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 was formed just over a year ago. Over the past year, we have developed an unmanned aerial robotic reconnaissance system to compete in the International Aerial Robotics Competition in July of 2004. The team consists of several undergraduate students and advisors from several different majors and grade levels. The goal of the team this year is to complete level three of the competition. This paper describes our approach to the problem, our competitive strategy, and our design strategy.

1. Introduction

The South Dakota School of Mines and Technology Aerial Robotics Team was formed in the spring of 2003 with the specific purpose of competing in the International Aerial Robotics Competition. The purpose of the competition is to design and build an aerial vehicle or pair of aerial vehicles that can travel 3 km, locate a specified building, and provide indoor reconnaissance from inside the specified building. More information about the competition can be found at http://avdil.gtri.gatech.edu/AUVS/IARCLaunchPoint.html. The team started with a generous donation from the Army Research Center. The competition teams at the South Dakota School of Mines and Technology have a history of doing very well at competitions. In addition, the team is supported by a unique South Dakota School of Mines and Technology organization known as the Center for Advanced Manufacturing and Production (C.A.M.P.). C.A.M.P. is a general organization that provides funding and manufacturing resources as well as training in teaming skills for various teams on campus. Considering the resources available to the team, a goal was set to complete level three at the first year of competition. With this in mind, the team decided to work on all aspects of the system concurrently. The team chose to employ the COTS (Commercial Off the Shelf Technology) strategy as used by the Army Research Center. This strategy involves the purchase of as much off the shelf equipment as possible to reduce maintenance costs as well as development time. Utilizing the COTS strategy, the team chose to use an off-the-shelf radio controlled helicopter and flight controller as the main flight platform. Furthermore, the helicopter is capable of both the speed required to ingress 3 km and the maneuverability required to identify the symbol and release the sub-vehicle. Without the burden of designing a helicopter or a control system for the helicopter, the team was able to concentrate on other tasks such as designing an image recognition system, implementing sensors, and producing a communication system. Despite the fact that many of the other teams appear to be using ground vehicles for the sub-vehicle, the team decided to use an aerial vehicle for the sub-vehicle. The group decided that the extra complexity of controlling an aerial vehicle would be worth the added maneuverability. The team chose to use a small, four rotor craft which is capable of both outdoor flight and safe indoor flight.

2. System Overview

The overall system designed by the South Dakota School of Mines and Technology Unmanned Aerial Vehicle Team consists of three major parts; the base-station, the main vehicle, and the sub-vehicle. The base-station is the control center for the mission. The base-station consists of a computer used to display the status of the helicopter, relay video from the helicopter, and allow the operator to control the helicopter. The base-station also has all of the power-distribution to power all of the equipment from one outlet. In addition the base-station has several high power transceivers for communicating with the helicopter.

The main vehicle is a helicopter capable of completing the 3 km ingress required for the competition. It also has the ability to recognize the symbol identifying the correct building. Finally the main vehicle is capable of dropping the sub-vehicle from the air and guiding it into the building.

The sub-vehicle is capable of being dropped from the air under a helicopter. It also has the ability to find its way into a building through a 1m x 1m opening. Finally the vehicle can navigate the interior of the building while relaying video back to the helicopter. The overall system can be seen in figure 1.

