A Natural Evolution in Flight: The Design and Development of the SamarEye System, A Method for Searching Closed Quarter 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 2009 International Aerial Robotics Competition. Responding to the challenges associated with flight in Closed Quarter Environments (CQE), the SamarEye AAS has evolved to incorporate distributed cognition, lightweight sensing, 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 apt CQE platform.

2 INTRODUCTION

2.a Problem Statement

IARC's 5th Mission, "Inside the Box", continues the tradition of pushing the boundaries of Autonomous Aerial System capabilities. To successfully complete the 5th mission, the system must be capable of launching an air vehicle from a mother ship outside the target building, autonomously entering through a one square meter window, and searching an 18m x 33m building. The target of the search is a gauge, located above a blue LED. While searching for the target gauge, SamarEye must also develop a map of the building. The map data includes the air vehicle's position relative to the launch point. The system must then transmit the map data, an indication that the target has been detected, and target imagery back to the Operator Control Unit (OCU) using the Joint Architecture for Unmanned Systems (JAUS) protocol. (Michelson)

2.b Conceptual Approach

The ERAU Robotics Team has developed SamarEye, a novel air vehicle platform, and a supporting system to accomplish the 5th mission. The name SamarEye reflects the samara-seed-inspired monocopter air vehicle, and the imaging mission it is designed to perform. As shown in Figure 1 and Figure 2, the SamarEye system is comprised of two subsystems: the SamarEye air vehicle and a mother ship. The SamarEye air vehicle uses a unique aerodynamic configuration, inspired by the works of McCutchen, Norberg and Hoburg, to operate as a mobile sensor platform. SamarEye employs an onboard microprocessor for time-critical and reactive behaviors.

The mother ship takes data from the air vehicle, formats it into a map of the explored space and a vehicle state vector, then uses deliberative techniques to select actions for the air vehicle to take. A digital datalink connects the two subsystems, forming a hybrid deliberative-reactive strategy for robot cognition. Reports to an external OCU are provided by a JAUS interoperable link from the mother ship.

