# Design and Development of South Dakota School 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 has created a five vehicle system to compete in the International Aerial Robotics Competition (IARC). The five vehicle system was created to accomplish stages 1-3 in the 15 minute time limit of stage 4. In order to complete this system, the team focused on the helicopter and Structure Entry and Reconnaissance Vehicle (SERV) for the 2006 competition. This paper describes the system needed to complete all four stages and outlines the design work done this year.*

## INTRODUCTION

### Problem statement

The International Aerial Robotics Competition (IARC) requires aerial robots to accomplish a single reconnaissance mission. The mission is broken down into four stages so teams have milestones for each year they compete. Stage one is sending the aerial robot on a three kilometer egress. Beginning stage two the aerial robot will find itself next to a town where it must search for a building with a specific symbol and recognize an opening into the building. In stage three the aerial robot must either enter and search the structure or launch a smaller robot to search the building. That robot must send data back to identify a specific area of interest inside the building. The final stage of the competition is completing the previous three stages continuously in less than 15 minutes.

### Conceptual Approach

The South Dakota School of Mines and Technology Unmanned Aerial Vehicle team (SDSM&T UAV) has devised a five vehicle system that can adapt to different aerial missions. The concept of using five vehicles is to shorten the time required to find the symbol and locate an opening in the building.

The system uses an airplane as a scout vehicle to fly the three kilometers in under five minutes then begin searching the town for the symbol. The plane will be carrying a secondary vehicle called the Scout Sub-Vehicle, (SSV), which is designed to look for the symbol and locate building openings. The SSV will be able to land and obtain the exact location of the symbol and building openings. By landing the SSV, error in locating the centroid of the symbol and openings is reduced.

The main vehicle is a helicopter designed to fly the three kilometers carrying two sub-vehicles called the Structure Entry and Reconnaissance Vehicles, (SERVs). The helicopter will arrive at the town after the airplane and begin looking for the symbol if the plane and SSV have not already located it. Once the symbol and opening have been located, the helicopter will move close to the location of the opening. When in close proximity, the helicopter will launch the SERVs to enter and search the building. The SERVs will continue searching the building until they have depleted their energy sources. The helicopter and plane will return to a waypoint designated by the base station operator after the SERVs have gone offline.

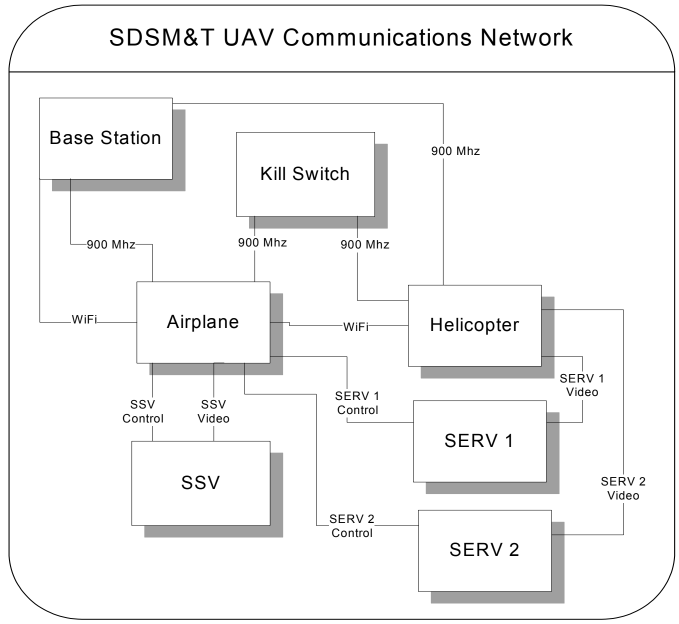


**Figure 1:** UAV Communications Network Diagram

## *Yearly Milestones*

The SDSM&T UAV team is focused on completing the five vehicle system in a two year time span. This year the team has focused on the helicopter and SERV vehicles. Over the next year the team will focus on the plane and Scout Sub Vehicle (SSV). The entire system will be completed for the 2007 competition.

