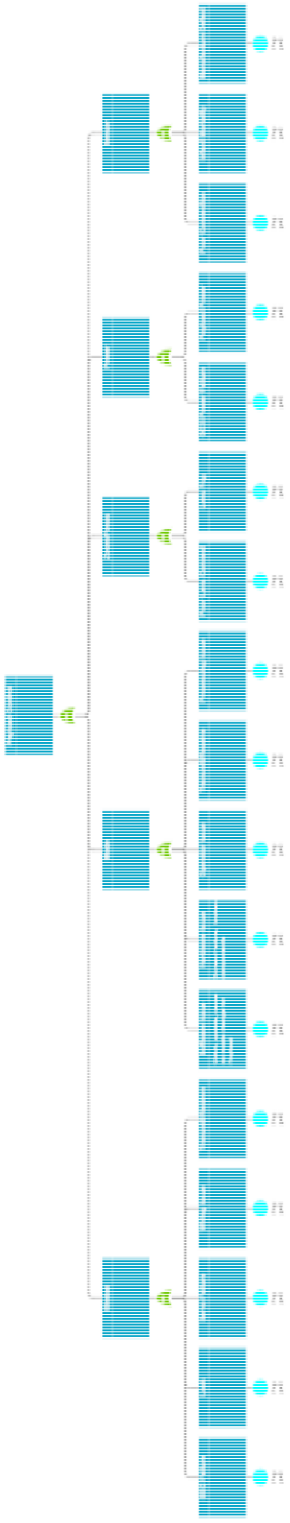


Figure 61. Payload Control Fault Tree Diagram: Full View

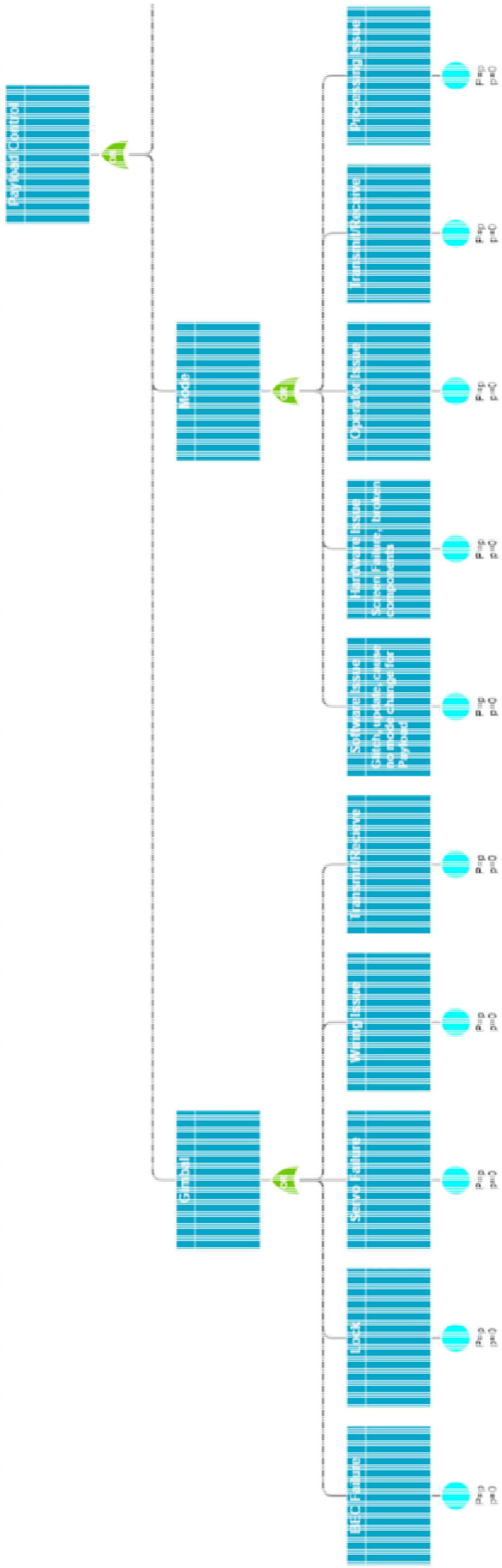


Figure 62. Payload Control Fault Tree Diagram: Gimbal and Mode Failures

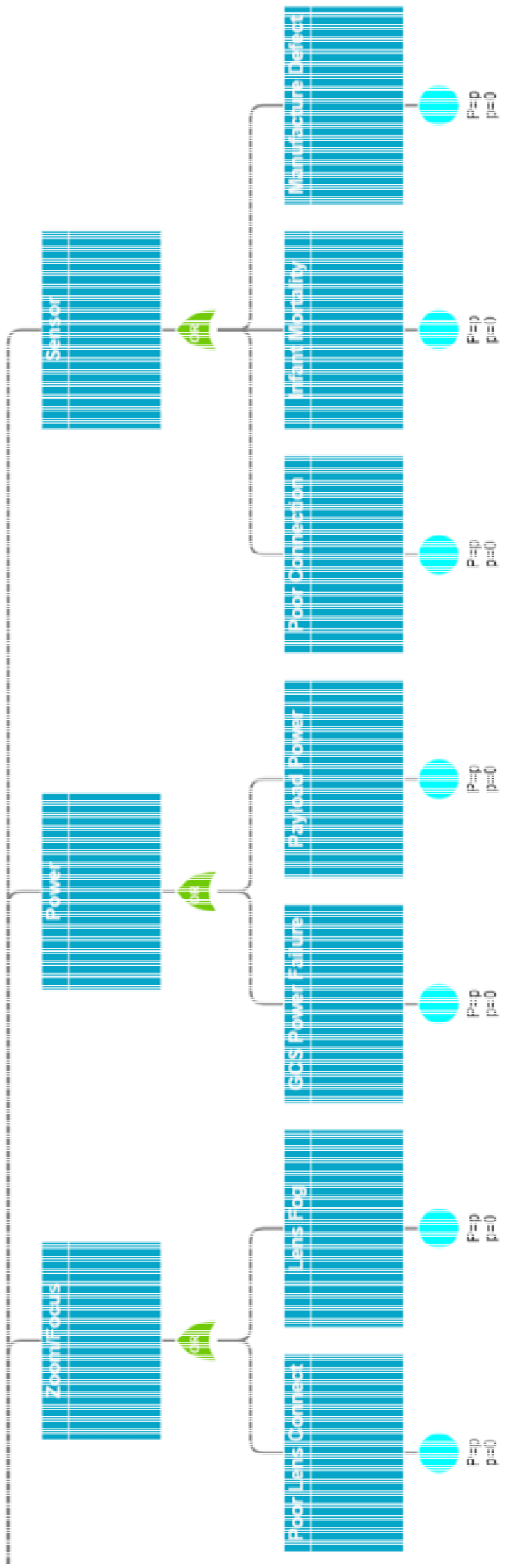


Figure 63. Payload Control Fault Tree Diagram: Zoom, Power, and Sensor Failures