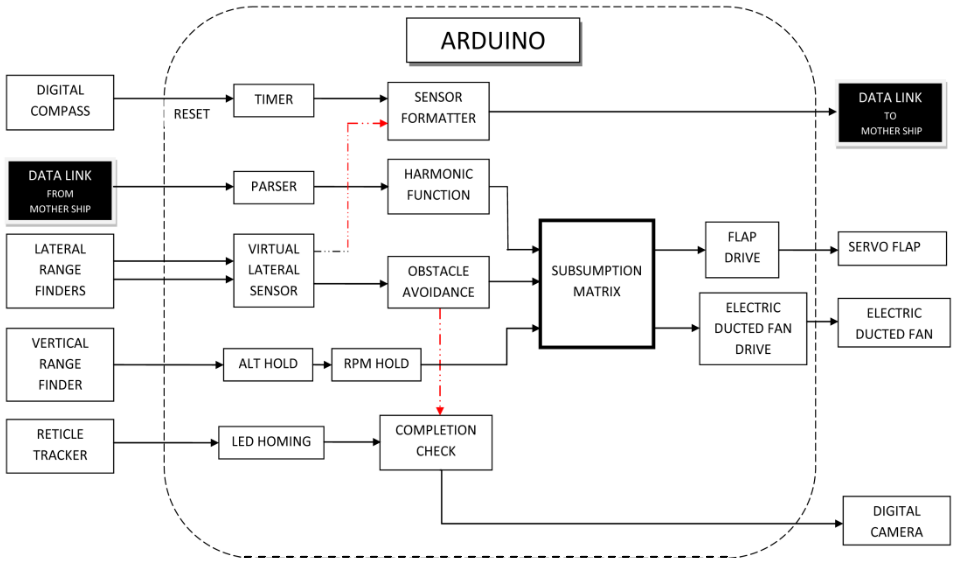

Figure 1. The SamarEye system architecture

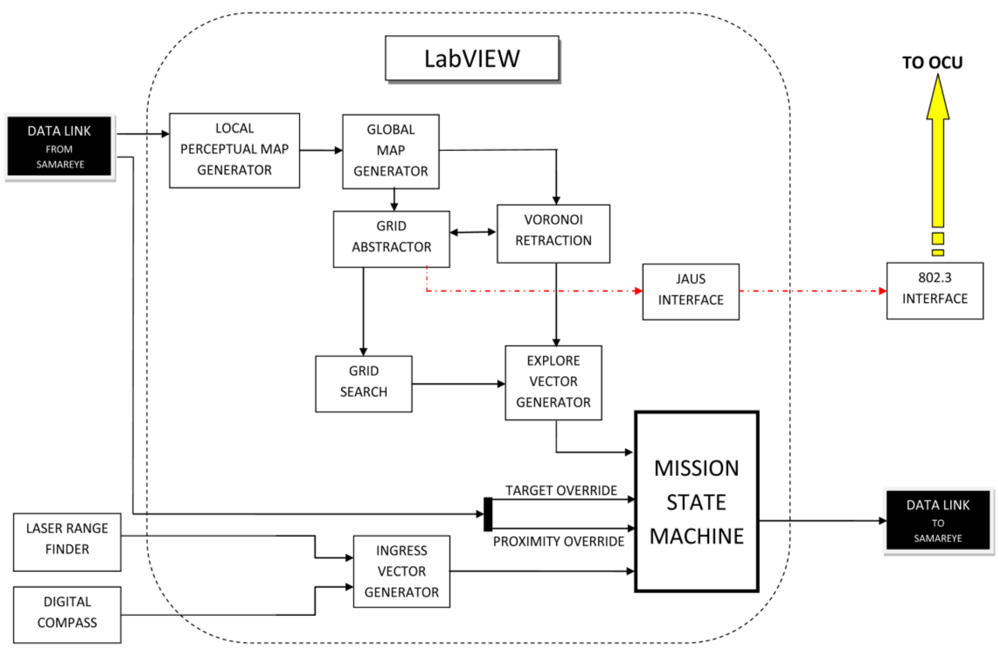

Figure 2. The Mother Ship system architecture

2.c Yearly Milestones

ERAU attended the 2007 IARC 4th mission, gaining an understanding of the scope of the 4th challenge. In the 2008 event, the team fielded an entry, placing third overall, and completed the autonomous 3 km flight portion of the competition. As part of that mission, a rolling sub-vehicle was developed to capture images from inside the building.

With the publication of the 5th mission rules, the team developed a performance specification to use for evaluating prospective configurations. This specification ruled out most off-the-shelf small UAV platforms. Development of the monocopter and several other concepts began in late September 2008. After a month of testing and evaluation, the monocopter convincingly won a "fly-off" against a quadrotor and a thrust-augmenting ejector concept called a "Turboplan", becoming the primary focus of the IARC team's attentions. Building on the successes of free flight gliders, the team continued to develop ever more capable versions of the monocopter. By January 2009, the team had achieved hands-off stability and flight times exceeding 11 minutes.

As air vehicle development continued, the team began building the Arduino microcontroller software for onboard sensor data collection and reactive behaviors. Much of this development was done on a surrogate ground vehicle model, using an omni-wheel configuration as a 3 degree of freedom model for the air vehicle. This was done to lower risk, and to allow parallel development. The LabVIEW mapping, localization, and deliberative behavior modules followed as example sensor data became available.

