Rose-Hulman Institute of Technology's Autonomous Helicopter for the 2000 International Aerial Robotics Competition

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1.0 Introduction

The Rose-Hulman Aerial Robotics Vehicle has undergone considerable redesign and improvement since the 1999 AUVS International Aerial Robotics Competition (IARC). The fuzzy logic controllers have been expanded to react to various hardware failures and to include more flight modes, such as takeoff and landing. A new telemetry system allows the user to select the operating parameters to log without recompiling. Several sensors have been upgraded to save weight and provide better data. The new sensors operate at a higher rate, allowing filters to be designed for the frequencies of noise occurring. Custom-made circuit boards have been redesigned to take advantage of the upgraded sensors. A new scheme for mounting the hardware to the helicopter has been implemented that reduced the weight of the vehicle by upwards of 4 pounds. Barrel, label, and fire imaging algorithms have been designed and proven to work with an incoming video stream. This combination of hardware, software, and imaging allows the 2000 Rose-Hulman Aerial Robotics Vehicle to complete its mission.

1.1 Competitive Strategy

The IARC Millennial Event requires an autonomous air vehicle to interact with its environment by surveying a disaster area and providing useful information to aid a rescue mission. The Rose-Hulman Aerial Robotics Team has two primary goals for the millennium competition. The first goal is to demonstrate fully autonomous flight, while second goal is to exhibit label and fire recognition. These goals should give the team enough points to place ahead of the competition.

The flight control system consists of 9 fuzzy logic control loops, each of which operates in one of two modes, depending on the vehicle's height above the ground. In addition, the software can switch between one of 6 flight modes in response to hardware failures and commands from the ground. The imaging system assigns ground targets a priority ranking following identification. Based upon priority assignments, the air vehicle's mission is updated to reflect the most prudent course of action. All of these modes keep the helicopter stable and above the desired points of interest.

Special emphasis has been placed on system reliability. History has shown that system malfunctions and equipment breakdowns are common causes for poor performances in the IARC competition. In addition, the failure of any individual system on an aerial vehicle can lead to disastrous consequences. From past experiences, maximizing the gross vehicle weight has proven to give more mechanical problems. The new platform has drastically decreased the total amount of weight on the vehicle, thus providing the team with more flight time and better reliability.

The telemetry program provides real time data to the ground station computer, allowing abnormal operating conditions to be diagnosed in flight. The telemetry system can be reconfigured on-the-fly, allowing up to 80 of the approximately 300 operating parameters to be viewed at once. This system saves valuable time by allowing on-the-fly debugging.

2.0 Elegance of Design and Craftsmanship

The Rose-Hulman Aerial Robotics Team learned a lot from its 1999 year. After extensive testing the team came to the conclusion that it would be impossible to run the position controllers with the information provided by the sensors. Noise in the GPS velocity forced the team to implement an accelerometer board, and the advantages of higher sampling rates became apparent. All the changes in the past year have improved the sensor readings by decreasing noise and increasing precision, thus making the sensor data better represent the actual state of the helicopter.

The 2000 Rose-Hulman Aerial Robotics vehicle is the first to incorporate a rigid hardware mounting system. All the designs in the past placed the hardware on a single dampened mount. This dampened mount design amplified the low-frequency vibration felt by the sensors. Low-frequency noise is very hard to take out of the sensor data without introducing an unacceptably long latency. The new design rigidly attaches the hardware mount to the helicopter. This eliminates nearly all the low-frequency vibration from passing into the sensors. Dampeners are then added to the individual sensors as to reduce the magnitude of high-frequency noise that might affect the readings from the sensor. Every sensor except the GPS is sampled at 500 Hz and then filtered down to 50 Hz for the controllers. This fast sampling rate will improve the precision of the value given to the controllers by reducing the noise due to reading the sensor. Filters are also designed for each individual sensor to reduce the amplitude of the frequency of the vibration that’s affecting it. The most common frequencies are derived from the speed of the main rotor and the speed of the engine. The benefits of running a higher sampling rate can be seen in Figure 1. The frequency of the noise picked up by the x-axis magnetometer shown is about 150 Hz, which was the engine speed during this test. The filter for the magnetometer can have a high attenuation at 150 Hz because the dynamics of a helicopter under normal conditions are not likely to react at this high rate.