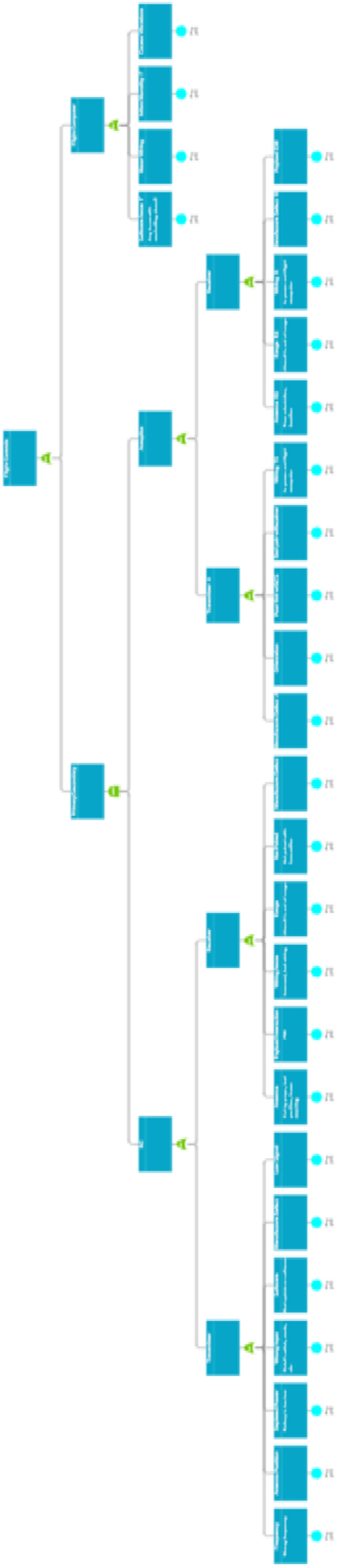


Figure 64. Flight Control Fault Tree Diagram: Full View

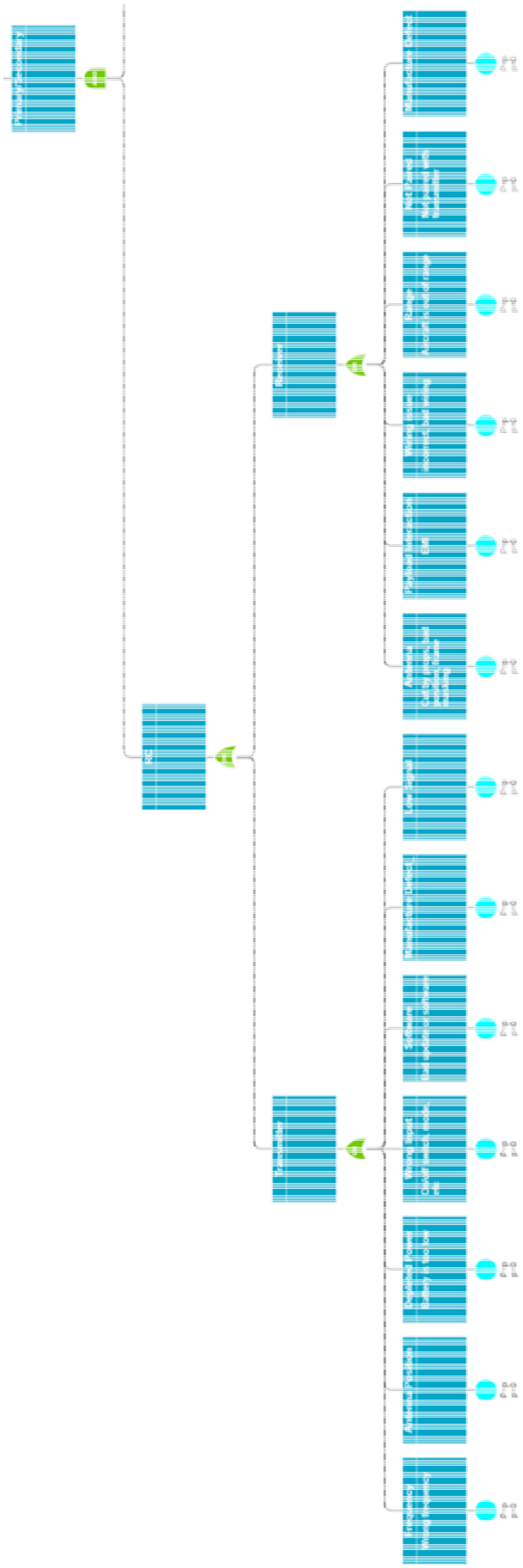


Figure 65. Flight Control Fault Tree Diagram: RC Failure

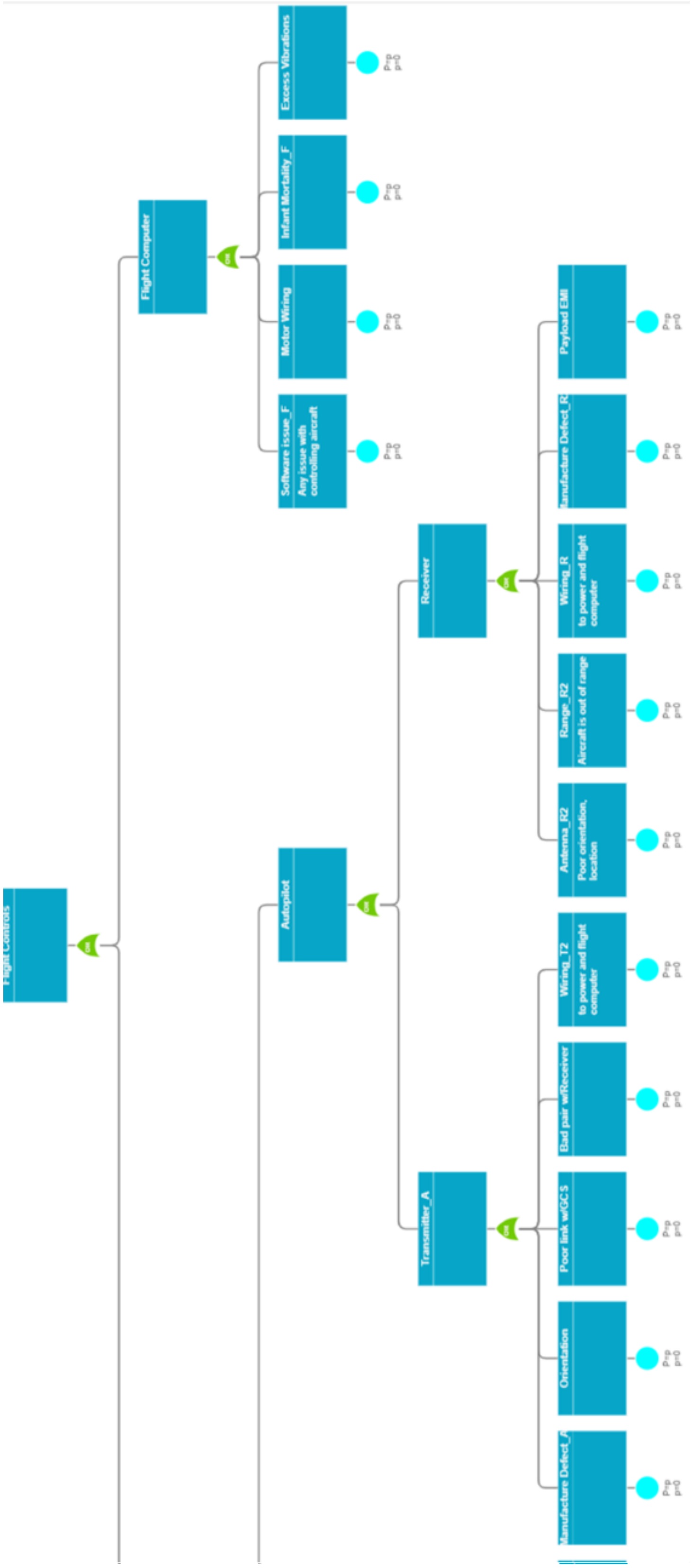


Figure 66. Flight Control Fault Tree Diagram: Autopilot and Flight Computer Failure

