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 initially competed in the International Aerial Robotics Competition (IARC) during the summer of 2004. Although the team was unable to complete any of the stages, the team felt it was a very successful first year. Over the past year, we have continued the development of an unmanned aerial vehicle system to successfully compete in the IARC in July of 2005. The team consists of several undergraduate students, graduate students and advisors from several different majors and experience levels. The goal of the team this year is to complete level three of the IARC competition. This paper describes our approach to the problem, our competitive strategy, as well as our design strategy.

1. Introduction

Figure 1.1: Symbol to be identified in IARC Competition

The SDSM&T UAV team is being sponsored by the Army Research Lab to compete in the International Aerial Robotics Competition (IARC). The competition requires autonomous completion of four specific stages. The first stage is to fly three kilometers through designated waypoints given at the time of the competition. Stage two is to locate a specific building identified by a symbol (Figure 1.1) and locate all the openings to that building. Stage three is to enter the building through a one-meter by one-meter opening and relay specific information about that building back to the judges. Stage four is to complete all three previous stages within a single fifteen-minute time frame.

In order to produce a competitive system, the team has chosen to design two large vehicles, an airplane and a helicopter, each designed to carry smaller sub vehicles. The Structure Entry and Reconnaissance Vehicle (S.E.R.V.) and Scout Sub Vehicle (S.S.V.) are both four rotor designs chosen as the sub-vehicle platforms. Each of the vehicles is modified to complete a specific portion of the competition. The two larger vehicles are designed so that the fixed wing carries one S.S.V. for stage two completion and the helicopter carries two S.E.R.V. for stage three completion. During the completion of stages two and three, the helicopter hovers above the town maintaining good communications with the S.E.R.Vs and plane circles around the town communicating with the base-station and all the vehicles. The larger vehicles are also equipped to help the smaller sub vehicles as necessary. The airplane is considered the main vehicle as it is the vehicle always located near the action. All of the control communications are also routed through the plane. The communications network for the UAV system can be found below in figure 1.2.

