Development of a Monocopter for Exploration of GPS-Denied Indoor Environments

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1 ABSTRACT

Embry-Riddle Aeronautical University (ERAU) has developed SamarEye, a novel Autonomous Aerial System (AAS), to compete in the 2010 International Aerial Robotics Competition (IARC). Responding to the challenges associated with flight in Closed Quarter Environments (CQE), the SamarEye has evolved significantly from the system entered in the 2009 IARC. The latest version of SamarEye incorporates a field programmable gate array (FPGA), a lightweight, high-speed line-scan camera, and simple robust behaviors in a compact, cost-effective package. The samara-based air vehicle embodies simplicity, low weight, and elegant aerodynamic design in an operationally capable CQE platform.

2 INTRODUCTION

2.a Problem Statement

IARC's 6th Mission, "Covert Operation", continues the tradition of pushing the boundaries of Autonomous Aerial System capabilities. To successfully complete the 6th Mission, the system must be capable of launching an air vehicle from outside the target building, ingress through a one square meter window, and search the five hundred and ninety-four square meter obstacle rich environment. The objective of this Mission is to further the operational capabilities and behaviors of flying autonomous agents operating in demanding indoor theatres. The agent must search the interior of the target building, and develop a map that integrates the vehicle's position relative to the initial launch point. Heading and status information must be transmitted back to an operator using the JAUS protocol throughout the Mission.

2.b Conceptual Approach

The name "SamarEye" is derived from the samara-seed inspired monocopter air vehicle, and the imaging mission it is designed to perform. The SamarEye system is comprised of two primary subsystems; the SamarEye air vehicle and the operator control unit (OCU), as shown in Figure 1 and Figure 2,. SamarEye uses a unique aerodynamic configuration commonly referred to as a monocopter, inspired by the works of McCutchen, Norberg and Hoburg. A single Field Programmable Gate Array (FPGA) is employed for time-critical and reactive behaviors, and formatting sensor data. This allows the onboard software to be written in such a way as to take advantage of the massive parallelism inherent to FPGAs. The OCU receives, interprets and relays data from the vehicle to any console using the JAUS protocol. Two way communication can be afforded to any external OCU outside of the SamarEye system utilizing the JUAS protocol

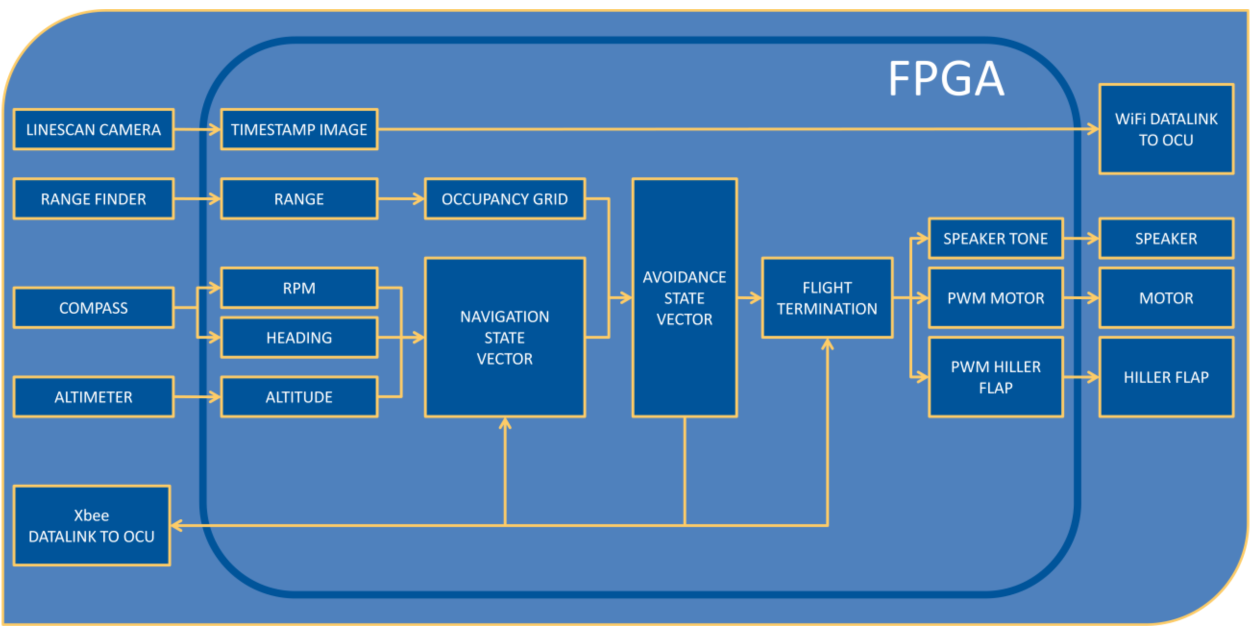

Figure 1. The SamarEye system architecture.