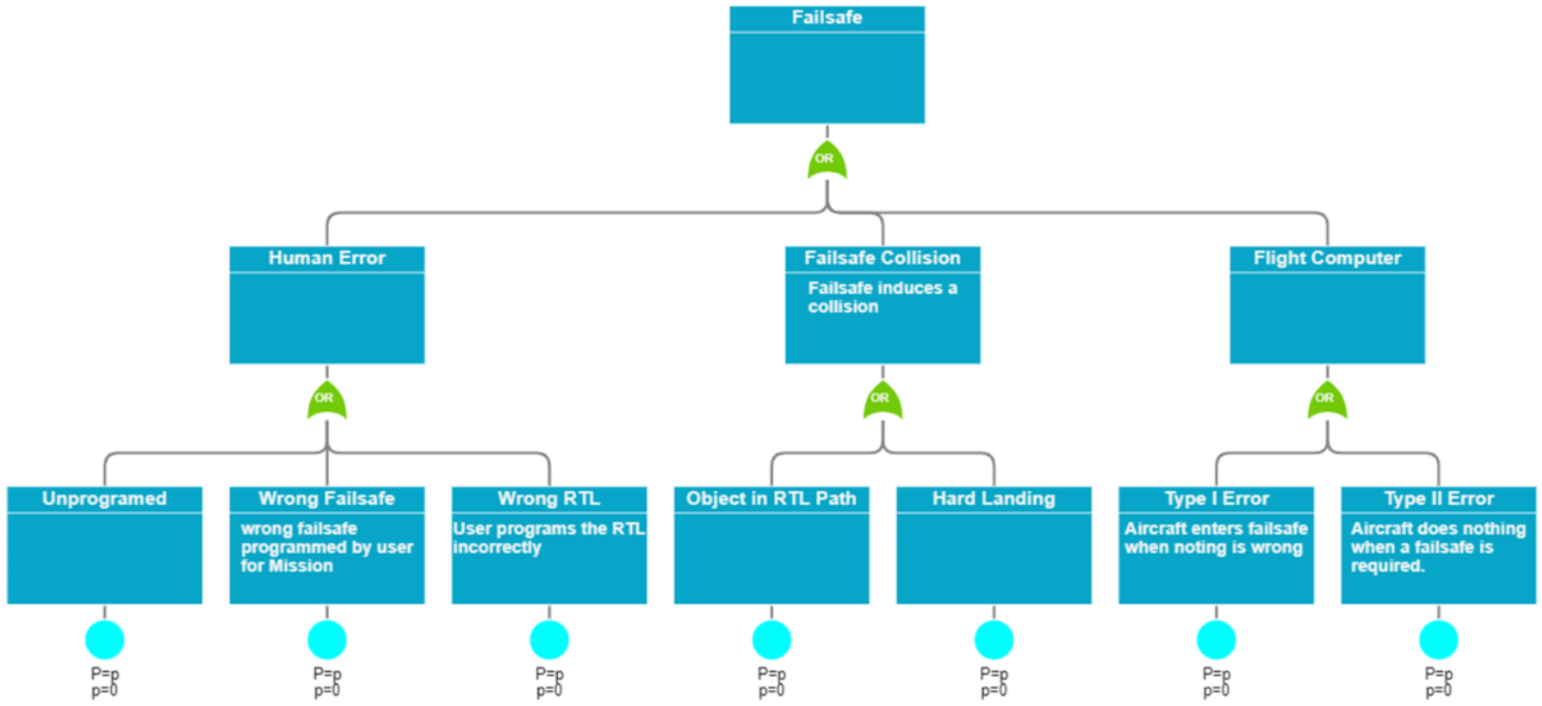


Figure 67. Failsafe Fault Tree Diagram

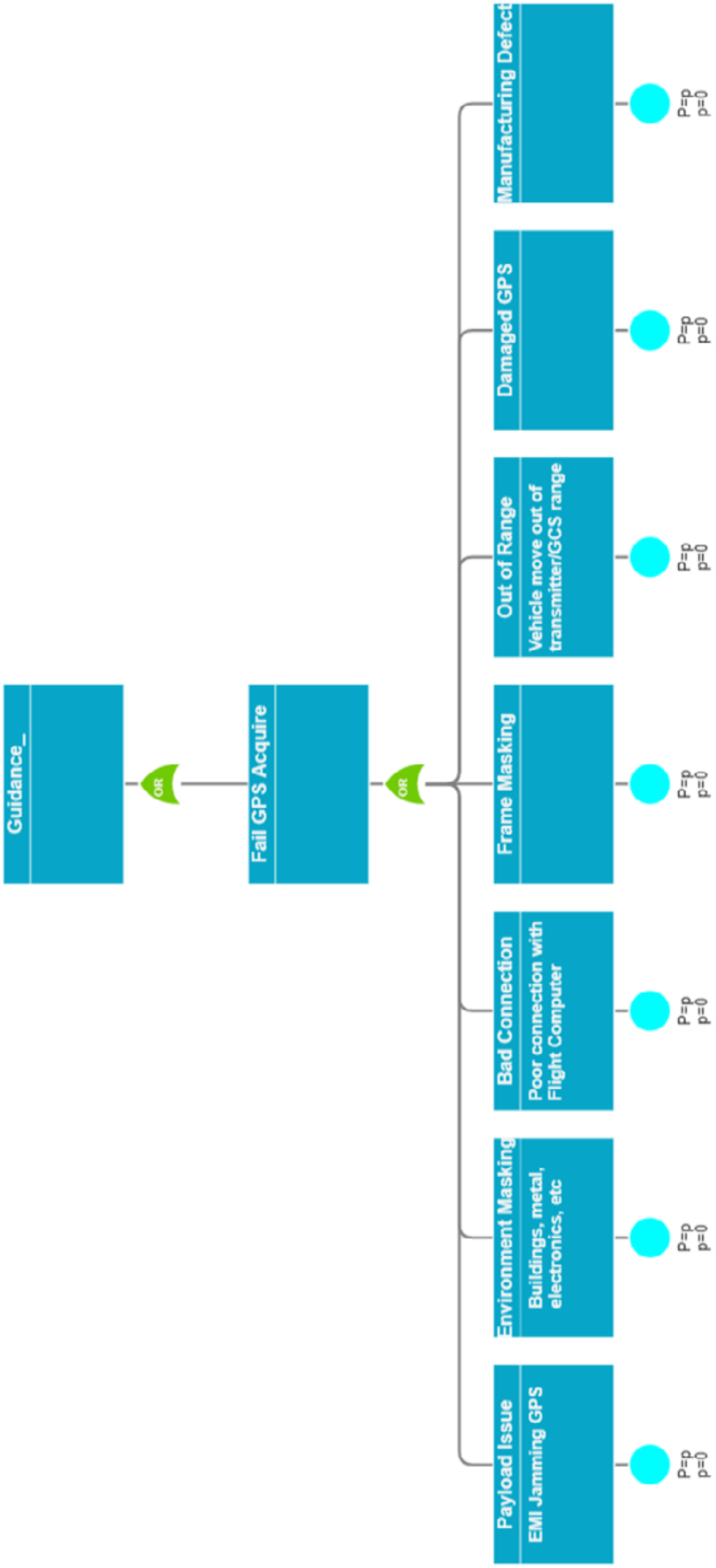


Figure 68. Guidance Fault Tree Diagram

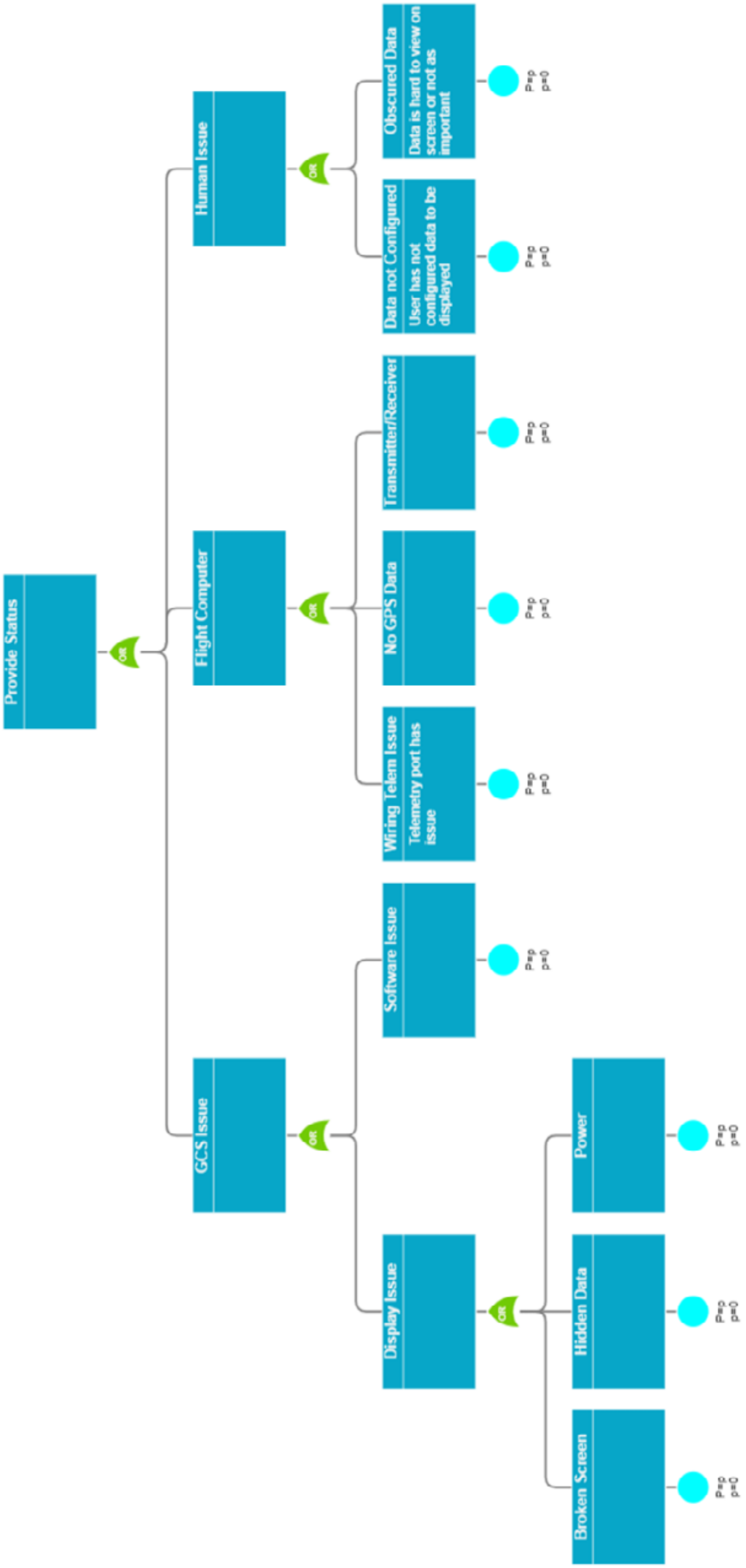


Figure 69. Provide Status Fault Tree Diagram

Appendix B. SUAS Design Online Sources

The sources detailed in this table were used to aid in building operator checklists, design checklists, design trade space, and component selection performed in Chapter IV of this thesis.

