Design and Development of South Dakota School of Mines and Technology's Aerial Robotic Reconnaissance System

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ABSTRACT

The South Dakota School of Mines and Technology Unmanned Aerial Vehicle Team will participate in the 2007 International Aerial Robotics Competition (IARC) with a two vehicle system consisting of an Airstar Mongoose helicopter and a quad-rotor X-UFO flying model. The vehicles have been modified to work together and complete stages 1-3 in the 15 minute time limit of stage 4. The team will use the helicopter to carry the Structure Entry and Reconnaissance Vehicle (SERV) and deploy it once the helicopter and its onboard systems have identified the target building and its openings. The SERV will then enter the building through this opening and begin its search.

1 INTRODUCTION

1.1 Problem statement

The International Aerial Robotics Competition (IARC) requires autonomous aerial vehicles to complete a multi-stage reconnaissance mission. The mission is broken down into four stages to give yearly milestones to competitors. Stage 1 is sending the aerial robot on a three kilometer, GPS guided flight path. To complete Stage 2, the UAV must find a group of structures, identify a specific structure within that group, and identify all actual openings on the structure. In stage 3, the aerial robot must enter the structure through one of the openings, search the interior for a specific target, and transmit still pictures or video of the target back to the launch point. The final stage of the competition is completing the previous three stages sequentially in less than 15 minutes.

1.2 Conceptual Approach

The South Dakota School of Mines and Technology Unmanned Aerial Vehicle team (SDSM&T UAV) has devised a two vehicle system capable of completing the mission in the allotted time of 15 minutes. The two vehicle concept is a result of extensive analysis of the team's previous five vehicle concept. Advances in controller capabilities now allow two vehicles to accomplish the mission more efficiently while providing a more elegant, simple, and adaptable solution to the problem.

The system uses a helicopter to fly the three kilometer flight path and then search the structures for a symbol. The helicopter is capable of traveling the three kilometers in under seven minutes. The secondary vehicle, called the Structure Entry and Reconnaissance Vehicle (SERV), is transported to the structure by the helicopter. The SERV is deployed from the undercarriage of the helicopter after the target opening has been identified. It is designed to enter the building through the opening and search the interior of the building for a target. Video is sent to and recorded by the main vehicle's onboard computer and simultaneously streamed back to the base station in compressed form. The SERV will continue to search the building until its onboard power has been depleted. The helicopter will return to a designated GPS waypoint after the SERV has been deployed. The overall system architecture is illustrated in Figure 1.

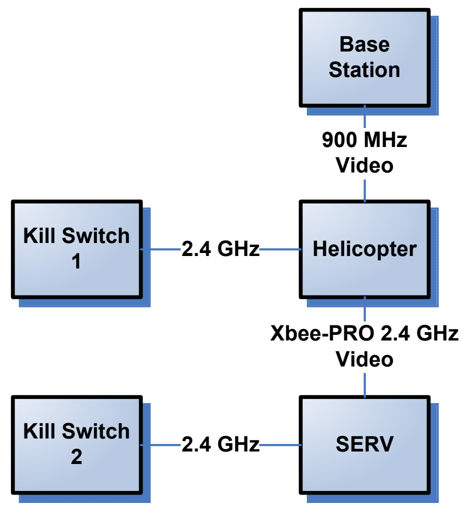

Figure 1. UAV System Architecture

1.3 Yearly Milestones

The SDSM&T UAV team has concentrated its efforts on improving the main helicopter and rebuilding the SERV sub-vehicle for the 2007 competition. An Airstar International helicopter was chosen as the main vehicle platform because of its improved reliability, simplicity, and efficiency as compared to the 2006 platform. As a result, the team has produced a highly adaptable autonomous helicopter capable of completing stages 1 and 2.

The main vehicle improvements have resulted in a platform that will be usable and expandable over the next few years. In addition, the current system was assembled at approximately 25% of the cost of the previous model. The team is currently testing stages 1 and 2, and the helicopter has been flown multiple times to prove its reliability. Search algorithms for stage 2 are being tested and demonstrated using the helicopter's camera and onboard PC.