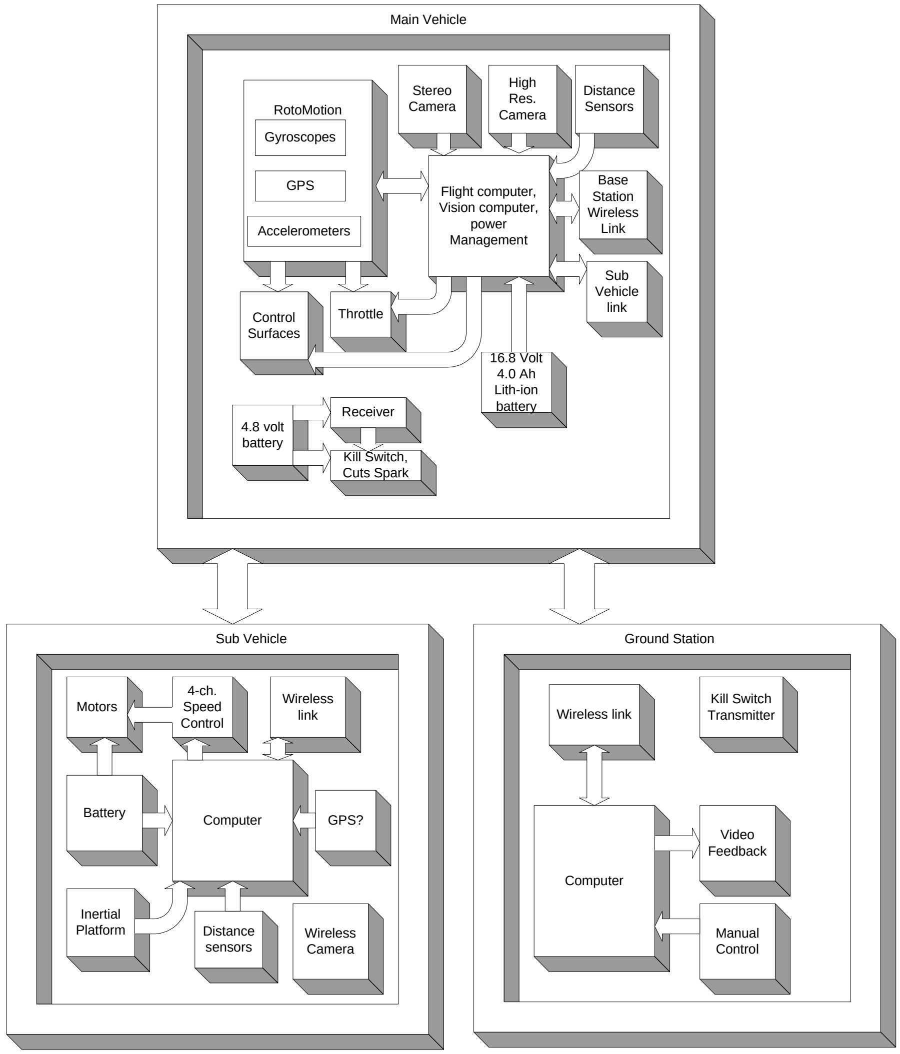

Figure 1: diagram of the overall system

2.1 Base-station

The base-station is the user interface for the entire reconnaissance system. Its primary function is to relay flight information back from the main vehicle and the sub-vehicle and present it to the user. The heart of the base-station is a laptop computer. The computer runs several different programs. One program is the flight status program which relays the current orientation of the helicopter back to the base-station. The program also displays the status of all the control surfaces on the helicopter along with their desired positions if the helicopter is in autonomous mode. This program also records the flight data from the mission into a log that can be viewed along with the video from the mission at a later time. Another program running on the computer is the flight interface program. This program allows the user to enter the waypoints for GPS flight into the computer. It also has several warning indicators such as low battery, which can be used to determine if it is safe to continue flying the mission. The base-station also has several links to the helicopter. One link is the high-speed primary link based on a

802.11g Ethernet connection. This link employs a 500-milliwatt amplifier as well as a high gain antenna to increase the signal strength. The team has decided it is best to use as much power as possible in this link to increase the reliability of the link. Unfortunately the high gain antenna is fairly directional so the antenna is designed to be movable, so it can be pointed directly at the helicopter at all times. The antenna is also mounted up in the air to minimize the effects of the ground and any obstacles that may get in the way. The second is a general link with a lower bandwidth, but the antenna is omni-directional so there is no need to move the antenna. The final component of the base-station is the kill switch mechanism. The kill switch consists of a small processor at the base station that continuously emits a signal to the helicopter over a high power, ultra reliable link. The processor also monitors a switch that is used to shut down the helicopter. In the event the button is pushed, the transmitter emits a different signal to the helicopter indicating the kill switch has been activated.

2.2 Main Vehicle

The main vehicle airframe is a Bergen Industrial Twin radio controlled helicopter. The helicopter has a 63-inch rotor diameter and a 4.5 horsepower twin cylinder engine. A larger fuel tank has been implemented to produce an operation time of approximately 40 minutes. The majority of the helicopter remains stock with the exception of the landing frame as seen in Figure 2.

