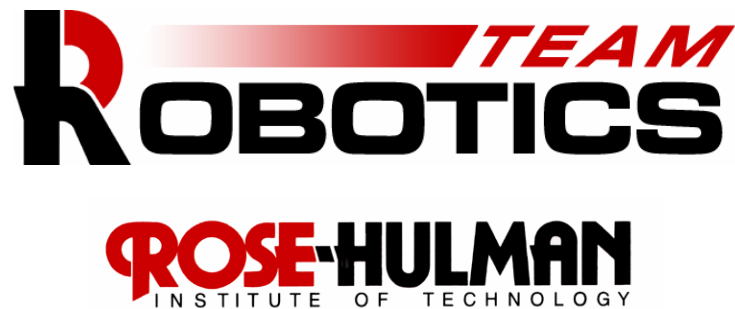


**Rose-Hulman Institute of Technology
Autonomous Helicopter for the 2004
International Aerial Robotics Competition**



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1 ABSTRACT

The Rose-Hulman Institute of Technology Robotics Team has designed an autonomous aerial robot for entry in the 2004 International Aerial Robotics Competition, organized by the Association for Unmanned Vehicle Systems, International (AUVSI). The competition requires teams to develop an unmanned aerial robot capable of autonomous flight and navigation, target acquisition, and payload deployment as well as necessary communication and safety features. Our team, comprised of entirely undergraduate engineering students, has made significant strides in development of such a robot. This paper details the progress made to date as well as a comprehensive description of the vehicle system.

2 INTRODUCTION

2.1 Background

The purpose of the RHIT (Rose-Hulman Institute of Technology) Robotics Team is to compete in the International Aerial Robotics Competition (IARC). The IARC is an annual, international collegiate engineering competition organized by AUVSI to promote research and development in the realm of autonomous aerial vehicles. The competition consists of 4 levels which must be accomplished in order. Level 1 requires teams to demonstrate fully autonomous flight over a set of waypoints spanning upwards of 3 km. Level 2 of the competition requires teams to identify a marked building among a group of buildings. The vehicle must not only identify the building with the target emblem but also identify a possible point of ingress, in this case a 1 m square window. For completion of Level 3, the autonomous vehicle must enter the window, or if the vehicle is too large, launch a sub-vehicle into the building. This vehicle must then navigate the building in search of a target image. Video of this image must be then transmitted back to human operators at the base station. Level 4 requires teams to complete all previous 3 objectives in one continuous operation with a completion time of less than 15 minutes. The competition is carefully constructed such that many aspects of potential applications of unmanned aerial vehicles are integrated into one event. These scenarios include nuclear disaster, hostage situations, or biological emergencies. Furthermore, the complexity of the competition requires teams to design and build a vehicle that is adept at all levels of competition rather than a platform that performs exceptionally well on one part of the competition but poorly on other levels.

2.2 Competitive Strategy

The team's goal for the 2004 IARC is to demonstrate an adaptable and robust autonomous platform capable of performing under multiple mission criteria.

2.2.1 Helicopter Platform

A helicopter-based aerial vehicle is most suitable for a highly-adaptable unmanned aerial vehicle. Helicopters offer many advantages over fixed wing designs as well as a few tradeoffs. Helicopters have the ability to stop and hover to investigate various targets and flight at lower altitudes at slower speed. The downside to a helicopter is its inherent

instability, requiring more time and effort to be devoted to a flight control system rather than autonomous algorithm design.

2.2.2 System Integration

A critical component of the RHIT Robotics Team competitive strategy is the continued miniaturization and integration of the systems required for effective autonomous flight. For the 2004 competition entry the team has begun to transfer the tasks of autonomous flight control and computer vision from software running on the computer to a dedicated hardware implementation. At present, two separate but identical custom built FPGA boards are being used; one dedicated to neural network flight control and sensor sampling, the other being used for camera capture and stereo depth resolution. For future competitions the team hopes to have the majority of necessary components for autonomous flight reduced to a single piece of silicon allowing for a single board implementation of a robust autonomous helicopter system. Such an implementation, along with MEMS (Micro Electrical Mechanical Systems) sensors and miniature cameras would permit the team to build autonomous helicopters cheaper and smaller than ever before.