Substantial progress has been made on the SERV sub-vehicle. The team has focused its sub-vehicle efforts on gaining a deeper understanding of quad-rotor design and control systems. A compact prototype of the X-4 ducted fan design was modeled, produced, and analyzed. The prototype has a 2:1 power to weight ratio and is theoretically capable of stable flight with all the necessary sensors, cameras, and powers supplies. Testing did not demonstrate anticipated results however, as significant losses in thrust efficiency and motor response were present in the model. Consequently, the team decided to implement a flight controller using a commercially available quad-rotor platform that is capable of stable flight. Currently, efforts are centered on autonomous controller development for this platform, and designs for a simple but reliable release mechanism for the platform are underway. The team plans to demonstrate stage 2 and 3 capabilities at the 2007 competition.

2 AIR VEHICLE

2.1 Propulsion and Lift System

The SDSM&T UAV Team is operating an Airstar International Mongoose airframe. The airframe is a modified radio controlled helicopter with primary flight systems consisting of the engine and drive train, main rotor and tail rotor assembly, control actuators, and structural components. The airframe is powered by a 26cc, single cylinder, Zenoah G260H engine producing approximately 1940W (2.2hp) at 12,000rpm. The engine speed is governed onboard to maintain constant rotor head speed. The engine drives a clutch through a belt drive reduction system, which is coupled downstream to both the tail rotor belt drive and a main rotor gear reduction set. The total reduction from the engine to the main rotors is 8.75:1 providing an operating head speed of approximately 1250-1500rpm.

The weight of the unmodified Mongoose airframe is approximately 6.1kg (13.4lb) dry, and the payload the airframe is capable of carrying is approximately 6.4kg (14lb). The fuel capacity is 475cc (16oz) allowing approximately 45 minutes of flight without payload, and approximately 30 minutes of flight carrying full payload. The battery powering all onboard electronic components will provide approximately 90 minutes of power-on time for the entire system.

Cost reduction efforts for the current airframe design reduced flying hardware costs from approximately $40,000 for the previous year's design to approximately $11,000 total airborne system cost. This effort was accomplished simultaneously while increasing actuator redundancy, reducing system weight, increasing airborne computational capabilities, and improving system modularity.

2.2 Guidance, Navigation, and Control

Autonomous navigation and control of the main vehicle is achieved via the combination of the Rotomotion Automatic Flight Control System hardware (AFCS) and SDSM&T's custom Mission Control System software (MCS). These two systems in combination allow the flight crew to design and execute pre-programmed waypoint paths, monitor mission-specific intelligent control software, and maintain full control of the vehicle at all times. The MCS software runs on the base station computer and manages the guidance and navigation control behavior of the UAV system.

The AFCS performs the attitude and position control of the UAV. It maintains the stability of the helicopter in hover and translational flight. The UAV will perform an autonomous translational maneuver only when the AFCS is sent a waypoint from the MCS. The AFCS computer can store and execute a way-point stack, allowing the helicopter to follow a pre-programmed course even if it is outside of radio range or line-of-sight. This option is only utilized during specific flight tests or in situations when the MCS is unavailable. As a safety precaution, the AFCS will be sent only one waypoint at a time by the MCS allowing a mission to be halted immediately at any point. In the event that the communication between the AFCS and MCS is broken, the AFCS will stop and hover the helicopter at the most recently received waypoint.

2.2.1 Stability Augmentation System

The Rotomotion AFCS consists of an embedded computer running Linux, a WAAS-enabled GPS unit, three accelerometers, three gyroscopes, and a three-axis magnetometer. It utilizes PID controllers to maintain attitude and altitude in translational flight and hover as well as flight during a fast forward flight mode. The GPS unit is primarily used to maintain course and speed as well as fixed hovering positions.