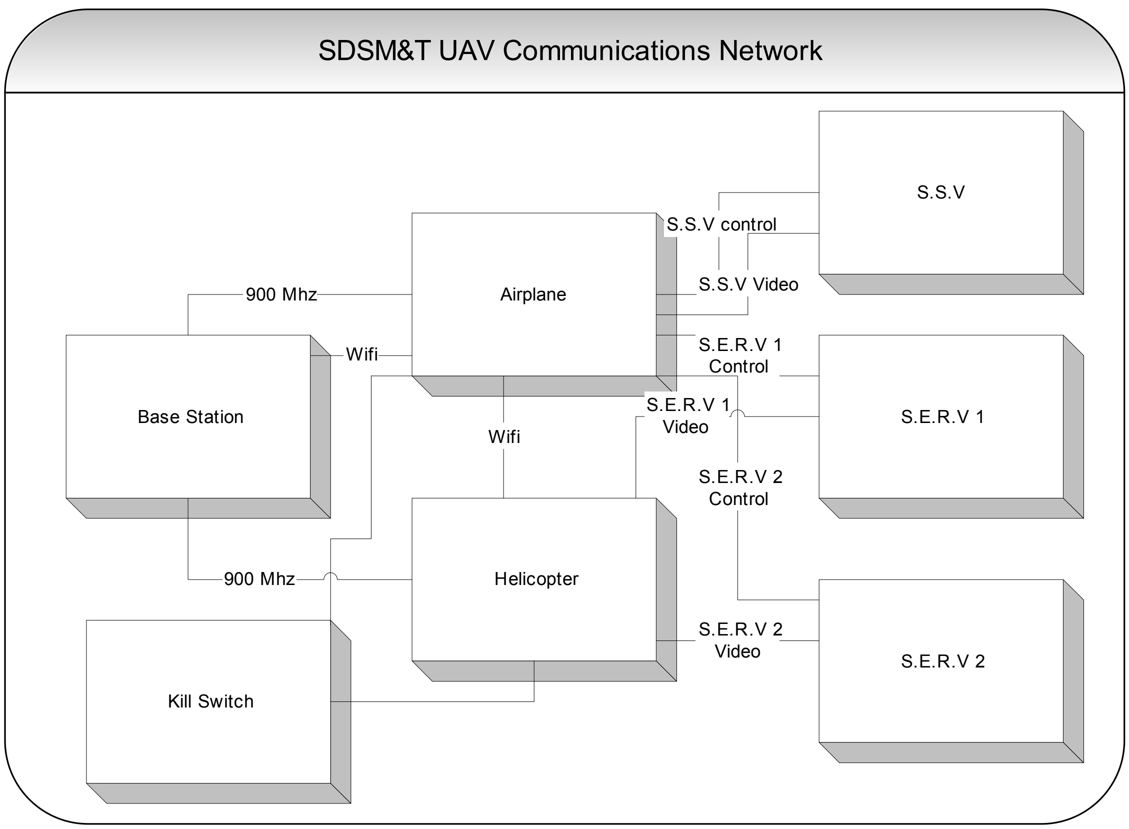

Figure 1.2: UAV communication network

The team is confident in their ability to complete stage 1 during the July 2005 IARC competition. The team also plans on making a valid attempt at stages 2 and 3 after the completion of stage 1. The team will then spend the next year refining stages 2 and 3 algorithms to achieve stage 4 during the 2006 competition assuming nobody completes the competition during the 2005 competition.

2. Air Vehicle

For our final design, two air vehicle systems complete the first stage of the competition in order to better our chances of completing all four stages. These two vehicles are the fixed wing and the helicopter.

2.1 Fixed Wing

The fixed wing being used for the competition is a Sig Rascal 110 (Figure 2.1) that is being modified to carry the necessary equipment. The plane uses a G-26 single cylinder 2-cycle gasoline engine to produce the forward thrust needed for the 12 ft. wingspan to produce up to 30 lbs of lift. The complete airplane system is outlined in figure 2.1.

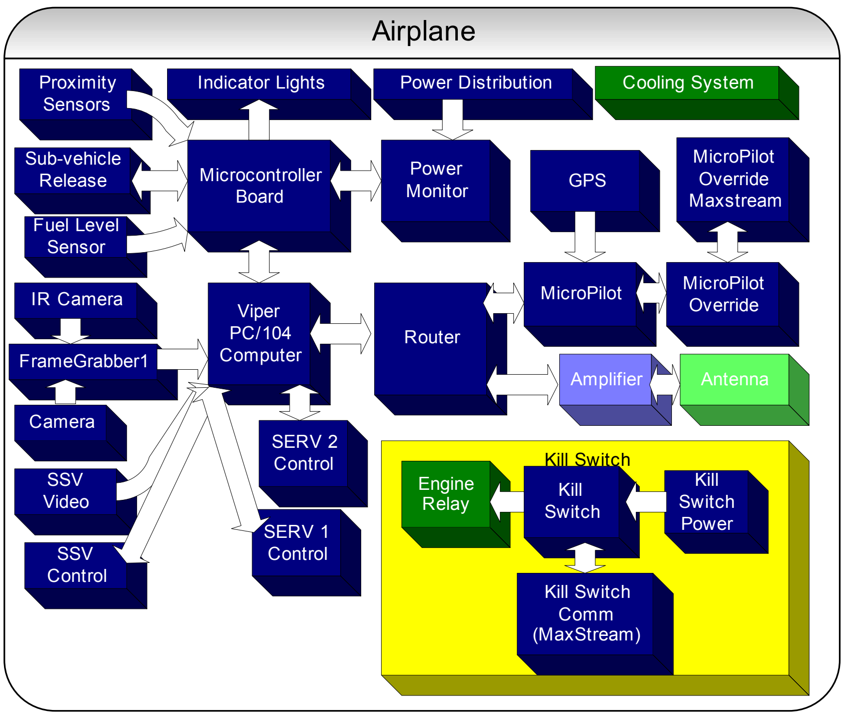

Figure 2.1: Airplane system outline

In order to make the plane autonomous a Micropilot MP2028g (Figure 2.2) autopilot system is being used to control the plane. The waypoints for stage 1 are loaded into the system before the airplane takes off. Once the airplane has completed stage 1, the base-station computer begins the control of the vehicle. It first commands the plane to go to the town. It then commands the plane to make several passes over the town to locate the

Figure 2.1: Sig Rascal 110 fully

buildings. All the processing needed to control the plane is done internally in the MP2028g.

Like all of the team's other large UAVs, the plane uses an active kill switch system. The system consists of a two-way radio in which the vehicle and the kill switch unit continuously send acknowledgements to each other. This allows the operator to verify that the kill switch is working and communicating properly. The airplane can also be setup so that if the kill switch loses communication, the airplane automatically kills itself. The kill switch is also integrated into the plane in such a way that it requires power in order for the engine to run. In addition, it is setup to monitor the power supply for the control surfaces. This way if the plane or kill switch loses power, the plane kills itself to prevent a fly away plane and increase the safety of the system.