3 AIR VEHICLE

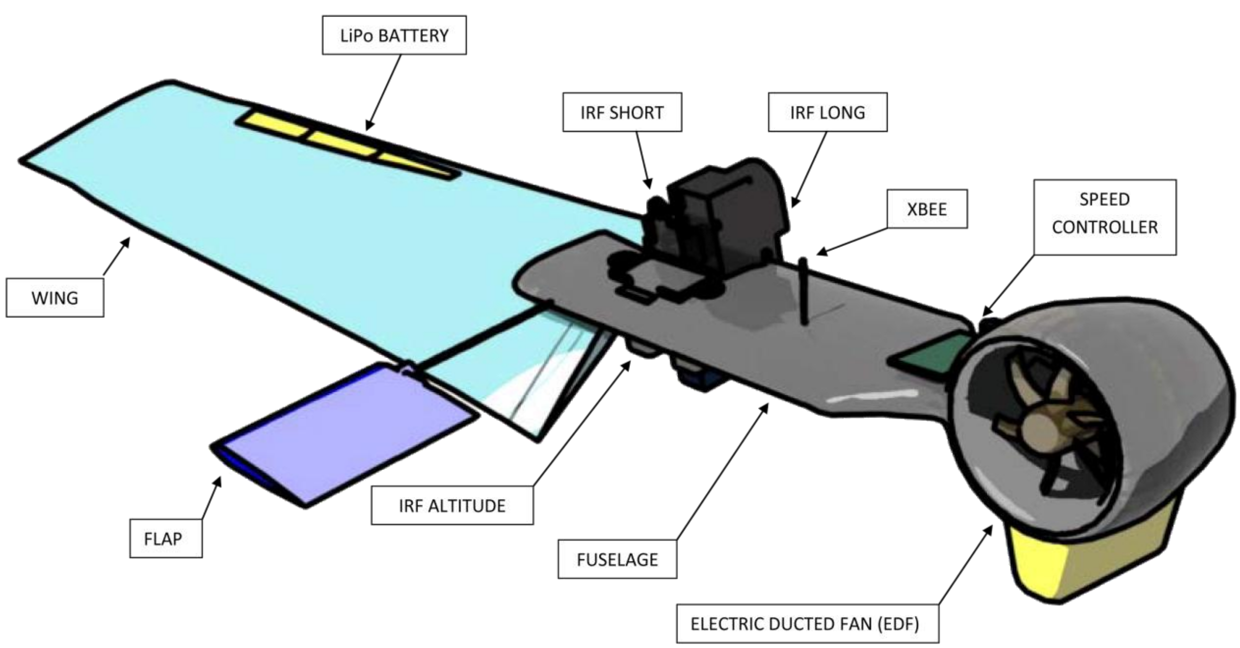

Figure 3. SamarEye monocopter general configuration

SamarEye's air vehicle is a unique type of rotorcraft, called 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 a SamarEye prototype. Although this configuration has historically been of no practical use as a manned aircraft, it is uniquely suited to the challenges of the 5th mission.

The key advantage of the 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 control over all six degrees of freedom with only two actuators: an electric ducted fan (EDF) and a responsive control flap. This configuration also reduces sensor requirements, as any fixed sensor on the vehicle becomes a scanning sensor due to vehicle rotation. The mechanically simple design of the air vehicle allows it to be stronger, lighter and more reliable than other configurations. The combination of a low rotor speed due to the large disc area and a lightweight, resilient structure creates an air vehicle that delivers very low impact forces, reducing the likelihood of damaging the vehicle or anything it may strike. Commercial off-the-shelf sensors and computers facilitated the development of a lightweight, inexpensive air vehicle design. This 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