Table 35. SUAS Design Online Sources

Name	**Type**	**Focus**	**Top Source***
ardupilot.org	Blog	Pixhawk flight computer help	X
rcgroups.com	Blog	general advice	X
phantompilots.com	Blog	DJI advice	X
diydrones.com	Blog	general advice	X
dronetrest.com	Blog	general advice	X
droneflyers.com	Blog	general advice	
reddit.com/r/Multicopter	Blog	general advice	
blog.ravpower.com	Blog	general advice on power sources	
dronereviewhot.blogspot.com	Blog	general advice	
foxtechfpv.com	Store	custom Builds	
store-en.tmotor.com	Store	motors/ propellers	
kdedirect.com	Store	motors/ propellers	
hobbyking.com	Store	drone components	
flir.com	Store	cameras	
castlecreations.com	Store	electronics	
team-blacksheep.com	Store/Infosite	cutting edge components	
myfirstdrone.com	Infosite/ Product reviews	DJI focus	
ecalc.ch.com	Endurance Calculator	analysis	
futabarc.com	Manufacture	RC transmitter specs	
amimon.com	Manufacture	video transmitter specs	
aopa.org	Pilots Association	news/tips/general advice	
blacktieaerial.com	How to Guide	build instructions and tips	
beginnerflyer.com	How to Guide/ Product Review	build, subsystem instructions and info	
oscarliang.com	Expert Advice	building/ components	X
dronethusiast.com	Expert Advice	tips, news, reviews	
thedronegirl.com	Expert Advice	tips, news, reviews	

*Top Source Indicates multiple design inputs or topics were used from source.

Appendix C. SUAS Reference CONOPS SENG Design Sequence

Rev 1: 13 Jan 2015

Section I - Issue

A. Problem Statement

In the past decade, the US Military and Department of Homeland Security have seen the numerous benefits, and have come to rely upon, Remotely Piloted Aircraft (RPA) and their role in combat and information operations. Fixed wing platforms such as the Predator (MQ-1)/Reaper (MQ-9) and the Global Hawk (RQ-4) have tremendous capabilities but they are low-density/high-demand (LDHD) assets; making their availability limited to all but the most critical missions. As a result, there has been rapid growth in the area of smaller, unit controlled, RPAs, referred to herein as small Unmanned Aircraft Systems (UAS). These are small (less than 20 lbs sized air vehicles capable of being operated by small forward deployed units or individuals. These vehicles provide critical Intelligence, Surveillance, and Reconnaissance (ISR) data before, during, and after ground operations. Current shortcomings of existing small UAS include unreliable imaging, high operator workload, and an inability to track and provide geo-coordinates for a target vehicle.

B. Overarching Vision

To deliver timely and relevant ISR to forward deployed ground based units via the use of a small UAS. Non-cooperatively track a target vehicle using a hand-launched, single operator UAS.

C. Purpose of the CONOPS

This document describes operational employment scenarios whereby military personnel could realize the benefits offered by a small, easily deployed and operated, UAS. A common command, control, and communications interface will be utilized, enhancing the system flexibility and making the system adaptable to a wide variety of situations and environments. The system will have a versatile payload configuration allowing for multiple ISR configurations.

D. Scope

This document is intended to be an Enabling Concept and is written at the tactical-level. Specifically, the Small UAS CONOPS will describe the anticipated utilization and supporting context required to provide tactical ISR to include vehicle tracking. The system must allow for deployment and operation from a single forward based operator in a denied access environment.

Section II – Overview

A. Synopsis

A Small UAS will provide forward deployed ground based units the capability to conduct low altitude, ISR and vehicle tracking operations from a safe standoff distance with minimal logistical support. Specifically, the use of the UAS will allow operators to:

- Rapidly setup and deploy Small UAS from austere location
- Covertly loiter over a desired target area, providing uninterrupted, or near-continuous video coverage over a target for a 10 minute interval
- Continuously track a moving vehicle
- Utilize payloads optimized for low altitude operations capable of providing sufficient resolution for target identification
- Monitor ISR data from safe standoff distance
- Conduct Small UAS operations while maintaining situational awareness of the location around the operator
- Provide timely ISR data for ongoing/future ground operations

B. Sequenced Actions (Phases)

Ground Control Setup & Teardown Phase: This phase encompasses all actions necessary to deploy the UAS including: unpacking, inventory, assembly, function checks, and mission planning.

Launch Phase: This phase encompasses all actions necessary to achieve initial stable flight starting from a properly configured air vehicle and ground control system. A single operator should be capable of launching the system. Launch phase ends once stable flight is achieved and the system begins navigation towards the target location.

Ingress/Egress Phase: This phase involves transit to/from the target area. The target area can be expected to be a minimum 0.5 miles to 1.0 mile from home base/ launch area.

Acquisition Phase: The UAS will autonomously detect and acquire a vehicle target. Upon acquisition, the UAS will commence with the surveillance phase.

Surveillance Phase: Surveillance of the target will be maintained for a minimum of a 10 minute time span. Surveillance data will be of sufficient resolution for an operator to perform identification of a target vehicle from the supplied video feed. While identification of the target vehicle may be confirmed by the operator, initial detection/acquisition/reacquisition of the target vehicle will be performed autonomously by the UAS. Continuous, or near-continuous, coverage of a target for a 5 minute interval is required. We define continuous as 100% of a 5 minute interval the target is in the field of view. Near-continuous is defined as greater than 85%. It should be expected that the target vehicle will be moving for at least a portion of the surveillance phase.

Recovery Phase: This phase involves recovering the air vehicle upon completion of the mission or as deemed necessary. A single operator should be capable of navigating the air vehicle to the recovery location, safely landing the vehicle, and retrieving the vehicle for re-use.

Overall Mission: The solution should have a minimum mission duration of 45 minutes. This shall be verified using a combination of flight test data and analysis of current draw and battery capacity.
External Environment: The UAS will generally operate in an austere and hostile environment under a myriad of environmental conditions. The operational environment will be assumed to have global positioning system (GPS) signal as it will be the primary navigation aid for the RPA. Operational employment may be dependent upon terrain obstacles and/or operational altitude as the primary human-to-vehicle communication pathway will be a high-frequency radio signal. Line-of-sight limitations will have to be accounted for in mission planning.

C. Description of Military Challenge

- Forward based operators would like to provide continuous, or near-continuous coverage of a target area for a 5 minute period.
- Forward based operators would like to be able to acquire and track a moving target vehicle for an XX minute period.
- Forward based operators would like a simplified interface and low workload for the above tasks so they can maintain situational awareness and security around their immediate location.

Section III – Context

A. Time Horizon

This CONOPS focuses on an enabling capability intended to provide ground based units with ISR data in support of theater directed mission taskings. This CONOPS provides employment recommendations for a proposed UAS. Through expanded operation and utilization, the recommendations provided are intended to evolve into strategic employment scenarios as best practices are collected and documented. The planned initial utilization begins in FY14 and is expected to be used for 2-3 years in the future.