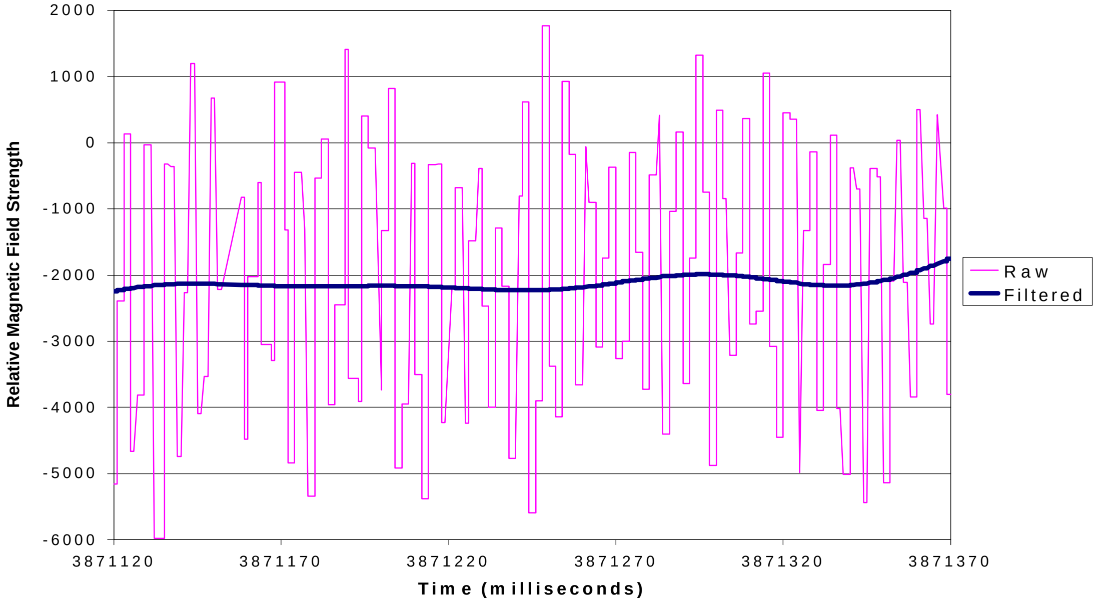

Figure 1. Raw and Filtered Data from the X-Axis Magnetometer

The new hardware mounting board is a kevlar reinforced foam board that allows the hardware to be mounted more compactly around the helicopter. This board weighs in under half the weight of past designs, thus serving its purpose more efficiently. The board is also more functional because it has more overall area to mount the electronics, and the team was able to shape it to match the dimensions of the electronics.

Aside from the addition of the accelerometer, the sensor system has the same functionality as last year's entry. A 3-axis accelerometer constructed on a custom printed circuit board (PCB) uses two dual-axis digital accelerometers. These accelerometers allow the vehicle to integrate the acceleration to find its velocity and position. The velocity and position data from the accelerometer are then weighted with the GPS velocity and position data to provide a more accurate representation of the helicopter's motion. The Watson Industries AHRS of last year's design was replaced with new sensors that provide the same information when combined. These new sensors consist of a Honeywell 3-axis magnetometer, a 2-axis vertical reference, and a yaw rate sensor from Watson Industries.

Other areas of the electrical system have been redesigned as well. The main battery, a 14.4V Nickel-Metal Hydride (NiMH) professional camcorder battery, has been replaced with a custom 16.8V NiMH battery pack. This new battery pack is 40% lighter while providing an equal flight time of 50 minutes. An intelligent battery charger has been designed to fast-charge up to four battery packs simultaneously. This charging system has been designed to maintain a fully charged battery when testing so that there is never down time due to charging restrictions. All the custom PCBs in the PC/104 stack have been integrated into two PCBs. This has reduced the height of the PC/104 stack and the number of board-to-board cable connections. This year's design retains the servo wiring from the 1999 vehicle, as described in [3].