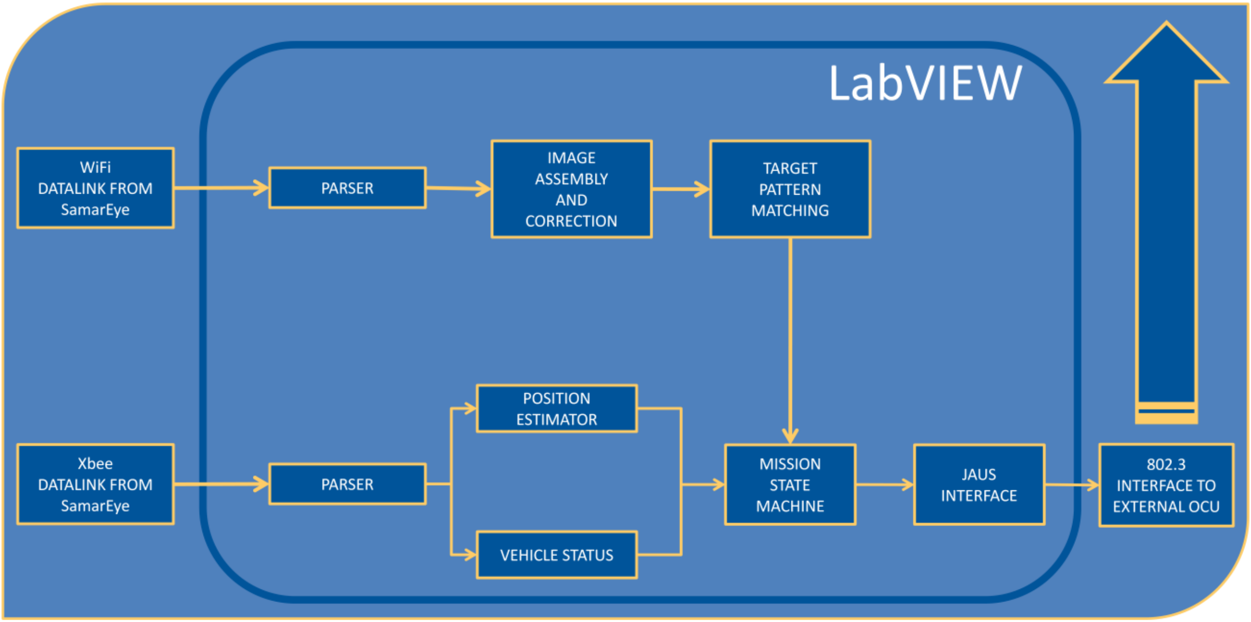

Figure 2. The OCU system architecture.

2.c Yearly Milestones

ERAU attended the 4th IARC Mission in 2007 to gain an understanding of the scope of the competition. In the 2008 event, the team fielded an entry, completed the autonomous three kilometer flight portion of the competition, and placed third overall out of twenty-seven. A rolling sub-vehicle was developed to capture images from within the building as an integral part of the 4th Mission.

The team developed a performance specification to evaluate prospective configurations for the 5th Mission. The specification ruled out most off-the-shelf small UAV platforms. After a month of testing and evaluation, the monocopter became the primary focus of the IARC team's attention. Building on the successes of free flight gliders, the team continued to develop ever more capable versions of the monocopter. The 5th Mission's air vehicle concept was centered on an Arduino microcontroller, with Sharp infrared ranging modules. This configuration proved to have numerous inadequacies that would need to be addressed. (Bakula, Hockley, Reinholtz, et al, 2009)

Work began on addressing the 2009 entries' shortcomings after completion of the 5th Mission. Chief among these shortcomings were the Arduino microprocessor, which was replaced with an FPGA. This switch made necessary the reimplementation of the entirety of the onboard software from a C based language to Verilog. At the same time, sensor specifications, selections and testing was undertaken in conjunction with the initial development of an analytical model for the monocopter platform. As part of the validation of this model, testing apparatus are being developed including a micro force balance and the full instrumentation of Embry-Riddle's low-speed 3D wind tunnel.