B. Assumptions

This CONOPS assumes that the capability gap identified herein is still present and unresolved. Additionally, it is assumed that airspace deconfliction issues will be resolved, if necessary, prior to each mission utilizing the small UAS as there is no intent to address that specific issue within this document.

C. Risks

The following risks were derived from a consortium of stake holders including, former RPA operators, systems architects, subject matter experts, system designers, and testers:

- Loss of RPA due to hostile detection and action
- Loss of RPA due to broken communications link
- Loss of RPA due to system malfunction
- Loss of RPA due to extreme environmental conditions

- Hostile detection of operator location
- Hostile acquisition of signal feeds and/or control of RPA
- Loss of mission due to unreliability of system components
- Loss of mission due to system degradation
- Loss of RPA and/or mission due to lack of logistical resources
- Loss of RPA and/or mission due to lack of operator knowledge
- Injury to operator and/or noncombatants from system operation

D. System Requirements

A Small UAS will provide forward deployed ground based units the capability to conduct low altitude, ISR and small payload deployment operations from a safe standoff distance with minimal logistical support. Specifically, the UAS will allow operators to:

- Rapidly setup, mission plan, and deploy Small UAS from austere location. You should assume power will not be available at the austere locations.
    - The system shall require one (objective) or two (threshold) operators to perform concurrent vehicle setup and mission planning.
    - Vehicle setup for the small UAS system shall take 10 minutes or less to complete, measured from the time unpacking begins to the time when the system is ready for launch.
    - Mission planning shall take nor more than 10 minutes to perform. Mission planning starts when surveillance and drop target coordinates are provided to the operator, and concludes when the vehicle is ready for launch.
    - Setup shall be performed without the assistance of any power source not provided as part of the UAS system
- Transit to Target
    - The system shall be capable of navigating to a target at a distance of 0.5 mile (threshold) to 1.0 mile (objective) distance from the deployment location.
- Autonomously acquire a vehicle target, and maintain track while the target is in motion.
    - The system shall provide video with sufficient resolution for target identification and tracking. Sufficiency of resolution is defined as 30 pixels/m^2 at the target plane (to identify vehicles).
- Loiter over a desired target, providing uninterrupted, or near-continuous imagery/video of the target for a 10 minute interval.
    - The system shall be capable of providing 10 minutes of continuous (objective – target in FOV 100% of time) or near-continuous (threshold – target in FOV 85% of time).
    - Continuously display geo-coordinates of the target vehicle to the operator throughout the time while the target is being tracked.
    - Accuracy of the target geo-location shall be 150 ft DRMS (or better).

  - The system shall loiter at an altitude not to exceed 1000 feet above ground level.
  - The system shall be capable of flight up to altitudes of 2000 feet above sea level.
- Monitor ISR date from safe standoff distance.
  - The system shall be capable of operating at a distance of 2000' from the operator/ground station, with an objective range of 2 miles from the operator/ground station.
- Conduct Small UAS operations while maintaining situational awareness of the location around the operator.
  - Control and operation of the UAS shall require not more than two dedicated operators, with an objective of a single operator.
  - The operator(s) shall be able to identify ground targets while simultaneously controlling the vehicle.
- Provide timely ISR data for ongoing/future ground operations.
  - Imagery/video from the UAS will be displayed in real-time to the ground operator(s).
- Recovery Phase
  - A single operator shall be capable of navigating the air vehicle to the recovery location, safely landing the vehicle, and retrieving the vehicle for re-use.
  - For purposes of flight test purposes, a safety pilot will land the vehicle once the rest of the mission has been completed.
- Mission Duration
  - The solution shall have a minimum mission duration of 45 minutes. This shall be verified using flight a combination of flight test data and analysis of current draw and battery capacity.
- The UAS must be capable of recovering from common operational problems
  - The UAS shall provide to the operator status of fuel and/or battery power available.
  - The UAS shall provide an automated "return to launch" if communication to the operator station is lost.
  - The UAS shall provide an indication to the operator in the event of GPS loss, and shall include a manual recovery mode if within LOS when GPS is lost.
- Other
  - Safe flight must be greater than 100 feet during all phases expect launch and recovery.

References

Abdallah, R., Kouta, R., Sarraf, C., Gaber, J., & Wack, M. (2018). Fault tree analysis for the communication of a fleet formation flight of UAVs. *2017 2nd International Conference on System Reliability and Safety, ICSRS 2017*, *2018–Janua*, 202–206. https://doi.org/10.1109/ICSRS.2017.8272821

ALD. (2018). Fault Tree Analyser. Retrieved December 18, 2018, from http://www.fault-tree-analysis-software.com/

Alex. (2015). Power Distribution Boards - How to choose the right one - Guides - DroneTrest, 1–3. Retrieved from http://www.dronetrest.com/t/power-distribution-boards-how-to-choose-the-right-one/1259

Amazon. (2018). 10000mAh 6S 10C Multi-Rotor Lipo Pack XT90. Retrieved November 18, 2018, from https://www.amazon.com/Multistar-High-Capacity-10000mAh-Multi-Rotor/dp/B07842PC4L

Amimon. (2018). CONNEX LR. Retrieved November 18, 2018, from https://www.amimon.com/connex-uav-market/connex-lr-receiver/

ArduPilot Dev Team. (2016). Choosing a Ground Station. Retrieved November 18, 2018, from http://ardupilot.org/copter/docs/common-choosing-a-ground-station.html

Army Technology. (2018). RQ-11 Raven, 1–20. Retrieved from https://www.army-technology.com/projects/rq11-raven/

Aslansefat, K., Marques, F., Mendonça, R., & Barata, J. (2017). Reliability Evaluation of the Propulsion System of Multi-Rotors based on Markov Model.

Baldwin, C. Y., & Clark, K. B. (2000). *Design Rules Volume 1: The Power of Modularity*. Cambidge: The MIT Press.

Blackfly S Color 1.3 MP USB3 Vision (ON Semi PYTHON 1300). (2018). Retrieved October 18, 2018, from https://www.ptgrey.com/blackfly-s-13-mp-color-usb3-vision-on-semi-python1300

Breunig, J., Forman, J., Sayed, S., Audenaerd, L., Branch, A., & Hadjimichael, M. (n.d.). Modeling Risk-Based Approach for Small Unmanned Aircraft Systems, 1–23. https://doi.org/10.2514/6.2018-3349

Castle Creations. (2013). Talon Series User Guide. Retrieved November 18, 2018, from http://dzf8vqv24eqhg.cloudfront.net/userfiles/4671/6540/ckfinder/files/Product Manuals/Aircraft %26 Helis/Talon Series/talon-user-guide.pdf

Castle Creations. (2018). TALON 25 AMP ESC, 6S / 25V WITH 8 AMP BEC. Retrieved November 18, 2018, from http://www.castlecreations.com/en/talon-25-esc-010-0128-00

Clarke, R. (2014). Understanding the drone epidemic. *Computer Law and Security Review*, *30*(3), 230–246. https://doi.org/10.1016/j.clsr.2014.03.002

Dagli, C. H., & Kilicay-Ergin, N. (2009). *Systems of Systems Architecting*. Hoboken, NJ: Wiley.