2.2.3 Expandability & Adaptability

Due to the very dynamic nature of the IARC competition series a highly expandable and adaptable vehicle is preferable. As previously mentioned, a helicopter-based platform is more suited to multi-mission capability, should the rules change in some fashion, the team could be in a more advantageous position than teams with fixed wing designs. Use of a Bergen Industrial Twin helicopter with an 8 hp engine allows the team to add additional payload without worrying about the vehicle's lift capacity. The compact PCI form factor allows for a modular and expandable computing system. Its PCI backplane provides more than enough bandwidth for existing requirements and can support future additions. Because the compact PCI standard is well supported, commercial off-the-shelf (COTS) components are readily available and can be added to the PCI bus with ease. Using FPGAs for I/O and sensor sampling also allow for great expansion of computer I/O.

3 Air Vehicle

The aerial vehicle is composed of mechanical, electrical, sensor, hardware, software, and safety subsystems.

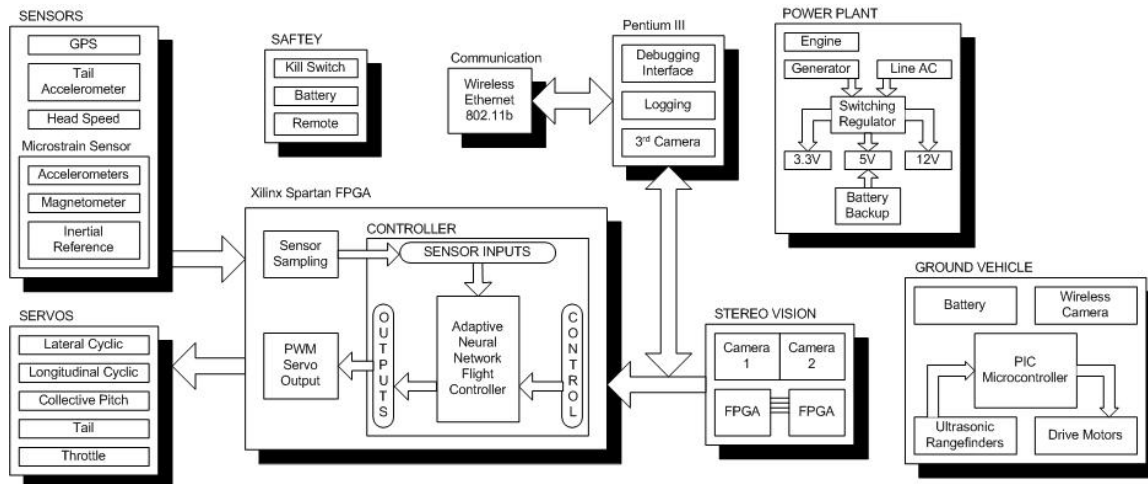


Figure 1: System Overview

3.1 Airframe

The primary aerial vehicle is a highly modified Bergen Industrial Twin model helicopter. Previous modifications to the helicopter have included enhanced engine cooling through modified air baffles, a conversion to a single carburetor to ensure balanced fuel mixture in both cylinders, non-perforated side panels for increased airframe rigidity, a durable custom landing gear, a higher power engine and a new servo suite with higher torque and metal drive gears. Modifications to the vehicle this year include the replacement of the large carbon fiber / G10 mounting platform with a single compact PCI computing cage, mounting of the onboard 300W generator and rugged metal fuel tanks and fuel line. The metal fuel tanks and steel braided fuel line protect against leakage and offer additional protection.

3.2 Propulsion and Lift System

In 2003 the 4.5 hp dual cylinder 46cc engine was upgraded to a larger 8 hp engine which provides the vehicle with additional lifting capacity and ample power for the onboard generator. With the 8 hp engine the helicopter has an estimated lifting capacity of 60 lbs and a flight time of ~ 1 hr with 2 L of fuel. To complement the new computer hardware and vision system a custom 300 watt alternator was added to the vehicle. The generator attaches to the drive shaft directly and is mounted directly underneath the engine. The generator can source a maximum of 5 amps at approximately 8 volts per 1000 rpm.