The team has flown stage 1 multiple times with the helicopter to prove reliability. Currently, the team is testing stage 2 algorithms using the helicopter. The deployment system for the two SERVs has also been finalized and will be ready to deploy a SERV at the 2006 competition. The team plans on demonstrating stage 2 and 3 capabilities by locating the symbol and opening, then launching a SERV at the 2006 competition.

# AIR VEHICLE

## *Propulsion and Lift System*

The SDSM&T UAV team is using a model SR-1B autonomous helicopter manufactured by Rotomotion, LLC. A two cylinder, two-stroke gasoline engine manufactured by Bergen RC powers the helicopter. The engine is capable of producing up to 8 horsepower at peak RPM giving the helicopter a gross lifting capacity of approximately 42 lbs. at standard temperature and pressure. The main rotor system is a Bell/Hiller mixed two bladed system with a span of 2.1 meters. Engine speed is governed to keep an average rotor head speed of approximately 1600 rpm. Collective pitch and cyclic flight controls are actuated by mechanically mixed servo motors. The team has decided to keep the weight of the helicopter below 36 lbs by offloading primary computational responsibilities to the base station CPU. This reduces the potential for equipment loss and increases flight performance.

The helicopter has been modified to carry two independently deployable SERVs below its airframe in a launch pod structure. The pod is a carbon/epoxy sandwich laminate structure constructed using a two part epoxy resin system and vacuum assisted wet-layup techniques. A balsa core was secondary bonded over an inner skin providing rigidity in a beam structure, and an outer skin of carbon/epoxy was bonded over the inner skin/balsa core assembly to create an integrated structure. Three servo motors actuate the pod doors, and a toothed belt deploys the SERVs. The pod replaces the main vehicle primary landing gear, and holds the fuel for the helicopter. This feature elevates the fuel supply to a closer proximity than the original configuration, reducing the load on the carburetor pump and increasing engine reliability. The pod also helps minimize the effect of in-flight moment of inertia changes on the PID controller by locating the SERVS close to the axes of rotation at the main rotor hub prior to launch.

## Guidance, Navigation, and Control

The navigation and control system is a combination of a Rotomotion Automatic Flight Control System (AFCS) computer located on-board the UAV, and the Intelligent Flight Control System (IFCS) software which runs on a computer located at the base station. The AFCS provides low-level control of the UAV for autonomous flight, while the IFCS allows a human operator or an artificial intelligence program to drive the UAV for mission control.

## 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 a standard proportional, integral, and differential (PID) controller to maintain attitude and altitude in translational flight and hover. The GPS unit is primarily used to maintain course and speed. The AFCS computer can also store and execute a waypoint stack, allowing the helicopter to follow a pre-programmed course even if it is outside of radio range or line-of-sight. However, the waypoint stack on the AFCS is only used during flight testing or in emergency situations when the IFCS is unavailable.

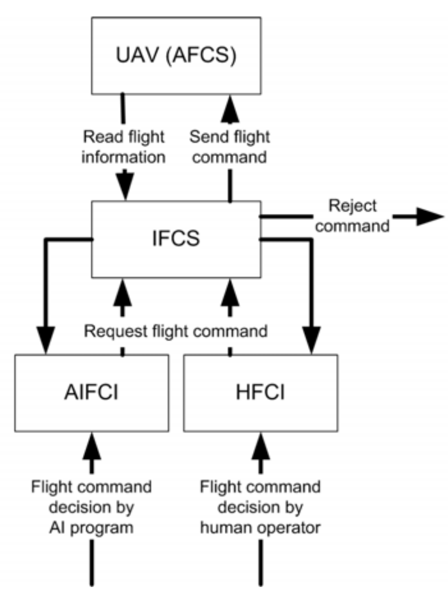


**Figure 2:** Control System Architecture

## Navigation

The IFCS allows a human operator or an artificial intelligence program to captain the UAV. The IFCS 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 on-board 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 IFCS 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 sent that will move the UAV over a pre-designated no-fly zone, then the IFCS will reject the command and warn the user. The IFCS 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.