DAU. (2017). System Engineering Process. Retrieved December 18, 2018, from https://www.dau.mil/acquipedia/Pages/ArticleDetails.aspx?aid=9c591ad6-8f69-49dd-a61d-4096e7b3086c

Dempsey, M. (2010). U.S. Army Unmanned Aircraft Systems Roadmap 2010-2035. *Federation Of American Scientists*, 1–140. https://doi.org/ATZQ-CDI-C

Dermentzoudis, M. (2004). *Establishment of Models and Data Tracking for Small UAV Reliability*. *Defense*. Naval Postgraduate School.

DIY Drones. (2013). Retrieved November 18, 2019, from https://diydrones.com/forum/topics/formula-for-determining-resolution-cm-pix

Ebeling, C. (2005). *An Introduction to Reliability and Maintainability Engineering* (Waveland P). Long Grove.

Federal Aviation Administration. (2016). FAA sUAS Part 107: the Small UAS Rule, 107. Retrieved from https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=20516

Flenar, K. A. (2018). *Determining Detectable and Exploitable Aspects of Rogue Unmanned Aircraft Systems*. Air Force Institute of Technology.

Foxtech. (2017). Foxtech Hover 1 Quadcopter With FH310Z Gimbal. Retrieved November 18, 2018, from https://www.foxtechfpv.com/foxtech-hover-1-quadcopter-with-fh310z-gimbal.html

Foxtech. (2018). Foxtech Hover 1 Quadcopter. Retrieved November 18, 2018, from https://www.foxtechfpv.com/foxtech-hover-1-quadcopter.html

FPV Blue. (2018). FPV Blue. Retrieved November 18, 2019, from https://fpv.blue/

Fricke, E., & Schulz, A. P. (2005). Design for changeability (DfC): Principles to enable changes in systems throughout their entire lifecycle. *Systems Engineering*, *8*(4), 342–359. https://doi.org/10.1002/sys.20039

Futaba. (2018). 14SG 14-Channel 2.4GHz Computer Radio System. Retrieved November 18, 2018, from https://www.futabarc.com/systems/futk9410-14sg/

getfpv.com. (2018a). Connex HD Mini Video Downlink (Transmitter only). Retrieved from https://www.getfpv.com/connex-hd-mini-video-downlink-transmitter-only.html?ccartCamp=95291356.3&srcId=4828.1

getfpv.com. (2018b). CONNEX LR - Long Range Receiver. Retrieved November 18, 2018, from https://www.getfpv.com/connex-lr-long-range-receiver.html

glassfox. (2017). Foxtech Hover 1 with FH310Z 10x Zoom camera Detail Display and Footage. Retrieved November 18, 2018, from https://www.rcgroups.com/forums/showthread.php?2813250-Foxtech-Hover-1-with-FH310Z-10x-Zoom-camera-Detail-Display-and-Footage

Hamby, J. (2003). Typical System Reliability/Availability for a Car. Retrieved December 18, 2018, from http://www.imakenews.com/tmeic_news/e_article000137852.cfm?x=b11,0,w

Hassanalian, M., & Abdelkefi, A. (2017). Classifications, applications, and design challenges of drones: A review. *Progress in Aerospace Sciences*, *91*(September), 99–131. https://doi.org/10.1016/j.paerosci.2017.04.003

Herrera, G., Dechant, J., Green, E., & Klein, E. (2017). *Technology Trends in Small Unmanned*

Aircraft Systems (sUAS) and Counter-UAS: A Five Year Outlook. Retrieved from http://www.dtic.mil/docs/citations/AD1047506

Hex. (2018). Pixhawk 2 Autopilot Quick Start Guide. Retrieved November 18, 2018, from http://www.hex.aero/wp-content/uploads/2016/09/PIXHAWK2-Assembly-Guide.pdf

How to Build a Drone - A Definitive Guide For Newbies. (2018). Retrieved July 18, 2018, from http://beginnerflyer.com/build-a-drone/

Hoyland, A., & Rausand, M. (1994). *Sytem Reliability Theory: Models and Statistics Methods*. New York: John Wiley and Sons.

Jacof, A. (2017). Standard Test Methods for Aerial Systems. Retrieved August 18, 2018, from https://www.nist.gov/el/intelligent-systems-division-73500/response-robots/aerial-systems

Jacof, A., Messina, E., Huang, H.-M., Virts, A., Downs, A., Norcross, R., & Sheh, R. (2013). Guide for Evaluating , Purchasing , and Training with Response Robots Table of Contents. *ASTM International Standards Committee on Homeland Security Applications; Operational Equipment; Robots (E54.08.01)*, 1–40.

Jenkins, D., & Vasigh, B. (2013). The Economic Impact of Unmanned Aircraft Systems Integration in the United States. *Association for Unmanned Vehicle Systems International*, (March), 1–40. Retrieved from http://www.auvsi.org/econreport

Joseph Pine, B. (1992). *Mass Customization: The New Frontier in Business Competition*.

Joshi, D. (2017). Exploring the latest drone technology for commercial, industrial and military drone uses. *Buisiness Insider*, 1–4. Retrieved from http://www.businessinsider.com/drone-technology-uses-2017-7

Justin, B., & Murtha, F. (2009). An Evidence Theoretic Approach to Design of Reliable Low-Cost UAVs . An Evidence Theoretic Approach to Design of Reliable Low-Cost. *Thesis*.

KDE Direct. (2018). KDE-CF155-DP PROPELLER BLADES, 15.5" X 5.3, DUAL-EDITION SERIES (CW/CCW PAIR). Retrieved November 18, 2018, from https://www.kdedirect.com/collections/multi-rotor-propeller-blades/products/kde-cf155-dp

Kevorkian, C. G. (2016). UAS Risk Analysis using Bayesian Belief Networks : An Application to the Virginia Tech ESPAARO UAS Risk Analysis using Bayesian Belief Networks.

Larman, C. (2006). *Applying UML and Patterns: An Introduction to Object-Oriented Analysis and Design and Iterative Development* (3rd ed.). Westford, Massachusetts: Pearson Education.