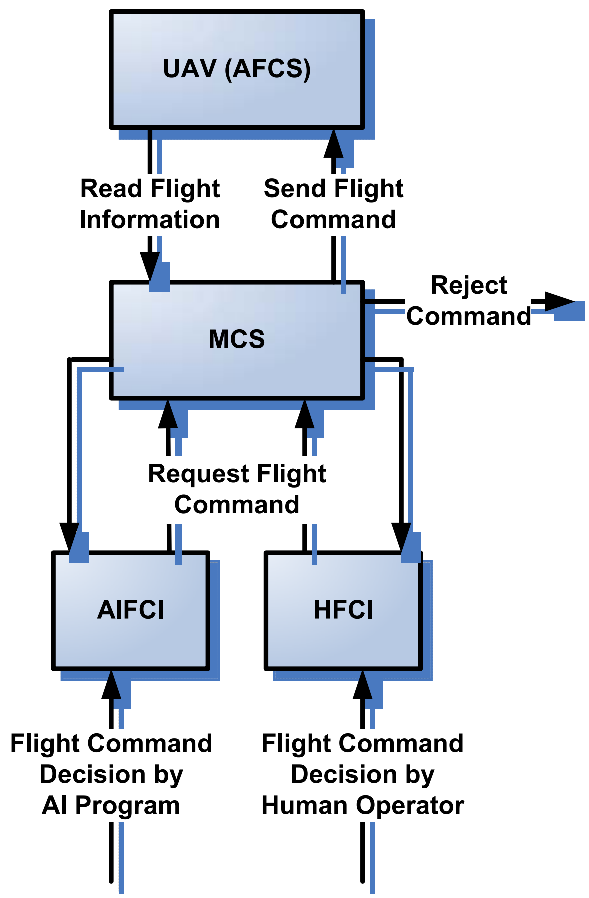

Figure 2. Control System Architecture

2.2.2 Navigation

The MCS allows a human operator or an artificial intelligence program to captain the UAV. The MCS consists of two programs that operate concurrently: The Human Flight Control Interface (HFCI), and the Artificial Intelligence Flight Control Interface (AIFCI). The HFCI allows a human pilot to send commands to the AFCS via a graphical-user-interface, joystick, or keyboard. The human operator has control of every system onboard the UAV, except for those systems which are activated via the transmitter or the kill-switch. The AIFCI allows an independent computer program to send commands to the AFCS. Unlike the HFCI, the AIFCI is limited to commands that control yaw, translation, altitude, and camera platform orientation. While the HFCI and AIFCI operate concurrently, the HFCI has priority at all times. The human operator can disable the AIFCI and take over control of the UAV at any time. When the AIFCI is disabled by the operator, or even if the program crashes, the UAV will stop and hover at the last commanded waypoint, which will usually be no more than 20 meters away.

The MCS can reject command requests that are sent by the AIFCI and HFCI. A command request is usually rejected if it violates safe flight rules. For example, if a command is sent that will move the UAV over a pre-designated no-fly zone, then the MCS will reject the command and warn the user. The MCS will also disable the AIFCI automatically if the human operator sends a command to translate or rotate the helicopter. This system allows the operator to stay in control of the vehicle at all times.

2.3 Flight Termination System

The kill switch systems employed by the helicopter and SERV are both fully independent. The kill switch on the helicopter is powered by a 11.1 volt Lithium Polymer battery and uses an XBee 2.4GHz modem to communicate to the base unit. A relay short-circuits the engine spark to ground when the kill switch is activated, killing the engine. The kill switch on the SERV uses a FET to disconnect the power to the motors when the kill switch is activated. The kill switch on the SERV also uses a watchdog timer to monitor the status of the flight control processor, so if the code on the processor crashes, the motors will shut off. Both the kill switch on the helicopter and SERV are capable of sending diagnostic information back to the kill switch operator.

3 PAYLOAD

3.1 Sensor Suite

The helicopter carries several sensors onboard whose outputs constitute the input to the control system, thus allowing it to fly autonomously in its surrounding environment and to perform other tasks required of it. In order to manage all of this data, it was deemed simpler to handle most of the data processing onboard the helicopter thereby eliminating communication issues of bandwidth and quality from air vehicle to base station. All of the components that constitute a standard computer have been assembled and mounted to the frame of the helicopter to form a fully functional computer with an Intel Core 2 Duo 2.00 GHz processor and 2 GB of RAM. The system is currently running Microsoft Windows XP. The onboard operating system allows most of the sensor data to be compressed and/or relayed directly to the base station.