### *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 9.6 volt Ni-mH battery and uses a Maxstream 900 MHz 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.

## PAYLOAD

### *GNC Sensors*

The Rotomotion controller on the helicopter uses several sensors to navigate. MEMs gyroscopes and accelerometers are used to keep the helicopter upright and stable during flight. To navigate between waypoints, the Rotomotion uses a GPS and magnetometer. The SERV and SSV use GPS, ultrasonic sensors and a laser line sensor to navigate. These sensors are discussed further in the sub vehicle section.

### *Mission Sensors*

The mission sensors are used to determine the location of the symbol and an opening in the building. The sensors are comprised of an Axis 213 network camera and laser range finder for the helicopter, plane and SSV. These sensors are used to detect the symbol and its location. The SSV and SERV use ultrasonic sensors to avoid objects and navigate close to the buildings,. A laser line sensor is also being developed to be used by the SERV to make a 3D distance map for deciding direction when entering and moving within the building.

## Target Identification

We use a 3-pass, multi-resolution, grayscale template matching algorithm to detect the IARC symbol. The algorithm is capable of finding the symbol reliably when it is 12x12 pixels or larger in the photograph, but it is limited by the fact that the ideal size of the template image must be accurately calculated prior to applying the algorithm. We use a laser range sensor to determine the distance to the center of the camera view.

**Figure 3:** Symbol recognized from the UAV.

The first pass of the algorithm takes a 704x480 pixel image from the camera and scales it down by a factor of 3. The scaled image is cross-correlated with the image of the IARC symbol, and the resulting correlation map is then used as a mask to choose which pixels in the image will be processed during the second pass. During the second pass, the image is scaled by a factor of 2, cross-correlated with the IARC symbol, and the resulting correlation map is added to the correlation map of the first pass. The sum of the correlation maps from the first and second pass is used as a mask to choose which pixels will be processed in the third pass. Finally, the third pass cross-correlates the full-resolution photograph with the IARC symbol. The result of the algorithm is the sum of all three correlation maps.

This approach tends to produce results that are just as good as full-resolution template matching, but at three to four times faster in practice. This represents a significant reduction in CPU requirements over the brute force algorithm. This algorithm can process one image per second on a 3.2Ghz PC, and can be further optimized to run even faster.

The template matching algorithm nearly always finds the symbol in the image if it is present and if it is the same size as the template image. However, the algorithm also produces many false-positives if the template image is small. False-positives tend to be generated where sunlight is reflecting off of cars or buildings, or where strong edges are present. We intend to reduce or eliminate these false-positives by sending the correlation hits through one or more multi-layer neural networks that have been trained to recognize the symbol at various angles and scales.

**Figure 4:** Windows detected by thresholding and attribute analysis.

To detect open windows on the target building, the team is experimenting with a thresholding and attribute analysis approach. A series of simple filters is applied to the photograph. First, an adaptive thresholding algorithm is applied to highlight dark and light objects. Next, connected components analysis, also known as "labeling", is applied to the thresholded image. This produces a set of segmented objects which can then 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. We are able to calculate the area of each window given the distance to the wall and the field-of-view of the camera at the given zoom setting. The distance to the wall is given by the on-board laser distance sensor.

The team has implemented and tested this approach in Mathwork's Matlab® on still images of the buildings at the McKenna facility. The algorithm produced excellent results on most of our test images, but did produce some false-positives. These images were taken with a high quality digital camera that produced clean images with good contrast and very little noise. The next step is to code the algorithm in C++ and run the algorithm on live video using the NTSC camera on board the UAV. It has already been discovered that a Gaussian noise filter is required to achieve good results with our adaptive threshold algorithm on live video.

### Threat Avoidance

The helicopter uses a laser altimeter to determine the distance of the helicopter from the ground. This allows the helicopter to fly at a safe altitude to avoid threats. The helicopter will fly at an altitude such that it will be able to avoid trees and other threats.