2.2 Helicopter

The main frame for the helicopter main vehicle is the SR1-B from Rotomotion (Figure 2.3). The SR1-B is a gasoline powered helicopter based off the Bergen twin R/C helicopter. The 2-cycle engine is based off of two Zenoah G-26's put together to make a two cylinder engine which can produce up to 8 hp. The SR1-B uses a 6 foot rotor span to lift up to 42 lbs. The complete system is outlined in figure 2.4.

Figure 2.3: SR1B from Rotomotion being flown at practice field.

The SR1-B comes from Rotomotion with an autopilot pre-installed. The Rotomotion auto pilot is capable of performing all of the lower level tasks required just to keep the helicopter flying. It is also capable of maintaining a hover as well as directing it to different waypoints. Because the Rotomotion only handles one waypoint at a time, there is an onboard computer which receives waypoints from the base-station and feeds them to the Rotomotion. For the completion of stage 1, the waypoints are all loaded into the onboard computer and the helicopter follows them on its own. Once the helicopter reaches the town, the base station feeds the helicopter new waypoints one at a time or a few at a time based on the feedback from all of the mission sensors. The kill switch used on the helicopter follows the same model as the one used on the fixed wing.

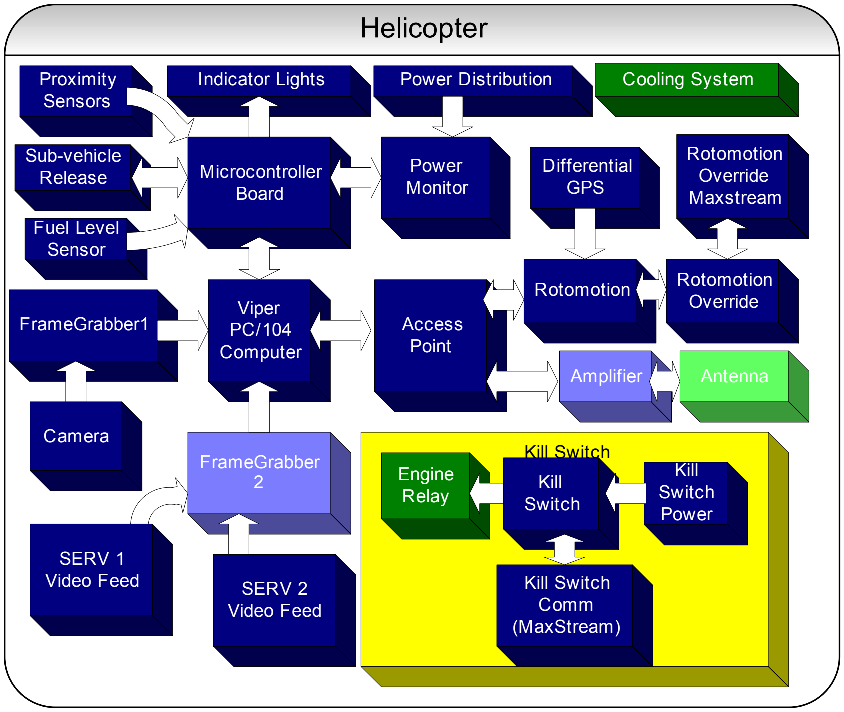

Figure 2.4: Helicopter system outline

The helicopter has multiple purposes in the actual competition. Because the helicopter flies at half the speed of the fixed wing aircraft, it arrives at the competition with the knowledge gained from the airplane. With that knowledge, the helicopter looks at the buildings mapped until it recognizes a symbol. In the case that the airplane fails to complete its mission, the helicopter has the capability to do building mapping at slower speeds. The helicopter carries two S.E.R.Vs that are deployed as soon as the symbol is recognized.

In order to package all the things that need to be put on the SR1-B, our team has decided to add two booms to the airframe. Each boom carries a S.E.R.V and a camera. The booms which protrude about 4 feet from either side of the helicopter allow the helicopter to carry and release the S.E.R.V sub-vehicles outside the rotor wash of the helicopter.

3. Payload

The payload of the plane and helicopter are the heart and soul of the SDSM&T UAV system. The reason for going with two larger vehicles was to enable the team to not only carry more payloads but more specialized payloads as well. The payload of both the airplane and helicopter consist of sensors, communication equipment, power management equipment and sub-vehicles.