3 AIR VEHICLE

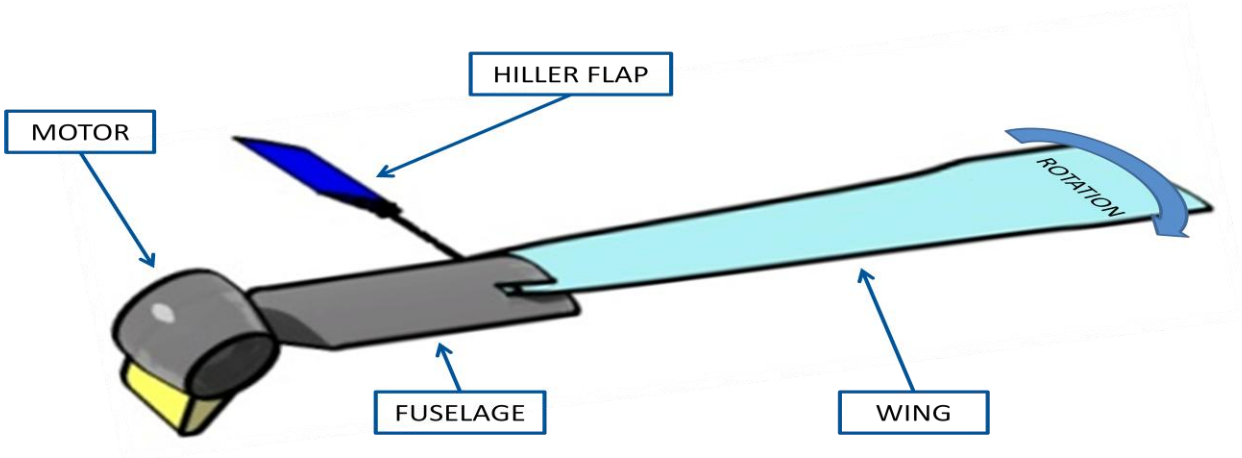

Figure 3. SamarEye monocopter general configuration.

SamarEye's air vehicle is a unique type of rotorcraft, known as a *monocopter*. The monocopter is a member of a small subset of rotorcraft called *free rotors*, in which the entire vehicle rotates, much like a maple [or, generically, a samara] seed. Figure 3 shows the general configuration of the SamarEye prototype. Although this configuration has historically been of no practical use as a manned aircraft, it is uniquely suited to the challenges presented by the 6th Mission.

The key advantage of this monocopter configuration is its inherent static stability. Unlike all other rotorcraft configurations, monocopters require no autopilot for a stable hover. As an autonomous system, a monocopter configuration can achieve complete directional control with only two actuators in this case: an electric motor and a Hiller-type control flap. Sensor requirements are reduced with the monocopter configuration; any fixed sensor on the vehicle becomes a scanning virtual sensor due to vehicle rotation. To maintain the advantages intrinsic to monocopter design a simple flash drive retrieval system is being developed consisting of a small adhesive pad on the base of the primary structure. The mechanically simple design of the vehicle allows it to be stronger, lighter and more durable than other configurations. The combination of a low rotor speed and a lightweight, resilient structure creates an air vehicle that delivers low impact forces, thus reducing the likelihood of damaging the vehicle or anything it may strike. Commercial off-the-shelf sensors and processors facilitate the development an inexpensive vehicle design. The combination of low weight, low cost, and reliability allows the SamarEye team to bring multiple air vehicles to the competition, maximizing system availability over multiple trials.

3.a Propulsion and Lift System

SamarEye has a closely coupled propulsion and lift system. The monocopter's thrust is provided by an electric motor located offset from the center of gravity on the longitudinal axis, oriented such that the thrust vector is transverse to the longitudinal axis. Lift is produced by the resulting rotation. The stability of the vehicle is achieved through the balance between the aerodynamic and gyroscopic forces.

Variations in the forces and moments can be used to modify principal characteristics of monocopter flight, including the wing's angle of attack, the coning angle (the angle which the spar of the vehicle makes with the horizontal plane), and the center of rotation. All of these parameters directly affect the performance of the air vehicle in both vertical and lateral flight.