3.3 Guidance, Navigation and Control

The RHIT Robotics Team aerial robot uses a tiered approach to guidance, navigation and control. At the lowest level is the autonomous flight controller, which based upon the difference between the current state and the desired state produces a set of servo values to minimize this error. The desired states are determined by a higher level controller, which is part of the HeliControl system. For example, to traverse a set of waypoints, HeliControl plots a path of sub-waypoints and sequentially commands the controller to visit each of these smaller waypoints, until the actual waypoint has been reached. This

approach simplifies the autonomous flight controller and allows easier implementation of complex behaviors by doing path finding at a higher level.

3.3.1 Autonomous Flight Control

Helicopters are notoriously unstable machines, and hence developing an autonomous flight controller is quite a difficult challenge. In previous years, the RHIT Robotics Team has attempted to solve this using a Sugeno-style fuzzy controller [Sugeno 1995].

However, finding an appropriate set of parameters for the fuzzy controller has proven to be very challenging. For this reason, the team decided to develop a neural network controller. Neural networks, however, pose their own set of challenges, such as finding an appropriate number of nodes and a method of weighing the connections between these nodes. The team chose to apply genetic algorithms to the problem of developing and tuning the neural network flight controller.

The genetic algorithm software used is based on DGENESIS [1] by Erick Cantú-Paz. DGENESIS is a program for doing genetic algorithms in parallel across several computers, and supports migration of populations between nodes. The software was modified to work with MPI to integrate well with the Rose-Hulman Cluster Computer. The software allows each node to evaluate genes based on different fitness criteria. For the purposes of this project, these criteria would evaluate based on factors such as oscillations, steady state time, and rise time for position and direction. The evaluators run the candidate controller on the simulator released by the Autopilot Project. The evaluators have been designed in a modular fashion, so that the genetic algorithm tuner could be applied to other types of controllers as well, such as PID or fuzzy.

3.4 Software

The software uses a modular approach to facilitate faster development and to encourage software reusability. By using a well-defined API between the mission-specific code and the autonomous flight code, the code becomes modular. This allows us to easily adapt our existing code to new missions. As shown below in Fig. 1, a single process runs on the onboard computer, and several clients communicate with it through the HeliServer proxy.

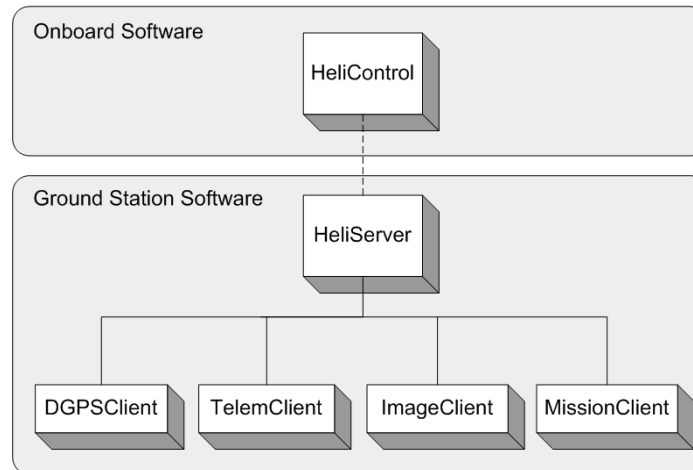


Figure 2: 2003-2004 Software Architecture

HeliControl is the main program that runs on the onboard computer. It handles

- communication with the ground station,
- obtaining and logging data from the FPGA board,
- running a controller that attains autonomous flight,
- mission control, and
- decision making based on the vehicle's environment.

HeliControl exports many variables and remote procedure calls (RPCs) organized in a hierarchical tree. Clients that connect to HeliControl can execute RPCs to affect the behavior of the helicopter or subscribe to exported variables to receive updates whenever their values change.