3.1 Sensors

One of the primary sensors being carried by all of the aerial vehicles is being called the laser line sensor. This is the primary range finder and proximity sensor for all of the vehicles. The sensor uses a laser diode to generate a line in the surrounding environment. The sensor also contains a small CMOS camera oriented with the scan lines perpendicular to the laser line. In addition, the camera has an optical filter at the same frequency as the laser diode, allowing the camera to filter out most of the light other than the laser light. The laser is also synchronized with the frame rate of the camera so that it is on during one frame and off during the next. This allows the sensor to subtract one frame from another frame in order to further filter out ambient light.

The laser line sensor uses a small angle between the camera and the laser to generate an effect. The laser moves across the field of view of the camera as the distance to a detected object is changed. This allows the sensor to correspond a distance to the position of the laser signal in each scan line. Using this technique the laser line sensor is able to generate 330 distance points 15 times a second. By scanning the sensor up and down once a second, a 3D distance map can be created in front of the vehicle with a resolution of 330 wide by 15 tall. The distance data is used by the vehicles to aid in the image processing as well as object avoidance.

The sub-vehicles also use 6 ultrasonic sensors to aid in navigation and obstacle avoidance. The Devantech SRF10 ultrasonic sensors communicate over I2C to relay the distance the vehicle is from walls and other objects. These are pointed six different positions in order to give the sub vehicle a general image of its surroundings. These sensors weigh 3 grams and can reliably measure distances of 12 feet or more.

All of the vehicles use a camera of some type to send video back to the base-station. The helicopter uses two cameras with good stabilization and zoom capability to help identify the symbol. The two S.E.R.Vs have simple light weight cameras to return images from within the buildings back to the base-station. The airplane has a high quality camera similar to the ones on the helicopter to identify the buildings. The plane also uses a thermal infrared camera to help in the detection of the buildings. In addition, The S.S.V has a high quality camera to detect the symbol and windows.

All of the vehicles also have GPS capability. The S.S.V has a high quality differential GPS to minimize the target location error when determining the position of the openings in the buildings. The helicopter and plane are equipped with GPS systems which are used for primary navigation. The plane also sends its GPS location back to the antenna controller at the base-station to direct the automatic antenna rotator. The S.E.R.Vs both have GPS on board to help them get close to the openings in the buildings. The S.E.R.Vs do not, however, use the GPS location for their primary navigation system as the GPS signal may become unreliable as the vehicles move down into the town and enter the building.

Both the helicopter and plane have several diagnostic sensors to monitor the status of the vehicle. These sensors monitor the safety critical system on the vehicles such as the fuel level, battery level and communication status. The information gathered by these sensors is sent back to the base-station so that the master chief can watch them and choose to terminate the mission based on the data returned.

3.2 Communications

The SDSM&T UAV system relies on three different types of communication protocols. The 72MHz R/C band is used by the safety pilots to control the aircraft when they are in manual mode. This communication is a one way link used to control the aircraft using a standard R/C system during takeoffs and landings and in the event that the mission must be terminated.

The 2.4GHz Wifi band is used for all of the high bandwidth communications. The primary link between the base-station, the airplane, and the helicopter is based on the 802.11g wireless communication protocol. The Wifi network is setup with the plane as the central communications hub. Both the base-station and the helicopter must log into the airplane to communicate with the system. Both the helicopter and airplane use an omni directional antenna with a 1 watt amplifier to achieve the 3 km communications needed. The base-station uses a high gain directional antenna to communicate with the airplane. The antenna is directed towards the airplane using an automated antenna rotator. The rotator uses the GPS location of the base-station and the airplane to create a vector to the airplane. The rotator then rotates to match the azimuth and elevation of the vector to the plane.

The high frequency used by the 802.11g protocol gives us a large bandwidth to send live video along with general status information back from the helicopter and airplane. However, the higher frequency also takes more power to communicate over long distances than lower frequencies. The higher frequencies are also more susceptible to noise and interference caused by buildings and other obstacles. For this reason, the team also uses a 900 MHz Maxstream serial modem. Although the 900 MHz link has a much lower bandwidth, it is more reliable than the primary link. It is capable of sending basic status information to and from the helicopter and airplane. The link is used to send the GPS location of the vehicles as well as other important status information such as the fuel level and the battery status.

The final communication link between the helicopter, airplane and the base-station is the kill switch link. The kill switch is another 900 MHz Maxstream serial modem, creating a reliable connection. The kill switches for the small sub-vehicles are routed through the large aerial vehicles to save weight on the small sub vehicles. So to kill the S.S.V, a signal is sent to the plane over the 900 MHz modem. The signal is then relayed to the S.S.V using a very lightweight FM transmitter.