Figure 2: Bergen helicopter complete with frame modifications

The landing frame is designed to accommodate the avionics box and the sub-vehicle while withstanding a 3-foot drop height. The landing frame materials and geometry are optimized through the use of finite element analysis to ensure an ultra lightweight design. One advantage of the landing frame is its ability to dampen vibrations from the helicopter through its unique mounting system. In addition, vibration isolators between the frame and the electronics box create a vibration-free environment for the electronics and cameras.

The sub-vehicle launcher is attached below the avionics box to provide reliable transportation of the sub-vehicle as well as simple deployment. The launcher consists of 4 forks and a servo-activated dome. While the servo is locked, the dome forces the sub-vehicle arms into the forks. When released, the dome rotates to free the arms from the forks which allows the sub-vehicle to drop.

The main vehicle is controlled by an off-the-shelf Rotomotion helicopter flight control system. The Rotomotion is a purchased control system for the helicopter. The onboard navigation computer simply tells the Rotomotion where to go and the Rotomotion takes care of flying the helicopter. Considering our limited time frame, the Rotomotion seemed like the best solution to complete level one of the competition. The Rotomotion is mounted directly to the body near the front of the helicopter. The Rotomotion controller cannot be mounted in the aviation box with the rest of the electronics because the isolators used to dampen the vibrations in the landing frame and electronics box create a delay and thus a higher order system that would be very difficult to control. With the Rotomotion mounted directly to the body of the helicopter, the system is much simpler and the rotomotion is able to control the movements of the helicopter using simple PID controllers for each axis.

Despite the fact that the Rotomotion cannot be mounted in the avionics box there are still several other electronic components to the system. There are two other computers in the electronics box. One is a Viper made by Arcom. It is a pc/104 computer with a 400 MHz Xscale processor. This is a very reliable and efficient computer which is used for over-all flight management. The Viper receives commands from the base-station and relays them to the Rotomotion to move the helicopter along the best path as determined by the base-station and the image processing computer. In the event of a primary communication loss the Viper will continue to direct the helicopter until communication is regained or the helicopter reaches the end of its defined path where it will enter a hover. The other computer is a Pentium M 1.1 GHz computer which is used for the image processing.

There are several sensors onboard the helicopter. The IMU integrated into the Rotomotion controller allows the rotomotion to sense the helicopters movements on all three axis of rotation as well as all three axis of linear acceleration. This is accomplished with three gyroscopes and accelerometers. The sub-vehicle also uses an IMU to sense its own orientation. It is possible to use the sub-vehicles IMU in the event that the rotomotion IMU fails. There are also several sonar ranging modules on the helicopter to determine altitude and to avoid obstacles. The primary sensor on the helicopter is the video camera. This camera is used to relay video back to the base-station station for the user to view. It is also used for the image recognition onboard the helicopter. The team chose to use a high-resolution camera to make the identification of the symbol easier. The team has also decided to use a thermal infrared camera to make the image recognition more reliable. The infrared camera is very useful in finding openings in the buildings. The infrared camera may also be used to keep track of the horizon and to identify the buildings.

2.3 Sub-vehicle

Despite the increased complexity of an aerial sub-vehicle, the team chose to pursue the design of an autonomous aerial vehicle because of the increased mobility. The sub-vehicle is based on the Draganflyer (www.rctoys.com) as seen in Figure 3.

Figure 3. Draganflyer Sub-vehicle

The Draganflyer is a small lightweight four rotor craft designed for indoor and outdoor flight. The four rotor design is much simpler than a helicopter making it more reliable and easier to control.

The only moving parts on the Draganflyer are the motors. Because two of the motors rotate clockwise while the other two motors spin counter-clockwise, all of the rotational torque is cancelled out as long as all of the rotors are spinning at the same speed. Adjusting the speed of different motors controls the movement of the Draganflyer. Adjusting the speed of all four motors simultaneously controls the elevation. Simultaneously increasing one motor while decreasing its opposite allows the Draganflyer to slightly pitch or roll in a given direction, which results in movement in that direction. Because the speed one motor is decreased the same amount as the other motor is increased the torque balance is still maintained. In order to allow for yaw rotation, the two motors rotating in the same direction are either increased or decreased together while the other two motors perform the opposite. Then because the motors on opposite sides of the Draganflyer are changed the same magnitude, the Draganflyer maintains its pitch and roll. The Draganflyer also uses foam blades which simply bend or break if they hit something, making the Draganflyer safe to fly indoors.