Directional flight is achieved by generating control commands using a harmonic function which is synchronized with the rotation of the vehicle as displayed in Figure 4. The commands drive a servo connected to a pure Hiller-type flap that is trailing the wing by 90 degrees. This flap works in a manner similar to the cyclic control on a conventional helicopter. By varying the pitch of the entire vehicle, the angle of attack of the wing can be increased or decreased, tilting the disc described by the wing tip. This disc tilt and its associated changes in lift is the vehicle's primary means of lateral propulsion. Controlling the phase offset of the harmonic function allows controlled flight in any direction.

3.b Guidance, Navigation, and Control

SamarEye uses a hybrid strategy for guidance, navigation, and control. The lowest levels of control reside on the vehicle, while higher level functions reside on the OCU, which transmits commands over a digital data link. The primary sensor for obstacle detection is a PixArt Imaging camera chip based infrared ranging module, which is used to sense boundaries in the vehicle's environment.

A single lateral sensor would be inadequate for most vehicles. However, the free rotor configuration of the vehicle applies a high-rate scanning motion to lateral sensors. Reading the single sensor multiple times within a revolution creates an array of virtual sensors. Each raw sensor reading is stamped in relation to the digital compass, effectively providing a reference vehicle orientation for each sensor reading.

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The vehicle uses two actuators to move in the environment. An electric motor provides power to maintains rotational speed to generate lift and a Hiller-type flap provides [in helicopter terms] both collective

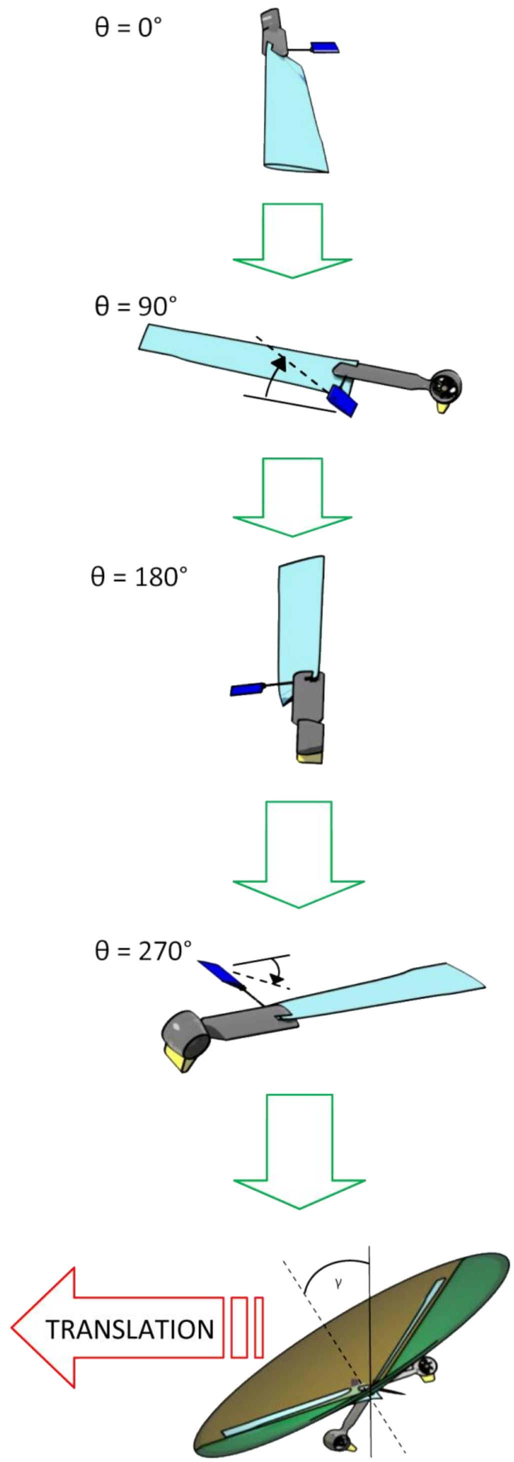

Figure 4. SamarEye translation

and cyclic control to translate through the environment. Similar to the sensor package, a single control surface would seem inadequate to actuate a vehicle in the five available degrees of freedom, however, the use of a highly responsive servo-actuator enables multiple control positions within each revolution. This virtual cyclic control is driven by the onboard FPGA.