Ground station client applications include

- DGPSClient, which sends differential GPS correction logs;
- TelemClient, which allows the user to dynamically view and log selected variables in real-time;
- ImageClient, which allows viewing of transmitted images; and
- MissionClient, which is aware of mission-specific functionality and provides high-level mission status and control.

DGPSClient and TelemClient work together to provide autonomous flight and general system debugging, while MissionClient provides an interface to assign waypoints and view the progress of the first two levels of the current competition. All four clients work together to complete the competition.

3.5 Flight Termination System

Should the need arise for a flight to be terminated an independently powered and controlled kill mechanism is in place. The termination system is a relay that runs on a separate radio receiver. The relay grounds the spark plugs, thereby killing the engine and shutting down the onboard electronics. A battery backup powers the servo and radio receiver and in the absence of a computer signal, the servo multiplexer board enables

human control. This allows the human pilot to potentially glide the helicopter down to a safe landing.

4 Payload

The RHIT Robotics Team aerial robot is equipped with a complete sensor suite and carries a sub-vehicle to aid in the completion of the mission objectives.

4.1 Sensor Suite

The helicopter is equipped with many sensors to determine position, orientation, velocity and acceleration, which provides input to the control system to allow the robot to autonomously complete its mission objectives.

4.1.1 NovAtel OEM3 GPSCard

The NovAtel OEM3 GPSCard calculates latitude and longitude within 2 centimeter CEP (Circular Error Probable) standard deviation and altitude within 4 centimeter CEP at 10 Hz. It repeatedly attains this accuracy while the GPSCard receives RTCA differential logs every 2 seconds. When differential logs are not received, the standard deviation slowly degrades to over 1 meter SEP (Spherical Error Probable). Once the differential link is re-established and current RTCA differential logs are received, the GPSCard quickly regains 2 centimeter CEP standard deviation.

4.1.2 Microstrain 3DM-G

The Microstrain 3DM-G gyro-enhanced inclinometer and orientation sensor contains a 3-axis gyro, 3-axis accelerometer, and 3-axis magnetometer. Although all raw samples are available, the vibrations and electrical noise from the engine make instantaneous samples unusable. Instead, the 3DM-G combines its sensors with a Kalman filter into a best estimate of the vehicle's orientation, angular rate, and acceleration.

4.1.3 Main Rotor Tachometer

The main rotor tachometer is a hall-effect sensor mounted close to and in the plane of the main rotor's tail gear. Two magnets 180 degrees apart on the gear trip the hall-effect sensor twice per rotation.

4.1.4 Ultra-sonic Range Finders

Two ultra-sonic range finders targeted below and in front of the helicopter detect the vehicle's distance from the ground and from any solid object in front of the helicopter.

4.2 Computer Vision

The helicopter's imaging systems consist of two primary parts: one part which recognizes and locates the given IARC logo, and one that builds a world map for the purpose of safe navigation through the world.

4.2.1 Hardware

There are two systems of vision in the autonomous flight platform: a pair of Pulnix cameras on the helicopter and a color wireless webcam on the deployable ground vehicle.

The Pulnix TM-1020 progressive scan cameras are monochrome, which allows for easier edge detection. The cameras are mounted towards the front of the helicopter on a TRAClabs Biclops pan/tilt unit, which allows the helicopter a wider range of vision without having to move the entire vehicle. Programs can track and search for objects by controlling the cameras over an RS232 line. Another feature of this setup is that the helicopter can look in one direction while flying in another, which allows for better path planning and a wider range to search for the IARC logo, building openings, or other targets.

4.2.2 Image Recognition

The logo-finding algorithm uses a grammar-based system to locate the black wedges that comprise the IARC logo. The first stage of this algorithm detects line segments using the Canny edge detector and a modified Hough transform. Once the line segments are found, the algorithm marches through the image to attempt to find segments that are near each other and that have grayscale gradients that are consistent with a black wedge on a white background. After the set of wedges is found, pairs of opposing wedges are found. Finally, having found all pairs of opposing wedges, the pairs are compared to find quartets of wedges that are in the right orientation to be the IARC logo [Heath 2004].