3.0 Innovation in Air Vehicle Design

The Rose-Hulman Aerial Robotics vehicle is designed to meet the criteria laid out in the IARC Millennial Event rules. The vehicle is based on a highly modified Bergen Industrial Twin helicopter. Figure 1 is a simplified block diagram showing the connections between devices necessary for fully autonomous flight. An array of sensors and components mounted on the helicopter provide data to the onboard flight control computer, which interprets the data using fuzzy logic. The computer then generates flight commands that are sent to the helicopter's servomechanisms at a rate of 50 Hz.

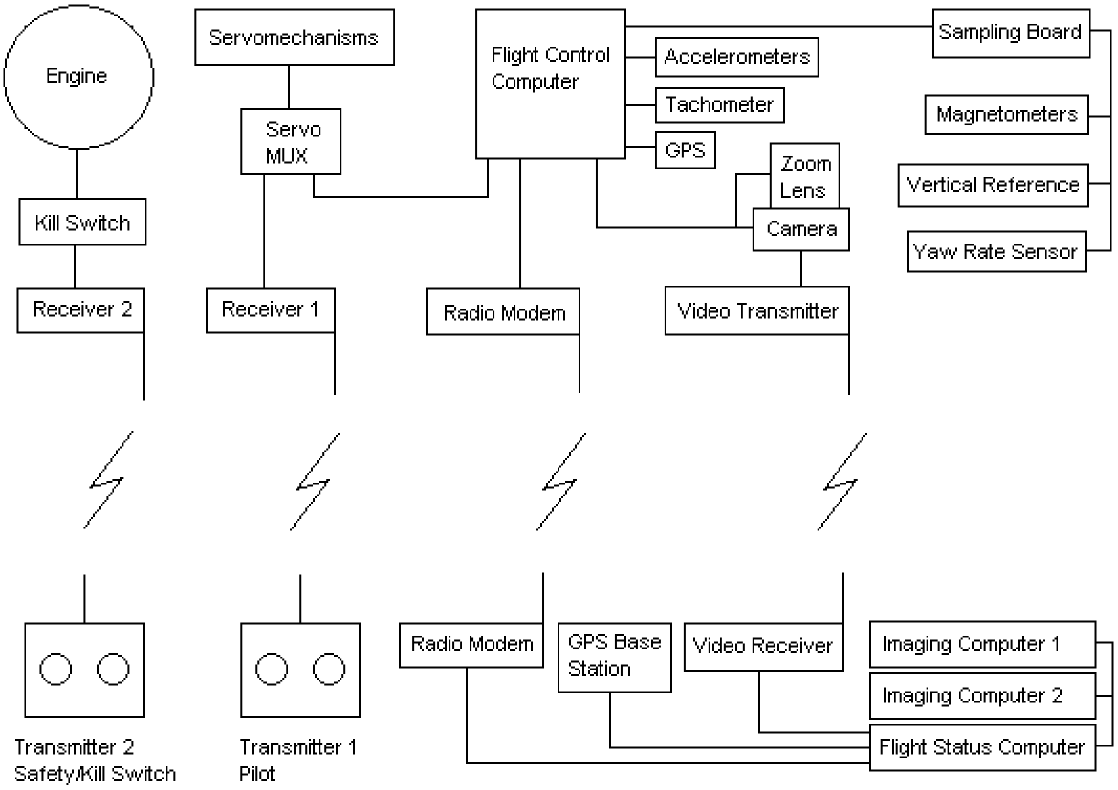

Figure 2 – System Architecture

3.0.1 Sensors

The aerial vehicle is made aware of its state through the use of inertial and navigational sensors. This year's design utilizes a 2-axis vertical reference and yaw rate sensor supplied by Watson Industries and a Honeywell 3-axis magnetometer. These sensors provide information on roll, pitch, yaw, and their respective rates. A differential global positioning system (GPS), provided by Novatel, Inc. runs in RT-2 mode to generate information concerning the aerial vehicle's position and velocity. Data from a custom-made 3-axis accelerometer supplements the velocity and position data from the GPS. Main rotor speed must be constant to ensure a consistent model of the helicopter's dynamics. A Hall effect sensor is mounted just behind the main rotor to detect the magnetic field produced by two magnets mounted inside the helicopter's main gear. The elapsed time between magnetic pulses corresponds to a rotor speed, which is subsequently used in the flight control routines.