There is also a 900 MHz serial modem between the helicopter and the sub-vehicle. This link is used to activate the sub-vehicle at the proper time and to send navigation commands to the sub-vehicle to help guide it into the building. Once the sub-vehicle is inside the building, the link is used to relay general status information between the helicopter and the base-station. This link can also be used as a kill switch for the sub-vehicle. The other link to the sub-vehicle is a wireless video link. This link simply relays video from the onboard camera on the sub-vehicle back to the helicopter. The helicopter then digitizes it and sends it back to the base-station over its primary link.

3.3 Power Management

The power system is recognized as one of the most critical areas of the UAV system by the team. The power system must always work properly every time in order for the UAV system to be considered safe. In the event of a power system failure, the aircraft may fly uncontrolled into a hazardous situation. The power system also has the potential to interfere with other areas of the operation such as the radio communications.

The primary source of power for the plane and helicopter is a 16.8 volt lithium ion battery. A switching power supply is then used to efficiently convert the power to the proper voltages needed for the various systems on the UAV. The vehicles also have a battery backup on each of the voltage buses to power the critical systems in the event that the primary battery or switching power supply fails. In the event that any part of the system fails the base-station operator is notified immediately.

The S.S.V and S.E.R.Vs both run off a single 11.1 volt lithium polymer battery. The motors are all run directly off the battery. For all of the other electronics, each vehicle contains a 6 volt switching regulator. The various voltages needed are then generated using simple linear regulators. The power system on the sub-vehicles is not as robust as the ones on the larger vehicles due to the weight restrictions. The team feels that the power system is robust enough to be considered reliable and safe. The team also feels that if one of the smaller sub-vehicles loses power and free falls not much damage would be done.

3.4 Scout Sub-vehicle

The scout sub-vehicle (S.S.V) is a four-rotored craft carried by the airplane. The purpose of the S.S.V is to find and locate the symbol as well as all of the openings in the buildings. The S.S.V rides on the airplane until the plane gets to the building complex, it then flies down into the town to gain a better view of the sides of the building. The S.S.V contains a high quality camera and GPS giving it the ability to identify the symbol and any openings in the building. Once the openings in the building are identified, the S.S.V lands and zooms into the opening. This allows the S.S.V to accurately identify its own position and accurately calculate the position of the opening using its own position, orientation and the distance to the opening. An outline of the S.S.V can be seen in figure 3.1.

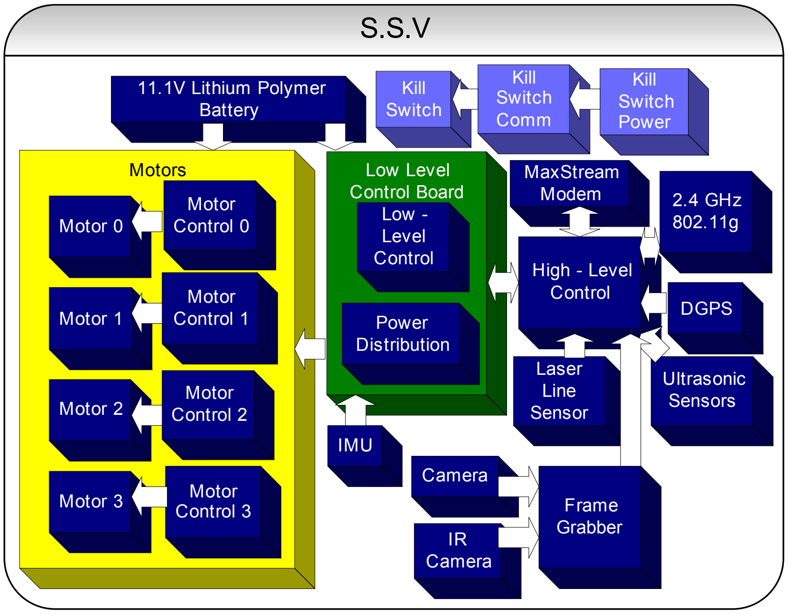

Figure 3.1: S.S.V system outline

Figure 3.2: Final design frame of SERV and SSV.

The S.S.V is based on a very simple and reliable flying design (Figure 3.2). The craft uses four fixed motors to produce lift. Two of the motors turn counter-clockwise and the other two turn clockwise. This allows the vehicle to cancel the torque generated by each of the motors. The vehicle moves by simply varying the speed of each of the motors. For example to move forward the craft decreases the speed of the front two motors and increases the speed of the rearward two motors. This causes the craft to tip forward and therefore move forward. In order to yaw, the craft decreases the speed of the two motors rotating in one direction and increases the speed of the motors rotating the other direction. This does not cause the craft to tip in any direction, but it upset the torque balance causing the craft to rotate.