Once potential IARC logos are found, it is a simple matter to rectify the region around the logo and to do a template match against known images of the logo. Once this is done, the best match is taken to be the position of the logo in image space. From this, the software calculates the location of the logo.

4.2.3 Stereo Depth

The map building algorithm uses a parallel census algorithm implemented on an FPGA board. The algorithm works by associating a vector to each pixel in an image. The vectors are generally the luminance (or grayscale value) of the neighboring pixels in the same row as the given pixel. Given a pair of images taken from a calibrated stereo pair, the vectors associated with the pixels in one image are compared to the vectors associated with the pixels in the other image. The pixels with minimal vector distance are considered to be associated pixels. Once the associations are made, standard geometric methods for finding depth are applied, and a depth map is generated.

This map is fed to a statistical world model, which correlates previous estimates of the position of objects in the world with the new data to update the model of the world. This is done using the state of the helicopter as estimated by the sensors, and the depth map generated by the census algorithm. Due to the ease of parallelization in the depth-mapping stage, this is ideally suited to implementation on an FPGA. The map-building is implemented on a general-purpose CPU, as it is used for interfacing with the flight planning system.

4.3 Threat Avoidance

Currently threat avoidance is done at a very immediate level. As far as threat avoidance is concerned, there are two main modes: flight and approaching the building. During the flight mode the helicopter is either making its ingress or searching for the correct

building. In this mode, the helicopter is flying at a high enough altitude that there are not expected to be many obstacles, and hence little is done for threat avoidance. In the future, the team plans to use vision data to build a model of the world, which will allow for more intelligent threat avoidance and allow the helicopter to fly in more congested areas.

When the helicopter is approaching the building to launch the ground vehicle through the open window, the ultrasonic rangefinders are used for threat avoidance. The rangefinders are good for finding short distances, and the helicopter uses data from these to maintain a safe distance from the buildings and the ground.

4.4 Communication

The Orinoco 802.11b PCMCIA, equipped with an 8 dBi omni-directional external antenna, enables at least a 1 Mb/s data link for transmitting telemetry data and control commands. With the remaining bandwidth, the vehicle acts as a wireless relay to forward images from the sub-vehicle to the ground station.

4.5 Power Management System

In previous years, the RHIT Robotics Team had used lithium-ion batteries to power the onboard computer and other electronics. This solution, however, gave limited flight time and large amounts of downtime between flights while batteries were charging. A custom generator provides more power than the batteries could have provided, and the power is available as long as the engine is running. A custom power board which rectifies and regulates the generator output into a stable voltage source powers the onboard electronics.

4.6 Sub-Vehicle

The ground vehicle's single D-Link DCS1000W camera does not allow for stereo vision, but is a color camera for human convenience. Pictures from the camera are relayed over a wireless 802.11b link to the helicopter, which then forwards the picture to the mobile command station, where it can either automatically process the image or display it for a human operator to analyze.

In order relay pictures from inside a building, a separate ground vehicle is used. The ground vehicle is carried by the main helicopter and will be launched using a spring loaded mechanism through the window of the building. The ground vehicle is a simple rover that employs a wall following algorithm that will enable it to retrieve pictures of the entire interior of most buildings. The ground vehicle uses three ultrasonic range finders from Hobby Engineering to facilitate wall-following behavior. Mounted to the ground vehicle is a D-Link DCS-1000W Wireless Webcam that will use the helicopter as a repeater and relay images from inside the building back to the mobile command station.

5 Operations

Flight preparation procedures vary widely depending on the purpose of each flight. Flights were often times conducted to test one particular subsystem of the aerial robot. In every case, some form of data logging was used; for example, to test the data gathered by

the Microstrain 3DM-G or to test the performance of the generator. After every flight, the fuel tanks were drained before the helicopter was brought back in for storage. The power system was not in place until relatively late in the year, so an alternate power supply had to be provided. Many times the helicopter only needed to fly a few feet off the ground to accomplish the particular goals of that flight, so an external power supply could be used.