In order to allow the helicopter to locate hazards and aid in a rescue mission, a camera is mounted to the front of the airframe. A progressive-scan color camera, made by Pulnix America, Inc., along with a 12.5mm-75mm 1:12 zoom lens, provides the capability for close-up photography of potential targets. With this combination of instruments, the Rose-Hulman Aerial Robotic Vehicle can fly autonomously and navigate preprogrammed flight patterns.

3.0.2 Hardware

The onboard flight control computer is a PC-104 style AMPRO Pentium 133. It interfaces with a digital I/O board, two timer boards, and a serial expansion board. Two additional boards were designed and built by the Rose-Hulman Aerial Robotics Team. The first of these boards contains the servo multiplexer as well as the interface to the accelerometers and zoom lens. In addition, it provides a low battery voltage warning buzzer and disperses power to all hardware on the vehicle external to the flight control computer. The second custom board provides power at the various voltages needed by the GPS, yaw rate sensor, vertical reference, and magnetometer. It also has analog-to-digital converters that sample the signals coming from the yaw rate sensor, vertical reference, and magnetometer. An onboard microcontroller communicates with the analog to digital converters and returns the data to the flight control computer over a single RS-232 serial interface. Placing all this functionality on only two boards greatly simplified the wiring of this year's vehicle.

3.0.3 Software

The software that runs on the helicopter can be divided into two categories: telemetry and control. All the software is written in C++ and runs under MS-DOS. The telemetry code is the portion of the software that handles communication between the Pentium 133 board, all the onboard sensors, and the ground station. The control code is the portion of the software that actually takes the input variables from the telemetry code and then decides how to make the helicopter respond in order to maintain stable flight.

The telemetry code consists of a set of protocols for encoding/decoding the various data and command formats used by each piece of hardware, as well as lower-level routines which transport data to and from the hardware. The new telemetry code allows on-the-fly changing of which parameters are logged to the ground station. This makes it possible to debug the performance of controllers being tested without landing or recompiling the flight control software. Telemetry is sent to the ground station at 5Hz, but data can also be stored on a RAMdrive on the helicopter at up to 500Hz. This saved data can be downloaded and analyzed at a later time. This makes offline tuning of the control loops possible.

The control code utilizes fuzzy controllers, similar to those developed by Michio Sugeno [2], which have successfully controlled large scale model helicopters. Independent fuzzy controllers are used for longitudinal cyclic control, lateral cyclic control, collective pitch control, tail pitch control, and throttle control. In addition, fuzzy trim controllers are used to eliminate steady-state errors in each of the fuzzy controllers. Each controller can run in two different modes, determined by the height of the vehicle above the ground. In addition, the vehicle has six different flight modes and can switch between them in response to changing flight conditions and commands from the ground.

The ground station software was ported to Microsoft Visual Studio and separated into two processes. One process, HeliServer, communicates with the helicopter via the radio data link and sends differential GPS updates to the helicopter from the GPS base station. The second process, HeliClient, communicates with HeliServer to receive telemetry and send control commands to and from the helicopter. HeliClient is responsible for waypoint-based navigation that will guide the aerial vehicle around the arena. The helicopter's onboard control software is still responsible for helicopter stability. This division of labor in the control software allows the helicopter to continue to receive dGPS updates in the event of an exit or crash of the main GUI program, HeliClient.

The HeliClient process communicates with the imaging process software running on two dual Pentium II 400MHz machines. Helicopter position and attitude telemetry is forwarded to the image processing software so that the world coordinates of objects can be determined. Currently each computer is able to analyze one frame for fire and barrels in about two seconds, allowing a total of one frame to be analyzed each second.

3.1 Propulsion

A highly modified Bergen Industrial Twin model helicopter lifts all of the electronics onboard the helicopter. The helicopter itself weighs approximately 18 pounds, and is capable of lifting more than 43 pounds. This high lift to weight ratio is what makes the Bergen Industrial Twin model helicopter a desired platform for the 2000 competition. This helicopter is a proven design that allows more time for developing autonomous control rather than having to develop and debug a custom design.