The free rotor design of the air vehicle renders the typical vehicle-centric coordinate frame useless for most mapping operations. To generate an external directional reference (i.e., a stable inertial coordinate system), the system uses a magnetoresistive compass (Honeywell® HMC5843). The vehicle uses the signal from the compass to measure the time since the last revolution, and to indicate sensor direction as a fraction of the revolution time. Onboard cognition and sensor synthesis is provided by a Xilinx Spartan 3E FPGA with 1.2 million logic gates. The massive parallelism afforded to the system by the FPGA allows for multiple asynchronous operations to be handled simultaneously.

3.b$_1$ Stability Augmentation System

The vehicle requires very little stability augmentation, because of the static and dynamic stability inherent to the free rotor configuration. A monocopter's stability is derived from the balance of gyroscopic and aerodynamic forces present in flight. Because of this inherent stability, simpler control logic and slower controller speeds are required compared to quadrotors, ducted fans and other common small Vertical Take-Off and Landing (VTOL) platforms. Furthermore, this stability extends to the dynamic flight regime, simplifying non-hovering flight. Control laws are utilized only in the altitude and throttle control subsystems. Both systems are based on an onboard running average, which is then controlled using a Proportional-Integral-Derivative (PID) control scheme which continuously updates at rates of up to 50 Mhz.

3.b$_2$ Navigation

The 6th IARC Mission poses three navigation problems: maneuvering from the launch point through the window, exploring the corridors of the building, and searching the walls and rooms within the building. The SamarEye System Strategy is based on the distributed cognition approach. The high-level navigation functions reside with the OCU; only the reactive obstacle avoidance and base navigation functions reside within the vehicle.

An onboard range-finder is used to sense walls and obstacles in the surrounding environment. Depending on rotational speed and lighting conditions, these sensors are read twelve to twenty-six times per revolution per light source, effectively creating a radial array of virtual sensors. Furthermore, up to four light sources can be tracked simultaneously. The sensors are read into the FPGA over the I2C bus, and are time stamped with the period reference. These sensor readings are then used to populate a vehicle-centric local perceptual map. The map is used by the onboard computer to check for collision threats. If a collision is imminent, a local reactive behavior subsumes all other tasks, maneuvering the vehicle away from danger.

3.c Flight Termination System

The SamarEye system incorporates multiple flight termination mechanisms. These termination systems are distributed across both the air vehicle and the OCU. If any one of these safety protocols are activated, the propulsion system is shut down and the main power is cut, forcing autorotation to the ground. Due to the volatile nature of the FPGA upon main power interruption the vehicle becomes completely inert and can only restart if it is repowered and software reloaded. Multiple software safety switches are provided for on the OCU. These switches can be activated from the attached flight controller, the independent kill switch, or directly from the OCU. Flight termination is handled by both the onboard data link and the onboard FPGA. Both of these systems have the ability to shutdown the vehicle regardless of where the request originated. In addition to external flight termination commands, the air vehicle's onboard FPGA also has a watchdog timer, which will automatically terminate flight upon loss or severe degradation of communications.

4 PAYLOAD

4.a Sensor Suite

The SamarEye vehicle carries a sensor payload in addition to its ranging, reference and altitude sensors. Visual data is collected by a single linescan (1x256 pixel) Taos TL 1402 camera. Taking advantage of the rotational motion imparted by the platform, multiple pictures per revolution can be taken resulting in a continuously updated panoramic image. The image slices are then transmitted to the OCU via a high speed data-link to build the panorama. This payload is integral to the vehicle, and uses the air vehicle's compass and timing information to generate heading defined data in the absence of a fixed inertial frame.

4.a_1 Guidance, Navigation and Control Sensors

Due to the highly integrated nature of the SamarEye platform, multiple sensors are required in order to gain an adequate navigational solution. Lacking a fixed inertial reference frame necessitates that all sensor data, with the exception of the altimeter, collected by the vehicle is fused in order for the data to contain any meaning. This necessitates all sensor data to be fused with heading data provided by the onboard magnetoresistive compass.

Heading is provided by the HMC5843. This MEMS sensor is capable of reading variations in the Earth's magnetic with a precision in the tens of micro-gauss. On-chip data processing, amplification and offset cancellation are all carried out by a custom application specific integrated circuit that possesses a 12-bit resolution ADC and I2C bus.