3.1.1 Guidance, Navigation, and Control Sensors

By interacting with various sensors onboard the helicopter, the AFCS navigates and flies the helicopter. It does this using MEMs gyroscopes and accelerometers which keep the helicopter upright and stable during flight. With the help of a magnetometer and GPS, the AFCS navigates the helicopter between waypoints.

3.1.2 Mission Sensors

The mission sensors are used to determine the location of the IARC symbol and the opening in the building through which the sub-vehicle will enter. They also allow the sub-vehicle to navigate through the target building. The main vehicle's mission sensors consist of a UEye 2220c USB camera and an OptiLogic RS-232 laser range finder. These sensors are used to detect the IARC symbol and locate the window through which the sub-vehicle will enter.

The sub-vehicle's mission sensors include a small digital camera and several ultrasonic sensors. The camera plays only a passive role in the mission objectives by sending back live video to the base station. The ultrasonic sensors are used actively to navigate the sub-vehicle through the rooms and hallways of the target building.

3.1.3 Target Identification

The IARC symbol is identified using a multi-pass, multi-resolution template matching algorithm. The algorithm is capable of finding the symbol when it is 12x12 pixels or larger in the photograph with very few false positives, and is highly reliable when the symbol is larger. Because it is a template matching algorithm, the size of the symbol in the image is needed so that the template may be scaled prior to correlating it with the image. To accomplish this, a laser distance sensor is used to measure the distance between the main vehicle and the target building. With this distance, the field-of-view of the camera lens, and the fact that the symbol is 1 meter in diameter, trigonometry allows calculation of the size of the template. The algorithm is fast enough to process several frames-per-second running on the onboard computer, but only 1 frame-per-second is processed to conserve computational resources.

Open windows are detected on the target building using an attribute analysis algorithm. A series of simple filters is applied to the image. First, an adaptive binary thresholding algorithm is applied to highlight dark and light objects. Next, a connected components algorithm, known as "labeling", is applied to the binary image. This produces a set of regions which can be tested for overall brightness, color saturation, shape, and area. Objects in the image that are relatively dark, have low saturation, quadrilateral shape, and have an area close to 1 meter-squared are classified as open windows.

3.1.4 Threat Avoidance

The helicopter uses the laser range finder as an altimeter to determine the altitude above ground level (AGL) of the helicopter. This allows the helicopter to avoid the threat of ground impact or other obstacles. The helicopter will fly at an altitude such that it will be able to avoid trees and structures.

3.2 Communications

The base station is connected to a 900 MHz Maxstream Ethernet bridge through which it communicates with a second identical bridge on the helicopter. Both bridges utilize 900 MHz high-gain antennas. The UAV antenna, mounted beneath the Rotomotion AFCS at the rear of the helicopter, swings down below the landing gear at take-off. The helicopter bridge is interfaced with the onboard PC via a modified Ethernet to USB adapter. The entire bridge/adapter system is enclosed within an electrically isolated, single-point grounded aluminum case to minimize RF/EMI interference. The Rotomotion AFCS interfaces with the onboard PC through an Ethernet cable, which connects to the external Ethernet port of the PC. The AFCS and the enclosed Maxstream bridge connect via a standard Windows LAN bridge setting on the PC.

Communication between the base station computer and the helicopter has been successfully tested at a range of 2.1 km with the helicopter idling on the ground. The maximum range of the system in flight has yet to be tested. However, full signal strength observed during the ground test indicates that the maximum range should exceed 3km.

3.3 Power Management System

The UAV's power system is a crucial component because all systems depend on a single power supply to function properly at all times. The power system must be reliable and sustainable during operation. Failure of the power system may cause critical failures throughout the entire integrated UAV system. For the 2007 competition, the team altered its approach to the power system in order to incorporate simplicity and dependability while maintaining performance capabilities. A single Thunderpower 3S2P, 4200 mAh, 11.1-volt Lithium-Polymer battery is used to directly power the onboard PC power supply and the AFCS. The Maxstream Bridge and the servo-control board are powered by 5-volt connections to the PC's power supply. The SERV uses its own dedicated 11.1-volt Lithium-Polymer battery, supplying power directly to the motors and onboard systems.