Liang, O. (2016). Types of Multirotors. Retrieved from https://oscarliang.com/types-of-multicopter/

Liang, O. (2018). 6S vs 4S for FPV Mini Quad & Racing Drone. Retrieved November 18, 2018, from https://oscarliang.com/6s-mini-quad-racing-drone/

Madni, A. (2012). Adaptable Platform-Based Engineering: Key Enablers and Outlook for the Future. *Systems Engineering*, *15*(1), 95–107. https://doi.org/10.1002/sys

Maier, M., & Rechtin, E. (2009). *The Art of System Architecting* (3rd ed.). Boca Raton: CRC Press.

Moore, J. (2018). Guessing When Your Drone Will Die. Retrieved October 29, 2018, from https://www.aopa.org/news-and-media/all-news/2018/march/05/guessing-when-your-drone-will-die

Morris, Z. (2018). Smaller , Less Capable Drones for the Near Future. *Military Review*, *May-June*. Retrieved from https://www.armyupress.army.mil/Journals/Military-Review/English-Edition-Archives/May-June-2018/US-Drones-Smaller-Less-Capable-Drones-for-the-Near-Future/

N, A. (2016). *Foxtech Hover 1 - From backpack to ready-to-fly in 150sec*. youtube. Retrieved from https://www.youtube.com/watch?v=Rqni02kYiG4

Newman, L. (2017). The Army Grounds its DJI Drones Over Security Concerns. Retrieved November 18, 2018, from https://www.wired.com/story/army-dji-drone-ban/

O'Reilly, J. (2017). How MTBF may kill drone delivery. Retrieved October 29, 2018, from https://www.eetindia.co.in/news/article/how-mtbf-may-kill-drone-delivery

Office of the Secretary of Defense. (2007). Unmanned Systems Roadmap 2007-2032. Retrieved from www.dtic.mil/dtic/tr/fulltext/u2/a475002.pdf

Ozdemir, U., Aktas, Y. O., Vuruskan, A., Dereli, Y., Tarhan, A. F., Demirbag, K., … Inalhan, G. (2014). Design of a commercial hybrid VTOL UAV system. *Journal of Intelligent and Robotic Systems: Theory and Applications*, *74*(1–2), 371–393. https://doi.org/10.1007/s10846-013-9900-0

Panasonic. (2009). Failure Rates. Retrieved October 18, 2018, from http://www.panasonic.com/business/toughbook/shareability-test-excalibur.asp

Pashchuk, Y., Salnyk, Y., & Volochiy, S. (2017). Reliability synthesis for UAV flight control system. *CEUR Workshop Proceedings*, *1844*, 569–582. Retrieved from http://ceur-ws.org/Vol-1844/10000569.pdf

Petritoli, E., Leccese, F., & Ciani, L. (2017). Reliability assessment of UAV systems. *4th IEEE International Workshop on Metrology for AeroSpace, MetroAeroSpace 2017 - Proceedings*, 266–270. https://doi.org/10.1109/MetroAeroSpace.2017.7999577

Phantom 1 MTBF. (2016). Retrieved October 29, 2018, from https://phantompilots.com/threads/phantom-1-mtbf.71306/

Phillips, W. (2004). *Mechanics of Flight* (2nd ed.). Wiley and Sons.

Pixhawk Autopilot. (2015). Retrieved August 18, 2018, from http://dronereviewhot.blogspot.com/2015/10/parts-diy-drones-parts-at-pixhawk.html

QGroundControl User Guide. (2018). Retrieved November 18, 2018, from https://docs.qgroundcontrol.com/en/

Reimann, S., Amos, J., Bergquist, E., Cole, J., Phillips, J., & Shuster, S. (2013). UAV for Reliability, (December). Retrieved from https://www.aem.umn.edu/~SeilerControl/Papers/2013/ReimannEtAl_13TR_Part1UAVforReliability.pdf

Ryan, E., Jacques, D., & Colombi, J. (2013). An Ontological Framework for Clarifying Flexibility-Related Terminology via Literature Survey. *Systems Engineering*, *16*(1), 99–110. https://doi.org/10.1002/sys

Schenkelberg, F. (2018). Accendo Reliability. Retrieved October 5, 2018, from https://accendoreliability.com/benefits-of-fault-tree-analysis/

Stamatis, D. H. (1995). Failure Mode and Effect Analysis: FMEA from Theory to Execution. *American Society for Quality (ASQ)*. Retrieved from https://www.researchgate.net/publication/283046997_Failure_Modes_and_Effects_Analysis

Stockwell, W., & Schulman, B. (2016). *Defining a Lowest-Risk UAS Category*. Palo Alto. Retrieved from https://www.researchgate.net/publication/315692475_Defining_a_lowest_risk_UAS_category

Sturdivant, R. L., & Chong, E. K. P. (2017). Systems Engineering Baseline Concept of a Multispectral Drone Detection Solution for Airports. *IEEE Access*, *5*, 7123–7138. https://doi.org/10.1109/ACCESS.2017.2697979

T-Motor. (2017). T-Motor MN3508 Navigator Series Motor. Retrieved November 15, 2018, from https://www.unmannedsystemssource.com/shop/motors/t-motor-mn3508-navigator-series-motor/

T-Motor. (2018a). Antigravity 4006 KV380 - 2PCS/SET. Retrieved November 15, 2018, from http://store-en.tmotor.com/goods.php?id=440

T-Motor. (2018b). MN3508 KV380. Retrieved November 15, 2018, from http://store-en.tmotor.com/goods.php?id=354

Thompson, P., & Anderson, C. (2016). Pixhawk Hardware Reliability. Retrieved October 29, 2018, from https://diydrones.com/forum/topics/pixhawk-hardware-reliability

Torun, E. (2002). Defense Technical Information Center Compilation Part Notice. *Response*, *758*. https://doi.org/ADP010487

U.S. Air Force. (2016). *Small Unmanned Aircraft Systems (SUAS) Flight Plan: 2016-2036*. Retrieved from https://apps.dtic.mil/docs/citations/AD1013675

Wang, Q., Mao, J., & Wei, H. yuan. (2018). Reliability Analysis of Multi-rotor UAV Based on Fault Tree and Monte Carlo Simulation. *Mechanisms and Machine Science*, *55*, 1525–1534. https://doi.org/10.1007/978-981-10-6553-8_100

Which Is The Best Quadcopter Transmitter? (2018). Retrieved November 18, 2018, from https://thefancyvoyager.com/rc-radio-transmitter/#tab-con-11

Wilkins, D. J. (2002). The Bathtub Curve and Product Failure Behavior (Part 1 of 2). https://doi.org/10.1097/MNH.0000000000000133

Vita

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