## *Communications*

The UAV and base station communicate via two LinkSys 802.11b routers, each connected to a 1-watt amplifier and a high-gain antenna. The ground-station uses a 32 inch diameter dish antenna which can be elevated up to a height of 35 feet above the ground on an extendable tower. The UAV uses a custom-built mono-pole antenna encased in a plastic sphere for protection during take-off and landing. The antenna is located at the end of a hinged arm that is attached to the bottom of the UAV. When the UAV is launched, the arm swings down so the antenna is not blocked by the landing gear.

The communication system has been successfully tested at a range of 2.4km with the UAV flying at an altitude of 40 meters AGL. We have also successfully tested the system at over 2km with the UAV in the back of a pickup truck, and with only partial line-of-sight. The dish antenna was also at ground level for that test. The maximum range of the system in flight with the base station dish antenna elevated to its maximum height is, as yet, untested. However, full signal strength observed during these tests indicates that the maximum range easily exceeds 3km.

## *Power Management System*

The power system for any UAV is recognized as a critical area. For the UAV to function correctly it must have a functioning power supply at all times. If the power system fails the helicopter becomes uncontrollable. A malfunctioning power system also has the potential to negatively interfere with other flight critical and non-critical systems.

The helicopter uses two sources of power. A 12 volt Ni-mH battery supplies power to the system when the engine is off or idling. When the helicopter drive clutch is engaged, a generator is driven providing a second source of power for the helicopter. The power inputs from these sources are fed into a power supply circuit that converts the voltages to 5 and 12 volts. The power supply draws from the battery until the generator voltage exceeds a lower threshold, upon which the circuit draws power from the generator, until the threshold is no longer met. The extra power from the generator is used to trickle charge the battery when not in use.

The SSV and SERV each use 11.1-volt Lithium-polymer batteries. The batteries supply power directly to the motors, and power for the rest of the system goes through a switching regulator. The voltage is regulated to 6-volts for the IMU, 5-volts for the modem, and 3.3 and 1.8-volts for logic circuits.

## *Sub-vehicle*

The SERVs carried by the helicopter are based on a simple X-4 rotor design. The aircraft uses four fixed motors to produce lift, configured two in the front and two in the rear. Two motors rotate clockwise and the other two rotate counter clockwise. This allows the vehicle to balance the torques generated by each of the motors. Vehicle motion is caused by varying and coordinating the speed and torques of each of the motors in a pair wise fashion. For example, to move forward the craft decreases the speed of the front two rotors and increases the speed of the rearward two rotors. This causes the craft to tip forward and therefore translate forward. In order to yaw, the craft decreases the speed of the two rotors rotating in one direction and increases the speed of the rotors rotating the opposing direction. This results in no bank or pitch of the aircraft, but does upset the torque balance, causing the craft to yaw.

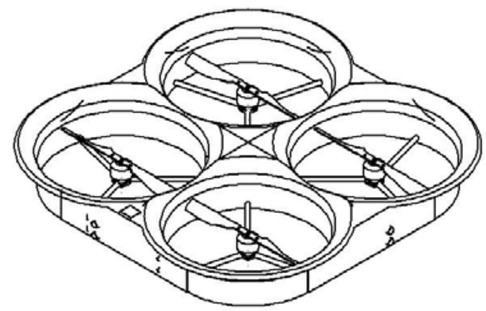

**Figure 5:** SERV and SSV Design

The SERV uses four 110-watt motors to effectively produce up to 1.7 kg of lift. The flight weight of the SERV is approximately 1.2 kg, providing excess lift for maneuvering. Utilizing an 11.1-volt, 4.2 Ah Lithium-polymer battery, the SERV is capable of flying for 12 minutes. The ducts surrounding each rotor are used to protect the rotor blades from impact and add an additional 20% to the lift generated by each motor. Additional lift is attributable to diminished blade-tip vortex production provided by the duct.

The vehicle is equipped with an inertial measurement unit consisting of a 3-axis accelerometer, a 3-axis gyroscope, 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. 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 then uses the angle of the vehicle along with the angular rotation of the vehicle to maintain a desired attitude. The vehicle uses 6 ultrasonic sensors in combination with a GPS to navigate to the window. Within the building ultrasonic sensors are used to navigate. A position controller uses feedback from the ultra-sonic 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 modes. The two modes 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.