3.4 Sub-vehicle

Following on the work of previous years, the team has developed a sub-vehicle utilizing an X-4 quad-rotor configuration. This platform consists of four fixed, upward-thrusting fan assemblies configured in two counter-rotating pairs and mounted into a single chassis as shown in Figure 3.

The design pursued early in the process consisted of a compact chassis, which housed four fans modeled after a commercially available ducted-fan assembly. The ducted-fan configuration was pursued due to its potential performance, safety, and durability advantages. The ducts act to protect the fans and surrounding objects from impact. Initial prototype efforts did not meet anticipated results, however, so development of a new design was halted, and commercially available units were pursued.

Currently, the development of a similar platform based on the commercially available X-UFO flying model is underway. The X-UFO design utilizes shrouded rotors in a manner similar to the ducted-fans of the previous concept as shown in figure 3. The X-UFO is, however, a readily available consumer device, which has proven its flight and control capabilities. The X-UFO device is configured to fly with a leading and a trailing rotor, both turning in the same direction, and two side rotors turning in the same direction, opposite the first pair. Flight maneuvering such as pitch and roll are accomplished by complimentary adjustment of rotor pairs.

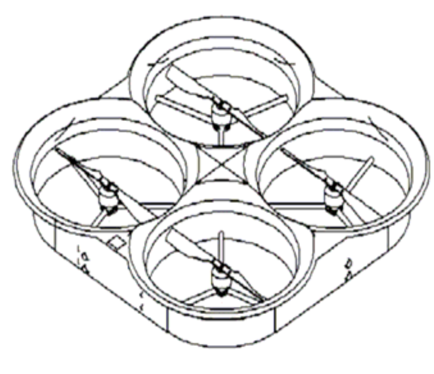

Figure 3. SERV design

The vehicle is equipped with a Memsense Nano IMU, a temperature corrected inertial measurement unit consisting of 3-axis accelerometers and 3-axis gyroscopes providing orientation information, and a 3-axis magnetometer to determine the attitude of the vehicle. A complementary filter is used to extract the angle of the vehicle with respect to the gravity vector as well as the earth's magnetic field, and work is progressing on an Extended Kalman Filter. The information gathered from the gyroscopes is combined with the information from magnetometer and accelerometer to create a responsive and accurate representation of the vehicle's attitude.

The attitude controller on the SERV uses the angle of the vehicle along with the angular rotation of the vehicle to maintain a desired attitude. The vehicle uses six ultrasonic sensors in combination with a GPS to navigate to the structure opening; ultrasonic sensors are used to navigate inside the building. A position controller uses feedback from the ultrasonic sensors and GPS to maintain a desired velocity and heading by controlling the attitude of the vehicle. A fuzzy logic navigation controller guides the vehicle to a desired point just outside the window when searching for the opening. The fuzzy control system has two modes, indoor and outdoor, which are designed to avoid conflict between indoor and outdoor control schemes. The outdoor mode consists of three controllers: a velocity controller, an outdoor rotation controller, and a translation controller.

The indoor mode has a velocity controller and an indoor rotation controller. The indoor rotation controller does not have the target following behavior of the outdoor controller; this enables the vehicle to search the entire building. Photocell sensors are used to change the modes based upon the environments encountered. Once the SERV enters a building, it changes to indoor mode and searches the building while relaying reconnaissance data to the base-station.