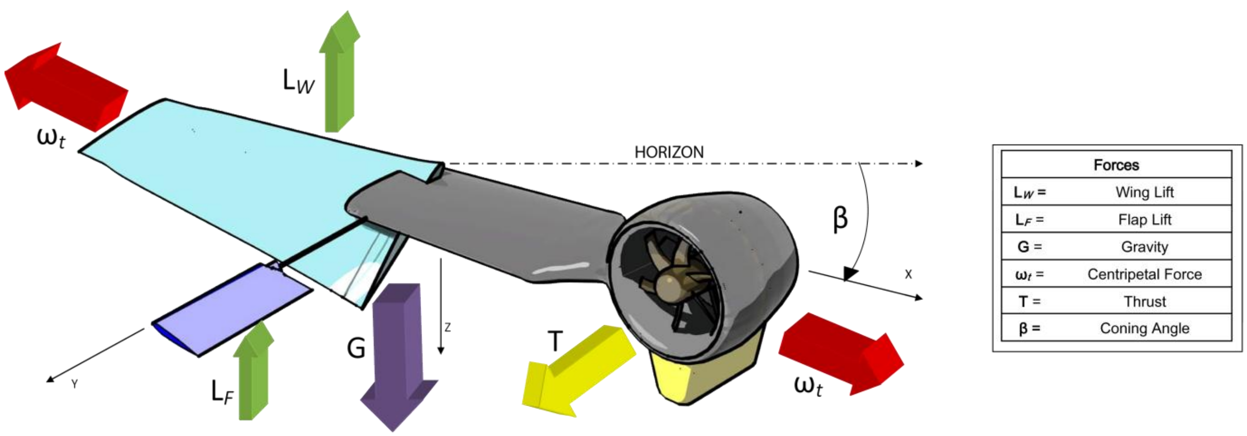

Figure 4. SamarEye simplified forces and moments

SamarEye, like all powered monocopters, has a closely coupled propulsion and lift system. As shown in Figure 4, a monocopter flies by rotating its wing through the air, producing lift. For SamarEye, thrust is provided by a GWS® EDF-40 fan and housing mated with a Feigao® FG-MBLN120L brushless electric motor This lift is then offset by the thrust and gyroscopic forces incurred by spinning the various masses which comprise the vehicle. When these forces are in equilibrium, the vehicle will rotate about the Z-axis perpendicular to the ground and take flight.

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 5. 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 is the air 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 air vehicle, while higher level functions reside on the mother ship, which transmits commands over a digital datalink. The primary sensors for navigation are three Sharp® infrared ranging modules, which are used to sense walls and other objects in the air vehicle's environment.

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

The air-vehicle uses two actuators to move in the environment. An electric ducted fan provides power to maintain RPM and lift for the vehicle and a Hiller-type servo-flap provides (in helicopter terms) both collective and cyclic control to move about. As with the sensor, a single control surface would seem to be inadequate for six degrees of control. However the use of a responsive servo-actuator enables multiple control positions within each revolution. The Arduino uses harmonic functions to drive the actuator as a virtual cyclic control.