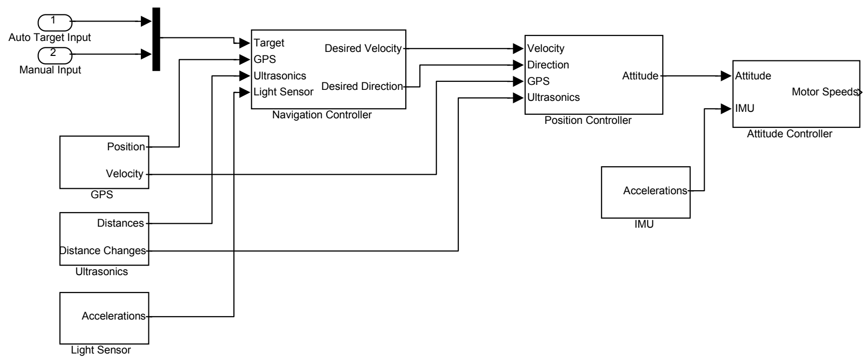


**Figure 6:** SERV and SSV Control Diagram

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

## OPERATIONS

### *Flight Preparations*

Several tasks must be completed prior to any flight. Team members are assigned only 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.

### *Checklists*

A series of checklists are employed to insure the vehicles and equipment are flight ready. Each vehicle has a checklist containing three sections: preflight, flight, and post flight. Before each flight the team creates a plan for the flight and checks off each part of the plan as the vehicle accomplishes the respective mission objective.

### *Man/Machine Interface*

The team is developing a base station application that will be capable of managing the entire mission on a single, inexpensive, PC or laptop computer. The program will sport a sophisticated GUI that will provide a single operator with maps, video, flight information, and mission information. The software will also allow the base station operator to control the UAV in-flight by clicking on USGS maps, executing a waypoint script, or by controlling it with a joystick. This software also manages the Intelligent Flight Control System.

For additional situational awareness the team intends to implement AT&T's Natural Voice TTS (Text-To-Speech) engine in our base station application. All errors that are detected by the base station software are alerted to the base station operator in several ways. Errors that are not critical to the operation of the UAV are printed to a console window and an audible tone is sounded to attract the attention of the operator. Errors that are critical to UAV operations will be spoken in English using AT&T's Natural Voice TTS engine, as well as printed to the console window along with an audible tone. Combat pilots will instantly recognize this voice as *"Bitching Betty"*.

The high-tech application of this TTS software is the introjection of *ego* into the AIFCI system. Not unlike HAL from *2001: A Space Oddesy*, our artificial intelligence software will have a voice that will be instantly recognizable as *intelligent*. This feature will not be a high-tech façade, but it will be an integral part of the application software. There are far too many variables to be monitored by a single person during the duration of a mission, and the base station operator must be made aware of the status of the vehicle and the mission at all times. We will use TTS to alert the operator to changes in the mission status, and when critical errors are encountered.

## RISK REDUCTION

### *Vehicle Status*

The status of the helicopter is monitored in several ways. Each flight is logged and the total flight time is recorded, giving the team the ability to keep a regular maintenance schedule for the vehicle. A mechanical and systems preflight is also accomplished prior to each flight to verify the vehicle is flight worthy. The helicopter uses several sensors to measure the status of critical systems such as battery voltage, generator voltage, avionics box temperature, engine temperature, clutch temperature, and engine RPM. The status of each critical system is then relayed to the base-station operator allowing a determination of continuing the mission or aborting. The AFCS also indicates whether it is safe to engage the autopilot. While the autopilot is engaged, the AFCS indicates if all of the sensors are within range and working correctly.

### *Shock/Vibration Isolation*

High frequency vibrations can lead to fatigue in various mechanical and electrical components. They can also lead to errors in the orientation sensor outputs. For this reason, the autopilot on each of the vehicles is isolated from sources of vibration such as the engine. The landing gear on each of the vehicles is also designed to minimize the shock during landings. In the event of a crash landing, the landing gear is designed to dissipate much of the energy and protect many of the vital system components. The rotors on the helicopter are also kept balanced and trimmed to minimize the amount of vibrations in the system.