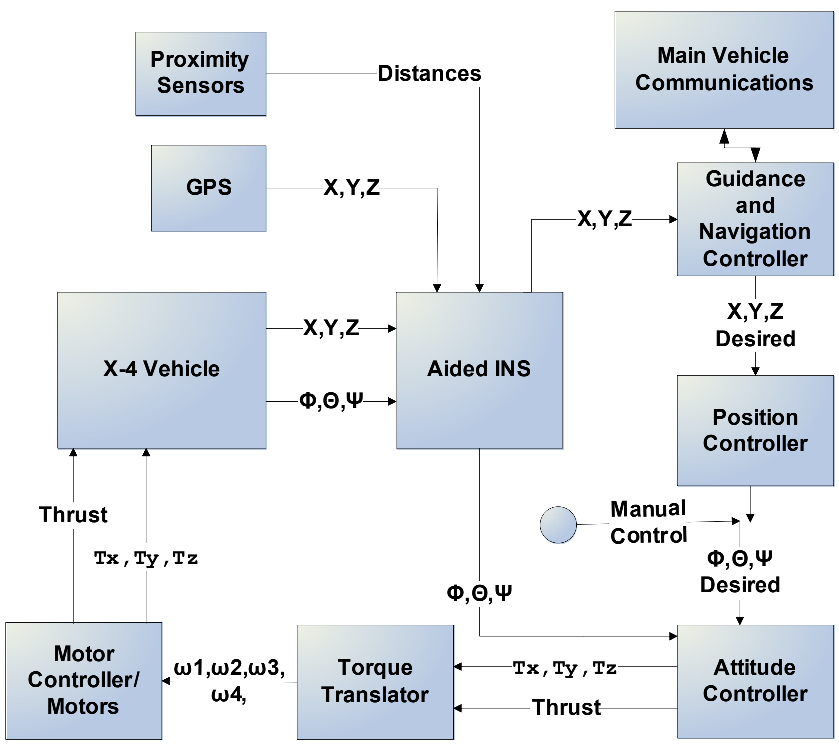

Figure 4. SERV Control Diagram

The SERV carries a variety of sensors. The IMU and GPS are both used to aid in the control of the vehicle, and ultrasonic distance sensors are used to gather information about the vehicle's surroundings. A photocell is used to determine if the vehicle is indoors or outdoors, as the ambient outdoor light level during daylight hours even on a cloudy day is substantially greater than that of typical indoor environments. A small camera is used to gather visual data, which is relayed back to the base station via the helicopter along with all other SERV communications. The communication link between the SERV and the helicopter uses the XBee/IEEE 802.15.4 protocol.

4 OPERATIONS

4.1 Flight Preparations

Several tasks must be completed prior to any flight. Team members are only assigned to tasks for which they have been trained. Before the system can be turned on, a safety briefing is held with everyone present at the field. The briefing covers all associated hazard areas and risks that are present. The final part of the briefing covers the flight plan and what vehicle behavior necessitates emergency procedures. The briefing ends with a question and answer period. This type of format has been successful at keeping everyone safe and informed on the events of that day.

4.2 Checklists

In order to ensure that the vehicles and equipment are flight ready, and also as a safety measure, a series of checklists are used. There are three main checklists: preflight, flight and post flight. In addition to this, the team also compiles a general flight plan which lists the various objectives of the mission for that specific flight. As these items are completed, they are checked off on the list.

4.3 Man/Machine Interface

The team is currently developing a single base station application capable of managing the entire mission on a single, standard PC or laptop computer. Through the use of a sophisticated GUI, the operator will be provided with maps, video, flight information and mission information. This software will also allow the base station operator to control the UAV in-flight by clicking on USGS maps, executing a waypoint script, or through a joystick attached to the computer. In addition, this software manages the Intelligent Flight Control System.

For additional situational awareness, AT&T's Natural Voice TTS (Text-To-Speech) engine has been implemented in the base station application for critical system warnings. Any non-critical errors encountered and detected by the base station are relayed to the base station operator by means of a console window where the error encountered is identified through printed text. An audible tone is sounded to attract the operator's attention. Errors of a critical nature are made known to the operator by words spoken in English using AT&T's Natural Voice TTS engine. In case the operator is working in a noisy environment, the error will be reported in the console window with the audible tone as well. The purpose of this is to ease the work of the base station operator in the event of any type of failure. There are too many variables to be monitored and understood all at once through the normal interface. Therefore, this notification system takes any information that is mission critical and presents it to the user in an expedient manner.

5 RISK REDUCTION

5.1 Vehicle Status

There are several ways in which the status of the helicopter is monitored. Each flight is logged and the total flight time is recorded, thus allowing the team to keep track of a regular maintenance schedule. Prior to each flight, a mechanical and systems preflight is carried out to verify the system is flight worthy. Several sensors onboard monitor the status of critical systems such as battery voltage, avionics box temperature, and engine RPM. The status of all these critical systems is relayed to the base station and kill switch operators, and based on this information, it can be determined if a mission should be aborted. In addition to this, the AFCS indicates in real time whether all the IMU sensors are within range and working satisfactorily.