The Draganflyer uses many of the same sensors as the main helicopter. However, due to the smaller size and the weight requirements on the Draganflyer, the sensors could not be purchased and had to be custom built. The primary sensor system on the Draganflyer is the inertial platform. This platform uses accelerometers and gyroscopes to detect the acceleration of the Draganflyer in all 6 degrees of freedom. The accelerations can then be integrated to determine the velocity and angular rotation of the Draganflyer in any direction. Unfortunately there is always error or drift associated with the integration process. For this reason, the Draganflyer also has an onboard GPS to determine the velocity of the Draganflyer in any direction. The GPS has a lower refresh rate, so it can only be used to check the output of the inertial platform. The Draganflyer also has several ultrasonic distance sensors to determine the distance from any obstacles. The Draganflyer also has some Infrared sensor to more accurately determine the distance to different objects at closer distances. The sensors are used to avoid obstacles and navigate through the building. The distance sensors are also used to determine the velocity of the Draganflyer similar to the GPS in the event that a GPS signal is not available.

The Draganflyer is programmed to use a simple wall following program to navigate though the building. It always stays a specified distance from the right wall unless it reaches a dead end. In the event of a dead end the Draganflyer turns around and continues following the right wall, which used to be the left wall. Using this algorithm, the Draganflyer can navigate the entire building unless there is an island or another opening in the building.

3. Communications

Due to the inherent problems with wireless communication, the team has decided to have three links helicopter and base-station. There are also two links between the helicopter and the base-station. The primary link is based on the 802.11g wireless communication protocol. 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. However, the higher frequency also takes more power to communicate over large 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 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. The final communication link between the helicopter and the base-station is the kill switch link. The kill switch is another low frequency, low data rate connection, but it is very reliable.

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.

4. Safety

Due to the inherent danger of autonomous flying vehicles, the SDSM&T UAV team has implemented several levels of safety on our vehicle. One of the largest problems with UAVs over ground-based vehicles is that the vehicle cannot always just be stopped in the event things go wrong. A UAV just falling out of the sky has the potential to cause a significant amount of damage. For this reason, the team has implemented several levels of fail-safes on our UAV. The fail-safes include the following:

1. Render helicopter ballistic- kill the engine, all electronics dead
2. Kill switch- kill the engine, attempt to auto-rotate.
3. Autonomous landing
4. Human take over
5. Warning lights

The helicopter is rendered ballistic as a very last resort. This fail-safe automatically kills the engine in the event that power is lost to the servos controlling the helicopter. This prevents the helicopter from flying away out of control. During the kill switch fail-safe, the engine is shut-down, but all of the electronics are active. The helicopter controller decreases the rotor pitch until the helicopter nears the ground. When the helicopter is a specified distance from the ground the controller flairs the rotors decreasing the energy in the rotors as well as the downward velocity of the helicopter minimizing the damage from the crash. Because the kill switch is ineffective if the signal is not being received from the base-station, the team has decided to go with an active kill switch. The kill mechanism is constantly looking for an OK signal from the base-station. As long as this signal is present the helicopter will continue to fly normally. If the signal is lost the helicopter flashes an on board strobe as well as a strobe on the base-station, indicating a problem. If the human pilot does not respond in a specified amount of time, the helicopter shuts down the engine. The kill mechanism is also looking for a KILL signal. In the event this signal is received, the engine is immediately shut down.

The autonomous landing attempts to land the helicopter autonomously. The controller slowly decreases the altitude until the helicopter is on the ground. The autonomous landing occurs if all communication is lost with the base-station except the kill switch and there is a warning condition such as low fuel or battery. The human take over fail-safe is a mechanism, which allows a pilot to take control of the aircraft at any time he feels the mission is not going properly. Warning-lights are not a mission terminating fail-safe. They simply provide the pilot with more information about the mission allowing him to make a more informed decision about terminating the mission. The warning lights on the base-station indicate potential problems such as low battery, low fuel, loss of primary communication, ect.

5. Conclusions

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 level 1 and 2 of the competition are currently being focused on more than the aspects needed for level 3. The team has designed a complete two-vehicle reconnaissance system which will be compete in the 2004 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.

6. References

Michelson, R., *Rules for the Current International Aerial Robotics Competition Mission* http://avdil.gtri.gatech.edu/AUVS/CurrentIARC/200xCollegiateRules.html