### *EMI/RFI Solutions*

The team has taken several steps to minimize the effects of EMI/RFI. The team found that the landing gear strongly affects the signal strength of the 2.4 GHz link; therefore, the team developed a system to safely lower the antenna below the level of the landing gear during flight. All of the sensitive electronics are also enclosed in grounded boxes to minimize the effects of EMI/RFI.

## *Safety*

The safety of the team and vehicle is outlined in a safety plan that the team created to inform members of hazards. The safety plan outlines basic safety rules that the team must follow. Each member of the team is held accountable for the safety of the entire team. A section of the plan outlines flight line safety to inform people on where they should be at all times and what to do in an emergency. Known flight hazards and possible hazards that were identified by the team are listed along with ways to resolve or mitigate these hazards. Before each flight day the team convenes a safety briefing and outlines individual assignments for each team member.

Safety while operating the system is also outlined with detailed procedures for setting up the base station, and helicopter startup and shutdown. Kill switch rules were created so that all team members are aware of what circumstances will result in use of the kill switch. The team also started a program of using red tags to mark an item that was either broken or had problems so that defective equipment is not used during a flight.

In order to keep equipment and team members safe, the team created training programs for the areas of helicopter, plane, base station, and battery charging. These programs outline each step necessary to complete the training. A certified team member conducts training. Once the trainee has completed all stages of training they go through a final test and are signed off as a certified member.

## *Modeling and Simulation*

To develop high-level behavior algorithms for the sub-vehicle, an interactive simulation called *SimSERV* was created. SimSERV is a 2D graphical simulation that allows a user to see how the SERV will enter the target building and search the corridors and rooms. The program simulates all of the sensors that will be on-board the actual sub-vehicle such as ultra-sonic sensors, ambient light sensors, and the laser-line sensor.

SimSERV was originally coded in Java, and is currently being ported to C++ to improve the graphics and speed. The C++ version of SimSERV will also include the ability pilot the real SERV via a hardware-in-loop mode. In this mode, SimSERV will receive the actual sensor output from the sensors on board the SERV via wireless serial modem. It will then pass the sensor data to the high-level control algorithm and send control commands back to the SERV.

The same algorithm, without any modification to the code, can be used in software-in-loop mode. In this mode, the sensor output is simulated. The obvious advantage to this system is that we can develop high-level behavior algorithms for the SERV in a software simulated environment to eliminate bugs and fine-tune the SERV's behavior. Once an algorithm appears to be working well in the simulation, it can immediately be tested on the actual vehicle.

### *Testing*

Testing has been a major portion of the UAV team's activities this year. After failing to complete stage 1 during the 2005 IARC competition, the team deemed it necessary to fly the helicopter as many times as possible prior to the 2006 competition. The team has repeatedly flown a 3 km course to demonstrate the ability to reliably fly stage 1. As mentioned previously, the communications system has also been tested to determine reliability at 3 km. Several flight tests have also been done with the SERV to tune the autopilot and move towards more stable flight.

## CONCLUSION

The autonomous vehicles discussed are capable of completing the IARC competition as well as other missions. Each of the five vehicles is designed for multiple uses making the team adaptable to new competitions and research. For stage 1 the helicopter and plane are used to carry the smaller vehicles the three kilometers to the town. Stage 2 starts with the plane, SSV and Helicopter searching for the symbol and openings to the building. The helicopter will launch the SERVs to enter and search the building completing stage 3. When the entire system is in place at the 2007 competition the team will be able to complete all three stages in the time limit set in stage 4. The coordination of all the vehicles is carried out by the IFCS located at the base station. With safety being a high priority for the system, users, spectators, and judges the team has taken many precautions that were outlined in this document. The five vehicle system gives the team that ability to complete the IARC competition as well as be adaptable to other UAV applications in the future.

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