The original dual carbeurator system has been replaced by a single carburetor with a manifold and velocity stack. The team worked in conjunction with Bergen R/C to create this new design to improve the reliability of all of his twin engine helicopters. This modification has improved the helicopter's reliability significantly by ensuring that both cylinders always receive a consistent and equal fuel-air mixture. With the original dual carburetor system, it was possible for one carburetor to temporarily stop pumping fuel, thus causing its cylinder to run lean and overheat. The new single carburetor system has also made tuning the engine much easier because the cylinders are automatically balanced.

The air cooling system has been overhauled extensively. Baffles and extra covers evenly direct air over the cylinder head fins. The baffles fit much more tightly around the cylinders to force the air through the cooling fins. A larger intake in the fan shroud lets the cooling fan increase the volumetric flow rate over both cylinders. These two modifications have increased the vehicle capacity by more than 10 pounds. The extra cooling effect will also benefit the team because there is less likelihood of an overheating problem.

Custom-built fiberglass gas tank mounts hang on either side of the helicopter. These mounts split the weight of the fuel on both sides, keeping the helicopter in balance as the engine consumes the gasoline. The tanks are also located near the helicopter's center of gravity meaning that there is little effect on the dynamics of the helicopter as the volume of gasoline in the tanks decreases. This keeps the controllers in a constant environment so that they don't have to account for the amount of fuel in the tanks.

In a past competition, transition out of ground effect flight was problematic due to the effect of the lower density air above the hot blacktop surface. A pair of flat bottom V-Blades improves the lifting efficiency of the 4.5 horsepower Bergen Industrial Twin helicopter. If the heat still poses a problem, a proprietary lift enhancement technique will be employed to aid in getting out of ground effect.

3.2 Attitude/Heading Adjustment Schemes

The helicopter control system uses 13 state variables to stay in the air: x, y, z and their velocities (from the GPS); roll, pitch, yaw and their rates (from the magnetometer, yaw rate sensor, and vertical reference); and main rotor speed (from a custom designed rotor speed sensor). Each state variable has a setpoint, which is the desired value of that variable. The setpoint values are set by the navigation system and may be adjusted by the controller to maintain a stable hover or to induce motion towards a waypoint.

The helicopter control system is still based on a fuzzy logic control system recommended by Michio Sugeno for a model helicopter [2]. At last year's competition, autonomous hover capability was demonstrated using a velocity control system. The control system now has more accurate sensor data, so positional control is achievable.

Integrated acceleration data is combined with GPS data to better estimate the vehicle's velocity. The accelerometer also provides some fault tolerance in the event that GPS solution is lost, or a broken data link to the ground station stops differential GPS updates.

Each controller has two operating regions, 'hover' and 'low'. The controllers shift smoothly between these modes in response to the vehicle's height above the ground. This allows the vehicle to maintain control as it moves through ground effect during takeoff and landing. In addition, the vehicle has six operating modes, corresponding to all segments of an autonomous flight. The vehicle can switch between these modes in response to hardware failures and commands from the ground. For example, should communication with the ground station ever be lost, the vehicle can automatically come to a halt and then begin a landing sequence.

3.3 Navigation Techniques

Waypoint navigation is accomplished by transitioning between flight modes. Fuzzy logic controllers have been developed to control both the helicopter's position (hover mode) and velocity (motion mode). When the helicopter is instructed to move to a new waypoint, a fuzzy logic mode controller determines which mode, or combination of modes, is necessary to reach the new waypoint. By navigating with the fuzzy logic mode controller, the helicopter may be partially in hover and partially in motion. Outputs from both mode controllers are combined, and the helicopter action results. Finally, when the helicopter nears its new waypoint, it smoothly transitions back into full hover mode.

An initial flight plan is programmed prior to takeoff, but discoveries made by the imaging system can alter the flight plan. If an object of interest is discovered, it would be advantageous to attempt to identify it. The flight plan is then updated by assigning a new waypoint near the object of interest. Once the object has been identified, the vehicle begins a spiral pattern outward from that object in an attempt to locate other objects in the vicinity. This is the optimal flight plan since targets are likely to be clustered together.