The primary ranging data is provided by a PixArt Imaging monochrome camera with a native 128x96 resolution. A unique feature of this sensor is the built in processor that enables the sensor to accomplish built in object tracking of up to 4 objects with 8x subpixel accuracy. This results in an effective sensor resolution of 1024x768. The sensor then outputs only the X-Y co-ordinates of the objects over an I2C bus at up to 100Hz. This minimizes the data transmitted out of the sensor and greatly simplifies the task of object tracking. In order to get range data through triangulation, a simple low voltage point source must be projected onto a surface for the camera to track.

Altitude sensing is provided by the SCP1000 MEMS sensor. The sensor performs almost all data processing internally and compensates for both pressure and temperature. It is accurate enough to detect the pressure difference in a nine centimeter column of air, while only drawing five milliamps with an update rate of 9 Hz.

4.a$_2$ Mission Sensors

Mission sensors for SamarEye include the navigation sensors and a small linear solid state camera. The camera is integrated with a custom FPGA implementation to provide timing and buffering of the captured image. The camera must be able to acquire still images at a high data rat and short integration time due to the vehicle's constant rotation. A panorama of the environment is continually updated with the still images being refreshed at a rate related to the rotational speed of the vehicle.

4.a$_{21}$ Target Identification

In order to identify the target the SamaeEye employs the onboard camera and off board image processing. Images taken from the onboard camera are sent over the high-speed, high-bandwidth data link and are subsequently processed in LabVIEW. The image analysis consists solely of image smoothing and simple pattern matching.

4.a$_{22}$ Threat Avoidance

The onboard path planner reads from the local perceptual map generated by the lateral ranging sensor. If a collision, or possible collision, is detected, an avoidance vector is calculated, and an avoidance maneuver is initiated. This reactive behavior subsumes any lower-level commands or behaviors until the obstacle has been successfully cleared or the flight has been terminated. The close coupling of the sensing and action loops in this process is made possible by the parallelism provided by the FPGA processor.

4.b Communications

The digital data link for SamarEye is comprised of a pair of Digi® Xbee Pro RF modules. These are 60 mW spread-spectrum 2.4GHz transceivers, using the 802.15.4 protocol. Transmission power for the Xbee Pro is 18dBm with a signal to noise ratio varying from 8 to 37 depending on environmental factors. High-speed, high-bandwidth communications is provided by a Roving Networks® WiFly GSX 802.11b/g serial module. The WiFly GSX talks over a standard SPI bus and combines a real-time clock, power management and TCP/IP protocols.

4.c Power Management System

The integrated design of the air vehicle enables a simple power management scheme. Air vehicle power is provided by a 930 mAh 3.7V lithium-polymer battery. Motor power, voltage regulation, over-current cutoff, and low-voltage cutoff are all provided by the onboard motor controller. Battery capacity permits flight times exceeding the 10 minute ission time limit.

5 OPERATIONS

5.a Flight Preparations

Pre-flight and post-flight preparations have been kept to a minimum through careful component selection and system design. Once range safety has been confirmed, bitstream programmed into the FPGA and flight termination systems tested, all bystanders are briefed as to the expected operations and safety glasses are handed out. At the end of each test flight, any unusual actions are discussed and high speed footage of the flight is examined to find the cause of the anomalous behavior.

5.a₁ Checklist

In keeping with the overall intent of rapid deployment and simplicity of use, the operational checklist has been intentionally kept as concise as possible. This allows for the vehicle to be rapidly deployed for testing. Before any sortie, the flight crew follows a detailed start-up routine that includes testing of vehicle structural integrity, vehicle behavior, OCU connectivity, SamarEye onboard computer and data link connectivity. Furthermore, this checklist includes set-up of documentation equipment.

5.b Man/Machine Interface

The primary method of interaction between the SamarEye AAS and the end-user is the OCU through the JAUS interface. Auxiliary control is available through the OCU diagnostic console. This software gives the user the ability to send commands to the air vehicle and receive telemetry. The JAUS protocol is used for all external communication.

6 RISK REDUCTION

As with any engineering project, safety is a primary concern, not only to ensure the protection of bystanders and flight crew, but to eliminate any unnecessary expenditure of time and resources. The SamarEye system has been carefully designed to mitigate the likelihood of any significant accidents through a low mass, low power design.

6.a Vehicle Status

Before any sortie, systems checks are undertaken to ensure proper mechanical connections of both primary hardware and battery. This is done in conjunction with thorough mechanical and electrical systems checks which include data link, battery voltage, and free operation of both the servo-flap and throttle.