3.5 Structure Entry and Reconnaissance Vehicle

The Structure Entry and Reconnaissance Vehicle (S.E.R.V) is designed to be carried by the helicopter. The two S.E.R.Vs are carried on the helicopter using a boom system. They are then released from the helicopter when it arrives at the building complex. Each one then flies down to a waypoint just outside one of the openings on the building. If the building is multiple stories, then one goes to an opening on the first story and the other one goes to an opening on another story. Once outside the building, the S.E.R.Vs enter the building through the opening using their onboard laser sensor to keep them centered in the opening. Once the S.E.R.Vs are in the building they begin a search algorithm using a fuzzy logic controller. The S.E.R.V is outlined in figure 3.3.

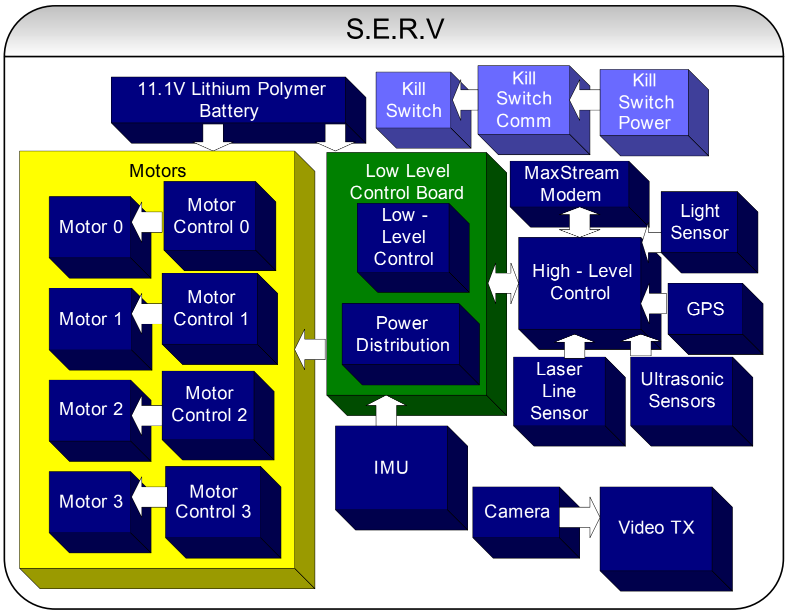

Figure 3.3: S.E.R.V system outline

As a result of the S.E.R.V being so small, it is a very high performance aircraft and requires a high performing control system. Therefore a lot of work has gone into developing a proper control system for the craft. The team has decided to use a layered approach to the control system for the S.E.R.V and S.S.V. The lowest level of the control system controls the actual angle of the craft. It uses a series of PI controllers to control the angle on each axis. The low level control system design requires several stages of design and analysis. The first stage is to determine the sensor needed to generate the proper feedback. The low level control system uses 3 gyroscopes and accelerometers to determine the orientation of the craft. The S.E.R.Vs and S.S.V also use a magnetometer to determine its heading. The gyroscopes are used to detect the rotational rate of the craft about the X, Y, and Z axes. The accelerometers are capable of detecting any acceleration static or dynamic. The current control system uses a low pass filter to separate the static acceleration of gravity from the short dynamic accelerations of the craft moving. By detecting the gravity vector, the craft is capable of determining it angle about the X and Y axes.

The next part of the control system development is to develop a model for the S.E.R.V and S.S.V. The first step to creating the model is to determine a transfer function for the sub vehicles. Along the linear axis the mass is needed to determine the transfer function and the rotational inertias, Ix, Iy, and Iz, are needed to determine the transfer functions for roll, pitch and yaw. The rotational inertias for the S.E.R.V are around $3\text{x}10^{-3}$ Kg m^2. Due to the fact that the rotational inertias are all very small the craft is capable of rotating very quickly with very little input force. This is the reason that the control system must be well designed and robust.

Once the dynamics of the craft are determined, the 3D equations of motion are used to determine the transfer functions of the craft. The 3D equations of linear motion are the same as the 2D equations of linear motion, except there is an additional term for the Z-axis. The rotational equations on the other hand are very different due to the gyroscopic effects of 3D motion. The gyroscopic effect implies that if you have rotations about 2 axes, then a moment about the 3rd axis is induced. The gyroscopic effect is shown in the second term of the following equations.