3.4 Target Identification Techniques

The image processing hardware is unchanged but software has been written to detect fire, barrels, and labels and control the motorized zoom lens onboard the helicopter. The hardware consists of a progressive scan camera and analog video transmitter operating at 2.4GHz onboard the helicopter. A motorized lens with zoom, focus, and iris control is mounted to the camera. The video transmission is received by one of the imaging computers with an image capture board installed.

Each imaging computer runs an identical image processing algorithm. Video frames are passed to the imaging software running on each machine as needed. Image processing results are forwarded to the machine with the image capture board for collection and the final decision is made there. This distributed image processing architecture is scaleable to a greater number of machines.

Fire detection is a straightforward algorithm. Images are converted to the hue, saturation, and value color system. Any pixels with an orange hue and high saturation are considered part of a potential fire. Objects are formed from sets of pixels that are connected together. Objects with a small mass are thrown out. It is assumed that only one fire can appear in a given frame. Therefore, the center of mass for the remaining objects becomes the computed center for the fire.

The label detection algorithm can detect all three labels and is rotation, scale, and perspective independent. The algorithm works by thresholding a grayscale image and segmenting this into connected objects. The algorithm attempts to find the four corners of the outside white perimeter line of the label. If an object does not have four distinct corners in a parallelogram shape, it is obviously not a label and thrown out. Any remaining object candidates are compared to the template labels using frequency domain-based correlation. Correlation is a slow process but using the altitude of the helicopter to filter out candidates that have the wrong size or mass reduces the number of correlation operations.

3.5 Threat Avoidance Schemes

The helicopter navigation system will avoid known obstacles in advance such as the light poles because this information has been given. New imaging algorithms added fire detection that will allow the helicopter to avoid any fires in its path along with its future paths. The video camera is pointed far enough forward to detect a fire 30 feet in front of the helicopter. This extra distance will give plenty of time for the ground station computer to warn the helicopter of hazards that are ahead.

Obstacles along the route to each new waypoint are avoided by including the output of an obstacle avoidance algorithm into the flight mode controller. If the computer knows of an obstacle in the path of the helicopter or if imaging detects one, it instructs the vehicle to move sideways to avoid the obstacle. The closer the helicopter is to the obstacle, the stronger this behavior. The list of known hazards is updated so as to avoid the object in future travels around the arena. Using this type of navigation scheme allows the helicopter to safely navigate around the competition arena.

4.0 Safety of Design to Bystanders

The helicopter is capable of graceful degradation in the event of some systems failures. If differential GPS positioning is lost, the helicopter will attempt to minimize its velocity and will begin to land unless the condition is reversed or the safety pilot intervenes. The onboard accelerometers will provide stability to the position and velocity controllers so that the helicopter will be able to maintain a rough position while attempting to land. Heading and main rotor rpm controllers will be unaffected by such a failure.

The ground station is also able to view the status of the onboard systems. For example, all battery voltages are monitored and transmitted to the ground station to ensure that onboard systems are operating within their acceptable limits. GPS solution quality is also transmitted to ensure that a valid GPS position is being calculated.

Many precautions have been taken to reduce the risk of a systems failure. For added power system reliability, there are three independent batteries in addition to the main NiMH battery pack. One battery powers the radio receiver and servo multiplexer, one powers the servomotors for controlling the helicopter, and the third is used exclusively for the emergency termination mechanism. A separate battery is provided for the servo multiplexer since the servomotors can foul the digital multiplexing circuitry by dropping the battery voltage.

Should an unrecoverable failure occur, there are two levels of response. The first response to a failure is for the human pilot to regain control of the aerial vehicle to bring it safely to the ground. The servo multiplexer allows for this type of remote switching from the safety pilot’s controller. Many precautions have been taken to ensure that the safety pilot is effective in stabilizing the vehicle after a malfunction. The final level of response to failure is the emergency termination mechanism. In the event that the pilot cannot stabilize the aerial vehicle, the emergency termination would be activated. The termination mechanism is a servo controlled by a second radio transmitter. When activated, the mechanism will ground the engine’s ignition coils. This prevents the spark plugs from firing and kills the engine instantaneously.

5.0 References

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