5.1.1 Shock/Vibration Isolation

High frequency vibrations may lead to fatigue in various mechanical and electrical components. They can also lead to errors in the orientation sensor outputs. For this reason, isolators for the autopilot and electronics mounts have been chosen to avoid natural frequencies near the forced vibration frequencies from sources such as the engine and main rotor blades: approximately 100-200Hz and 20-25Hz respectively. In the event of a crash landing, the landing gear and electronic component mounts are designed to dissipate energy by separating and protecting the vital system components from damage. The helicopter is also mechanically balanced and maintained, and careful attention is paid to preflight and post flight inspections to reduce the amount of harmful vibrations in the system.

5.1.2 EMI/RFI Solutions

Continued attention has been paid to the negative effects of EMI/RFI to the onboard electronic and communications equipment. Communications failures and system problems have been experienced in the past attributable to EMI/RFI generated by onboard components. Current efforts have focused on identifying onboard sources of EMI/RFI and eliminating the sources or attenuating their negative effects. System component power requirements have been standardized to eliminate interference sources from multiple power regulators. Noise-producing systems have been eliminated wherever possible. Individual components and un-amplified signal wires have been shielded and ground loops minimized to protect from EMI/RFI.

5.2 Safety

The team continues to use a safety plan that outlines numerous procedures and possible hazards so as to ensure the safety of the team and the vehicle. The safety plan outlines basic safety rules that every member of the team is expected to follow. Each member of the team is held accountable for the safety of the entire team. Flight line safety information is outlined specifying where people should be at all times and what to do in case of an emergency. Known and possible flight hazards are outlined and solutions to these hazards are specified. Prior to any flight, the team convenes and every team member's tasks are outlined and clarified.

In addition, procedures are outlined for helicopter startup, shutdown and base station setup. There are also procedures outlining the use of the kill switch, and all members of the team are made aware of the implications and consequences of using the kill switch.

In order to further our focus on safety, the team uses a red tag system to mark broken items so that defective equipment is never unknowingly used. In addition, the team has continued training programs for critical systems. A certified team member conducts the training and once all the stages of training are completed, a final test is administered prior to sign off.

5.3 Modeling and Simulation

Low-level and high-level control simulators have been developed to aid in development and testing of the SERV. The low-level control simulator, coded for Matlab, simulates the IMU and the PID controller, which maintains the stability of the aircraft. Our high-level simulator application, called *SimSERV*, simulates the mission sensors onboard the SERV, such as ultrasonic sensors and the experimental laser-line sensor. *SimSERV* has been used to develop complex fuzzy-logic control algorithms which use ultrasonic sensors to decide how to navigate hallways, make turns around corners, and enter windows. In the future, *SimSERV* may be combined with our low-level simulator to produce a highly realistic, fully functional, sub-vehicle simulator application.

5.4 Testing

Testing has been an integral aspect of the UAV team's activities this year. Individual component testing has taken place since January 2007, with main vehicle full system testing beginning in April 2007. Flight testing continues to take place with final system demonstrations scheduled in early June. Bench and flight tests have also continued with the SERV to tune the autopilot and progress towards more stable flight.

6 CONCLUSION

All of the systems discussed above when fully integrated and operational will be capable of performing the four required stages of the IARC competition. The integrated system design will ensure success in the competition while proving itself suitable for other applications such as disaster relief and surveillance. This makes the team and its equipment adaptable to new competitions and research. In order to complete stage 1, the helicopter will fly the required three kilometers while carrying the sub-vehicle. After reaching the group of structures at the end of the three kilometer course, the helicopter will use its onboard camera and the image recognition software to search for and identify the symbol. It will then locate openings in the building to complete stage 2. Following this, the sub-vehicle will be deployed from the helicopter. The sub-vehicle will enter and search the building through the opening, and in order to complete stage 4, the first three stages will be completed within a 15 minute time period. With the current technology and control systems, it is possible for the SDSM&T UAV team to have a system capable of completing the first three stages in the 2007 IARC competition.

7 ACKNOWLEDGEMENTS

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