The gyroscopic effect depends on the rotational velocity about two axes. Because the craft is never expected to rotate at a very high rate, the gyroscopic effects are being neglected for now. The team is prepared to add the full 3D equations into the control

$$\sum M_X = I_X \dot{w}_X - (I_Y - I_Z) w_Y w_Z$$
$$\sum M_Y = I_Y \dot{w}_Y - (I_Z - I_X) w_Z w_X$$
$$\sum M_Z = I_Z \dot{w}_Z - (I_X - I_Y) w_X w_Y$$

system if they are necessary to build a truly robust control system. The sub vehicles also have a tendency to remain level due to the fact that the rotor are angle toward the center at 3 degrees and the center of lift is above the center of gravity. Excel is used to model this tendency as a spring force on the craft. Once all of the equations of motion are determined they are put in to a transfer function. The transfer function for the motors and speed controllers are also determined experimentally to be used in the control system loop. Once all of the independent transfer functions are determined, they are used to generate the control loops for each of the axis. The team has found that a PI controller works best for each of the axis.

The next level in the control system is an interface layer between the high level control and the low level control. The control system takes the desired translational inputs from the high level control system and converts them to the angles needed to achieve the translations. The mid level control system also corrects for any drift that the vehicle may experience to imperfections in the control system or air currents.

The final level in the control system is the high level control system. The high level control system directs the craft to the waypoint outside of the opening in the building. It then directs the craft through the opening in the building. Finally it applies the search algorithm to direct the craft through the building.

4. Operations

After crashing two helicopters, the SDSM&T UAV team has recognized that the flight operation procedures are just as important or more important than the actual vehicle design. For this reason the team as taken care to develop an elaborate system of operational procedures.

4.1 Checklists

The team uses a series of checklists to ensure the safety and functionality of the UAV system. Each of the individual vehicles in the system has its own preflight checklist to verify the functionality of the mechanical systems, the electrical systems and the computer control systems. The team also uses an equipment checklist to verify that all of the equipment needed to operate the system is present and operational before the mission is begun. During the setup and operation of the flights, the team also uses a detailed mission plan so that everything is set up correctly and everybody knows exactly what is going on. Finally the team uses a post-flight checklist to check the results of the mission and to verify that everything gets shutdown and stowed correctly

4.2 Team Organization

In order to ensure the efficiency of the team during any mission operation, everybody on the team has a specific and well defined task during the mission. Some of the positions include the kill switch operator, the base-station monitor, the safety pilots, camera man, and the mission coordinator. All of these people must be present in order to attempt any mission. Any additional people are assigned to other positions such as additional camera men, pilot wing men, tool coordinator, and runner. All of the people on the team are in constant communication using business class radios.

4.3 Man/Machine Interface

The two interactions between the vehicles and the team are the base-station and the safety pilots. The safety pilots are in control of the aircraft while they are in manual mode. They are also ready to take control of the craft at any time while the craft is in autonomous mode. The base-station control interface is used to control the aircraft while they are in autonomous mode. The base-station operator can either control the vehicles using fly to command to direct the vehicles to fly to specific waypoints, or let the base-station software direct the actions of all the vehicles while he just monitors the status of all the vehicles.

5. Risk Reduction

The team has considered safety and risk reduction to be a very important issue throughout the entire design of the system. Safety is always a factor when making any decision. The team has also taken several steps to improve the safety of the system such as extensive check lists and redundant systems.

5.1 Vehicle Status

Each of the vehicles uses several sensors to measure the status of critical systems on the vehicles such as battery and fuel levels. The status of the critical systems is then relayed back to the base-station operator allowing him or the mission coordinator to determine whether it is safe to continue the mission or not. The status of each vehicle and the environment is also checked before takeoff. The autopilot also indicates whether is it safe to engage the autopilot. While the autopilot is engaged, the autopilot indicates that all of the sensors are with in range and working correctly.

5.2 Shock/Vibration Isolation

High frequency vibrations can lead to fatigue in the electronic components. It can also lead to errors in the outputs from the orientation sensors. For this reason, the autopilot on each of the vehicles is isolated from sources of vibration such as the engine using rubber isolators. The landing gear on each of the vehicles is also designed to minimize the shock during landings. The sensors also have low pass filters to prevent aliasing due to vibration.

5.3 EMI/RFI Solutions

The team has taken several considerations 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. The team also found that the power supply can decrease the range of the R/C radio system, so filters are used to minimize the noise from the power supply.

5.4 Safety

The team has addressed the issues of safety by creating a reliable and robust system. The team also takes several precautions to ensure the system is in proper operating condition before flying. The smaller sub-vehicles are also designed to be as safe as possible as they are designed to fly in the most hazardous environments. They have ducts to prevent the rotors from colliding with anything. The also use their sensor to create a virtual area around the craft in which nothing can enter without the craft moving in the opposite direction.