5.1 Mobile Command Station

The mobile command station functions as a monitoring station, field supply, and storage. The top surface of the station is large enough for the helicopter to be easily transported to demonstrations and competitions. Its frame is constructed using modular 80/20 aluminum extrusion, making future upgrades hassle-free. There is a wide variety of computing equipment housed inside the station, so 120V AC power is provided at many internal and external outlets. A UPS battery backup keeps the station running in the event of an unintentional loss of power.

Remotely monitoring the helicopter is simple using the four CRT displays on the front of the command station. A television in the middle can play video or live camera feeds at competitions and demonstrations; it can also be used as a secondary computer monitor. The two side monitors are attached to the two computers inside the command station. The GNU/Linux system to the right of the TV houses a Concurrent Versions System code repository and eGroupWare project management and information database. It also runs much of the helicopter monitoring and control software. The Windows XP machine to the left is used for presentations and monitoring the helicopter. The bottom screen is a Nematron industrial terminal attached to the Linux server; in addition to being used as a secondary interface to the Linux machine, it is the only display on the UPS because it displays a majority of the flight-critical data.

6 Risk Reduction

The safety of the vehicle, and particularly that of any humans in its proximity, is of paramount importance. Thus, the vehicle has been designed with multiple failsafe systems. The first is a manual control mode that allows a safety pilot to regain command of the vehicle should it become unstable under autonomous control. An independently powered servo multiplexer system selects whether computer generated signals or safety pilot controls are sent to the servos. The safety pilot can use a switch on his RC transmitter to instantly gain control of the helicopter servos.

The secondary failsafe mechanism is an independently powered and controlled remote kill mechanism. The device uses an independent 900 MHz transmitter and an encoded command to actuate a relay that grounds the spark plugs ceasing combustion in the engine. In the event that the autonomous control system fails and the safety pilot is unable to stabilize the vehicle through manual control, the safety kill mechanism is employed to protect spectators by bringing the vehicle down immediately.

6.1 Modeling and Simulation

An open source helicopter simulator based on the NASA Simplified Rotorcraft Model and released as part of the Autopilot Project was used for simulation. Simulation is primarily used in the development and tuning of the autonomous flight controller. Several slight modifications were made to the simulator to allow it to integrate with the genetic algorithm tuner, as well as to run simulations faster than real time, which enabled candidate controllers to be automatically evaluated very quickly. Several parameters in the simulator were also changed so the simulator better models the RHIT Robotics Team aerial robot. After a controller was found that performed reasonably well according to the automatic evaluation criteria, that controller was evaluated by a human in real time on the simulation for a more subjective scoring of it.

The team is considering modifying the simulator to support obstacles so that obstacle avoidance algorithms can be developed and tested in simulation.

6.2 Testing

Testing of the autonomous flight controller is primarily done through the simulator, which is believed to be based on a relatively accurate model of the helicopter. Other components were tested independently to isolate issues that would be applicable for them. For example, several tests were done to evaluate quality of the data provided by the Microstrain 3DM-G while subjected to the vibrations from the running engine. The vision algorithms were also tested extensively, and were shown to be able to correctly identify the IARC logo in a wide variety of conditions.

7 CONCLUSION

The RHIT Robotics Team, in preparation for the 2004 IARC, has designed and built a stable, extensible, autonomous platform capable of competing the objectives set forth for the competition. As a prerequisite to all the objectives, the vehicle must be capable of flight without human intervention. During the competition, the RHIT Robotics Team plans to demonstrate Level 1 behavior by autonomously navigating a three kilometer sequence of waypoints. After completing this sequence, the team expects the vehicle to identify the building marked with the IARC logo, as well as all openings in the building. Once an appropriate opening has been found, the aerial robot will deploy a sub-vehicle designed to relay video from inside the building to the ground station. The team believes to have developed a vehicle that will be well suited to these tasks.

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