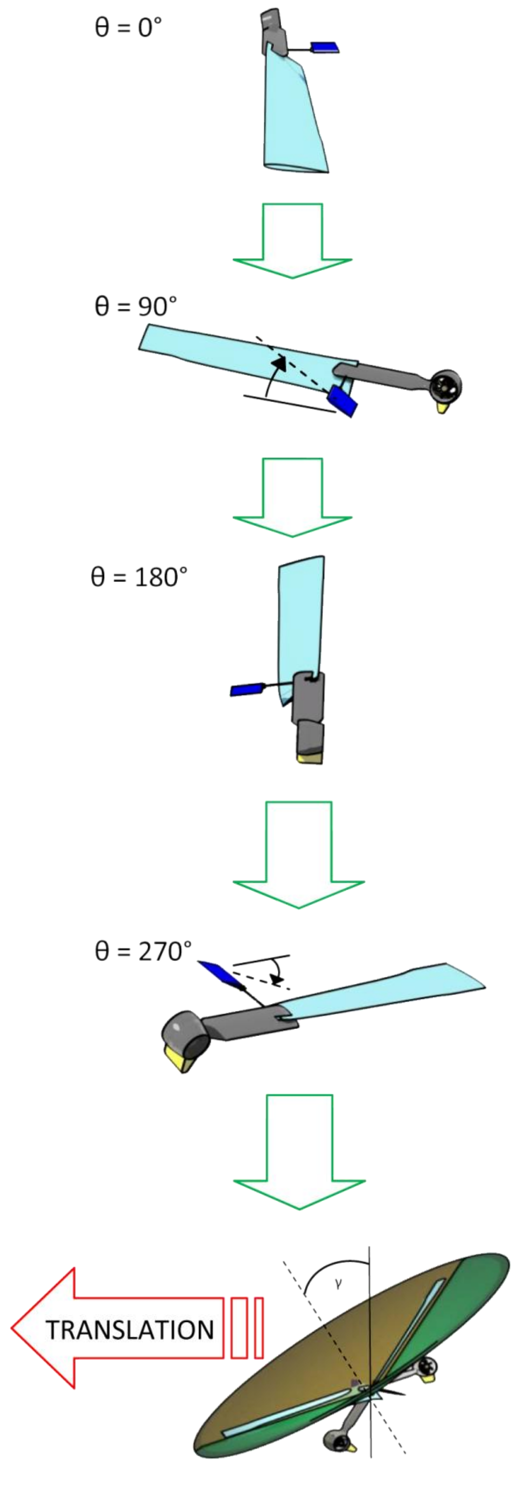

Figure 5. SamarEye translation

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), a magnetoresistive compass (Honeywell® HMC 1052L) is used. The compass signal is amplified and sent though a comparator to generate a once-per-revolution signal referencing magnetic "north." The air vehicle uses this periodic signal to measure the time since the last revolution, and to indicate sensor direction as a fraction of the revolution time. Onboard cognition is provided by an Arduino Pro-Mini microprocessor, an open hardware/open source board based on a 16 MHz Atmel ATMega 168. Clocking, a UART, analog and digital I/O lines are provided, making the Arduino a complete microcontroller on a board the size of a postage stamp. The Arduino Integrated Development Environment (IDE) is also open source; this enables rapid application development in a C programming environment with very low overhead.

3.b_1 Stability Augmentation System

The air 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 updates at approximately 10Hz.

3.b_2 Navigation

The IARC 5th mission poses three navigation problems: maneuvering from the mother ship through the window, exploring the corridors of the building, and searching the walls of the rooms within the building. The strategy used by the SamarEye system is based on the distributed cognition approach. The high-level deliberative navigation functions reside in the mother ship, only the reactive obstacle avoidance and target tracking functions are handled exclusively by the air vehicle.

For the air vehicle to maneuver from the mother ship and enter the building, both the mother ship and the air vehicle use sensing to identify the window. The mother ship includes a Sick® LMS-291 laser rangefinder (LRF) and a digital compass to identify the course to the window and translate that course into a navigation solution for the air vehicle. Corrections to this course are then made by the mother ship using LRF feedback to ensure ingress.

The air vehicle uses onboard IR rangefinders to sense walls and obstacles in the competition environment. Depending on rotor speed and other processing requirements, these sensors are read nine to sixteen times per revolution, effectively creating a radial array of virtual sensors. The sensors are read into the microcontroller as voltages, and are time stamped against a period reference. The Arduino then sends the sensor readings (voltage and time) over the data link to the mother ship. At the same time, the onboard computer checks each reading for collision threats. If a collision is imminent, a local reactive behavior subsumes global control momentarily, maneuvering the vehicle away from danger.

The mother ship converts a series of sensor readings from each revolution (voltage and time) to distance-angle. It then compares them against the current map using a Hough transform in the vehicle position domain as described in Howell. A position match is indicated by a maximum in the Hough voting array. The best match is selected as the vehicle's current pose. Sensor readings are transformed from that pose into the global coordinate frame, and are added to the global map.

A separate LabVIEW process looks at the global map, and abstracts it into 8 x 8 foot squares. (It is known a priori that Ukrainistani architecture is based on 8 foot modules.) A modified depth-first search algorithm selects the next unexplored square, generating a new air vehicle course.
A specialized payload sensor, a reticle tracker, scans for the blue LED. Once the LED is located, an interrupt overrides the previously computed course, and the LED location is used as the basis for navigation. As it homes on the LED, the Arduino compares the attraction vector with any obstacle avoidance vectors. When the LED attraction and obstacle repulsion vectors reach equilibrium, the air vehicle is as close as possible to the target. The digital camera then takes the picture, completing the mission.

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 mother ship. If any one of these safety protocols are activated, the EDF is shut down, forcing autorotation to the ground. The air vehicle can only be restarted once its power has been cycled or its onboard computer has been manually reset. Multiple software safety switches are provided on the mother ship; these switches can be activated from the attached flight controller, or directly from the mother ship computer. The air vehicle's onboard computer handles all flight termination requests, regardless of whence they originate. In addition to mother ship flight termination commands, the air vehicle's onboard computer 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 air vehicle carries a sensor payload in addition to its ranging sensors. These payload sensors include a reticle tracker to find the blue LED and a digital camera with flash to collect desired images. This payload is integral to the air vehicle, and uses the air vehicle's compass and timing information to generate control signals which subsume the mother ship's course selection function. All data transmissions, including sensor status and collected imagery, are sent over the existing vehicle digital data link.

4.a$_1$ Guidance, Navigation and Control Sensors

The only sensors used for navigation within the building are Sharp infrared ranging modules. Two models are used: the GP2Y0A02YK0F for altitude and short-range lateral sensing from 20 to 80 cm, and the GP2Y0A700K for long-range lateral sensing between 60 and 550 cm. Both types use 880 nm infrared light to measure distances by triangulation. (Sharp) Although these sensors are subject to errors from specular reflections and attenuation, their modest weight and power consumption more than offset these limitations. Reading the sensors at a high rate and from varying positions as the vehicle moves also mitigate the limitations of IR triangulation sensing.