5.5 Modeling and Simulation

Modeling and simulation are both very useful for the development of new systems. Therefore the team tries to model and or simulate as many portions of the system as possible. One application of simulation is the sub-vehicle control system. The team starts by creating a Matlab model for the low level control to determine the type of controller and the gains needed to make it fly. The team also created a model of the high level control system to figure out how to search the building effectively.

5.6 Testing

In order to ensure the reliability of the various systems being incorporated into the UAV design, the team has adopted the NASA Technology Readiness Levels (TRLs) as a guide line for the stages of development and testing needed for each component. The NASA TRLs illustrate 9 steps of the design process which should be met to accomplish a successful design. The team used the 9 steps outlined below to verify the progress of the entire project as well as the sub-projects.

TRL 1 Basic principles observed and reported
TRL 2 Technology concept and/or application formulated
TRL 3 Analytical and experimental critical function and/or characteristic proof of concept
TRL 4 Component and/or breadboard validation in laboratory environment
TRL 5 Component and/or breadboard validation in relevant environment
TRL 6 System/subsystem model or prototype demonstration in a relevant environment
TRL 7 System prototype demonstration in a flight environment
TRL 8 Actual system completed and "flight qualified" through test and demonstration
TRL 9 Actual system "flight proven" through successful mission operations

Following the TRL outline the team is able to verify that each system is developed and tested fully before it is implemented on the final system. The team also used several prototype systems to verify the functionality of each of the systems. For example, the booms are tested on a small electric helicopter before the are used on the UAV to ensure they do not interfere with the flight dynamics of the helicopter. The booms on the electric helicopter are also used to measure the effects of the rotor wash under the helicopter. The testing setup can be seen in figure 5.1.

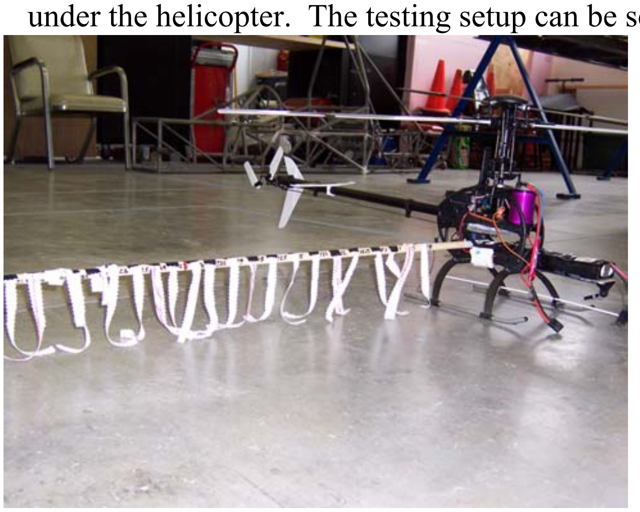

Figure 5.1: Logo electric helicopter equipped with rotor wash analysis boom.

The team also determined that several test are needed to develop the control system for the smaller sub-vehicles. It is very difficult to determine how effective the control system is while the vehicle is fluttering around in the air. For this reason, the team developed several tests which restrict one or more axis of freedom of the craft. This setup allows the team to test various portions of the control system in an isolated environment without repeated crashes.

6. Conclusion

In conclusion, this paper described the SDSM&T UAV Team’s approach to the problem, our competitive strategy, and our design strategy. Although not all of the teams design concepts are currently implemented, the team is still planning to implement all of them by competition time. However, the items needed to successfully complete stage 1 repetitively and reliably are currently being focused on more than the aspects needed for stages 2 and 3. The team has designed a complete five-vehicle reconnaissance system which will compete in the 2005 International Aerial Robotics Competition. The team then plans on spending the next year refining the system to be able to complete level 4 of the competition.

7. Sponsors

The team would like to give a special thanks to the following groups for making our efforts to complete the IARC UAV competition possible

8. References

Kannan Suresh. Georgia Tech UAV site. 8 April 2003. 20 October 2003. http://controls.ae.gatech.edu/gtar/2001review/target1.jpg

Mankins, John C., Technology Readiness Levels, http://64.233.167.104/search?q=cache:1k-qmIwQQtoJ:www.hq.nasa.gov/office/codeq/trl/trl.pdf+nasa+technology+readiness+levels&hl=en, 6 April1995. 1 June 2005

Michelson Robert. International Aerial Robotics Competition. 18 September 2003. http://avdil.gtri.gatech.edu/AUVS/CurrentIARC/200xCollegiateRules.html#Mission