Taking advantage of the distributed nature of SamarEye, in-flight vehicle status can be ascertained from the reported in-flight rotational speed, altitude, and lateral sensor data. This data can be viewed by the end-user in near real-time using the JAUS OCU interface, or through the LabVIEW interface on the OCU diagnostic console.

6.a₁ Shock/Vibration Isolation

Vibration isolation is handled primarily by the air vehicle's free-rotor design. The balanced multi-blade fan and brushless DC motor were selected for low vibration. The primary cause of in-flight vibration is the propulsion unit which is attached to the primary structure using a vibration damping material.

The three primary sources of shock during air vehicle operations are landing loads, handling loads, and in-flight impact loads. Damage due to landing loads has been lessened due to the low mass and low operational speeds of the vehicle. Handling loads are concentrated on the vehicle's mid-section, where the root of the wing intersects with the fuselage, which is where the vehicles primary structure is concentrated. Of the three sources of shock loading, in-flight collision is the most severe and most difficult to account for in the design. Fortunately, the nature of the monocopter platform makes it highly probable that any object encountered in-flight will be encountered by the outer portion of the wing. Minimizing these shock loads was achieved by having the primary spar not run the entire length of the wing and by angling the wing tip. These design features help ensure that, any time the vehicle encounters an object in flight, it receives a glancing blow, tending to move the vehicle away from the object and allowing continued flight.

6.a$_2$ EMI/RFI Solutions

The SamarEye has few systems that are directly affected by either EM or RF interference. Of primary concern, however, is the magnetoresistive compass. To decrease the likelihood of interference, coaxial cables are used on all high-current lines. Furthermore, the compass is situated far from both the electric motor and the Hiller flap servo, minimizing its exposure to high currents.

6.b Safety

The SamarEye monocopter has numerous safety features. These features include low operational rotational velocity, and low overall vehicle mass. All onboard electrical systems, including the battery, are protected from impacts by their physical location, and are protected from electrical damage by the integral smart motor controller. The volatile nature of the FPGA's memory has been leveraged such that in the event of a loss of system power or a termination of system power by the OCU the vehicle is rendered completely inert.

6.c Modeling and Simulation

Modeling and simulation of a monocopter in flight requires an in-depth quantitative understanding of the forces involved and the way those forces interact. The low Reynolds Number flow around the vehicle is an incredibly complex analytical problem that is still being investigated. Any vehicle dynamics model would require an external physical model to validate it. To that end, both simulation environments and physical testing environments are being developed, including the upgrade of a low speed wind tunnel specifically for monocopter testing. When this information is coupled with the qualitative knowledge the team has gained from the iterative prototyping approach taken for the 5th Mission vehicle, it is hoped a better understanding of the static and dynamic qualities of this deceptively simple vehicle will be achieved.

To further aid development, wherever possible, key systems were separated into standalone test platforms. The first of these platforms were free-flight gliders, which allowed the investigation of monocopter autorotation stability and flight characteristics. Subsystem testing was achieved using a vehicle dubbed "Omni-base." This vehicle consists of four Kornylak® omni-wheels, each with its own drive motor, encircling a central spinning sensor platform. Taking advantage of the mobility afforded to the platform by the omni-directional wheels and the sensor platform, a full range of system integration and programming issues were solved, without resorting to the expense and risk of flight testing a new configuration or code block. Code block separation is simplified by the parallel nature of software development in Verilog for the FPGA, with each code block being able to be separately validated and integrated to ensure desired operation.

6.d Testing

Testing for the SamarEye monocopter took place in multiple stages. First free-flight testing of gliders was undertaken to determine proportions and proper location of the center of gravity to ensure stable flight.. These tests included variations in wing chord, overall planform shape and variations in wing twist. Testing then progressed to include simple remote controlled flights, checking for overall system rotational speed and maximum lift capacity. Sensor testing took place using bench testing, the Omni-base and data analysis methods using mockups to ensure compatibility with the environment.

7 Conclusion

The SamarEye system is a complete and competitive solution to the complex challenges posed by flight inside closed quarter environments. While radical in both concept and appearance, the SamarEye monocopter inherits the characteristics of nature's simplest flyer; the samara seed. The inherent simplicity and stability allowed attention to be focused on overall mission requirements and system integration. This approach focusing on simple and robust systems has allowed ERAU to address every aspect of the 6th Mission from ingress to target acquisition.

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SAMAREYE
a natural evolution in flight