4.a_2 Mission Sensors

Mission sensors for the SamarEye system include the reticle tracker and a small CMOS solid state camera designed for cell phone use. This was integrated with a custom field programmable gate array (FPGA) to provide timing and buffering of the captured image. Due to the vehicle's constant motion, still pictures are taken with a short integration time, requiring a high shutter speed. To ensure that sufficient light is available for a clear image, a high-brightness LED is used as a flash to supplement the ambient light in the room. A timing signal provided by the reticle tracker triggers the camera when the subject is in view. Sequential images can be taken at the rate of vehicle rotation, typically four to five revolutions per second, to provide trend data from the subject.

4.a_{21} Target Identification

The reticle tracker is a specialized non-imaging optical sensor optimized for sensing the unique characteristics of the target, in this case the blue LED under the target gauge. Reticles use spatial filtering of the field of view (FOV) to discriminate point sources like LEDs without forming an image that has to be interpreted (Wolfe, Zissis 17-11). In SamarEye, the reticle is composed of vertical bars (or "fenceposts") that chop the FOV into stripes. As the vehicle rotates, the bars passively scan across the FOV. Diffuse light sources and reflected light are continuously visible between the bars, generating a steady amount of light which is then concentrated on the photosensor. Point sources such as LEDs pass behind the bars sequentially, causing variations in the total amount of light on the photosensor, and a signal at the sensor output. LEDs can be discriminated from broad changes in ambient light due to the characteristic phase and frequency of the signal; these characteristics are factored into the design of the reticle system. When combined with an optical bandpass filter for the color of interest, LEDs of a given color can be detected. Careful design of the reticle and integration with the air vehicle's timing system allow both the direction and the altitude of the LED to be determined in the air vehicle's coordinate system. The reticle tracker is a simple, inexpensive (in mass, power, and processor cycles), and robust sensor for the 5th mission.

4.a_{22} Threat Avoidance

The onboard Arduino tests each range reading from the lateral IR sensor against a proximity limit (specified in voltage) and, if it senses a collision threat, calculates an avoidance vector which is applied to the control flap. The avoidance behavior suppresses any higher-level commands from the mother ship until the limit is cleared. A proximity override message is also sent up the datalink to the mother ship.

4.b Communications

The current digital datalink candidate for SamarEye is comprised of a pair of Digi® Xbee Pro RF modules. These are 60 mW spread-spectrum transceivers, using the 802.15 protocol. Verification of noise figures and potential processing gain is in progress.

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 730 mAh 11.1v lithium-polymer battery. Motor power, voltage regulation, over-current cutoff, and low-voltage cutoff are all provided by a Castle Creations®

Thunderbird 6, 6-amp brushless motor controller. Battery capacity permits flight times exceeding the 10 minute mission time limit.

5 OPERATIONS

5.a Flight Preparations

Pre-flight preparations have been kept to a minimum through careful component selection and system design. Once range safety has been confirmed 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 abnormalities.

5.a$_1$ 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, mother ship computers, SamarEye onboard computer and datalink connectivity. Furthermore, this checklist includes set-up of documentation equipment, such as the completion of a test placard and the deployment of a high-speed camera.

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 mother ship diagnostic console. This software gives the user the ability to send commands to the air vehicle and receive telemetry, including sensor data. The JAUS protocol is used for all communication. A further function of the LabVIEW user interface is to display the map being built as the air vehicle explores its environment.

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. To ensure safety, the SamarEye system has been carefully designed to mitigate the likelihood of any incidents arising.

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 datalink, battery voltage, and free operation of both the servo-flap and throttle.

Taking advantage of the distributed cognition paradigm, in-flight vehicle status can be ascertained from the reported in-flight RPM, altitude, and sensor data. This data can be viewed by the end-user in near real-time using JAUS OCU interface or through the LabVIEW interface on the mother ship diagnostic console.

6.a_1 Shock/Vibration Isolation

Vibration isolation is handled primarily by the air vehicle's free-rotor design. The balanced fan rotor and brushless DC motor were selected for low vibration. The primary cause of in-flight vibration is the electric ducted fan (EDF). The EDF was then attached to the air vehicle structure, which itself is made up of vibration damping Polystyrene material. Adhesive was used to attach the EDF to the airframe, which also helps mitigate vibration compared to mechanical fasteners. When this is added to the natural aerodynamic viscous damping and the inherent stability of the platform in the gyroscopic flight regime, little vibration is present in flight. The stability and inherent vibration damping properties of the platform were rigorously investigated over multiple flights using in-flight telemetry and high-speed camera footage.

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 using energy-absorbing polystyrene foam for all primary points of contact, and adhesive connections on the majority of the primary structure. Handling loads are concentrated on the vehicle's mid-section, where the root of the wing intersects with the fuselage. This coincides with the main spar, and with the main landing gear leg. 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

Because of careful design decisions at its inception, the SamarEye has few systems that are directly affected by either EM or RF interference. Of primary concern, however, is the magnetometer onboard the air vehicle. To decrease the likelihood of interference, coaxial cables are used on all high-current lines. Furthermore, the magnetometer itself is placed in a location as far away as possible from both the EDF motor and the servo flap motor, minimizing its exposure to high currents. To keep the power system onboard the air vehicle as noiseless as possible, a brushless motor was selected.

6.b Safety

The SamarEye monocopter has numerous safety features. These include a low operational RPM (below 600 RPM), soft foam wing, shrouded fan, and low overall vehicle weight (below 160 grams). The onboard battery is protected from impacts by its location, and it is protected from electrical damage by the integral smart motor controller. The onboard software has been designed to fail-safe in order to prevent uncontrolled vehicle operation.

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. A single rotary wing, moving in low Reynolds Number viscous flow through not only its own wake and wingtip vortex but also the turbulent stream tube produced by its EDF propulsor is a complex problem. Given the complexity of the wing, coupled with the gyroscopic loading produced by the vehicle in a dynamic loading regime, it quickly became clear that an iterative prototyping process would yield a qualitative model of monocopter flight characteristics in a far shorter time than the team could develop a comprehensive analytical model. Iterative prototyping was facilitated by the simple and inexpensive nature of the system.

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. The Omni-base sensor surrogate platform is shown in figure 6. Taking advantage of the mobility afforded the platform by the omni-directional wheels and the sensor platform, which is spun at or above flight speed, 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.

6.d Testing

Testing for the SamarEye monocopter took place in multiple stages. Free-flight testing of gliders was first undertaken to determine proportions and proper location of the center of gravity to ensure stable flight. Following successful glider flight testing, a battery of ever more successful flight tests took place with airframes of differing designs. These included variations in wing chord and control methods, including testing trailing edge flaps, a mass elevator, and wing twist. Sensor testing took place using the Omni-base, using mockups of various test environments to ensure compatibility with the environment and data analysis methods.

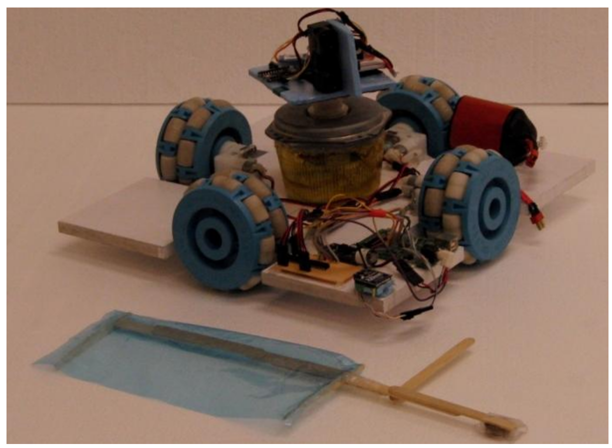

Figure 6. Free-flight glider and omni-base

7 Conclusion

The SamarEye system is a complete and competitive solution to the complex challenges posed by the IARC 5th mission. While radical in both concept and appearance, the SamarEye monocopter inherits the characteristics of nature's simplest flyer-the samara. This 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 5th mission from ingress to image capture.

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SAMAREYE
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