Rose-Hulman Institute of Technology's Autonomous Helicopter for the 2003 International Aerial Robotics Competition

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Abstract

In preparation for the 2003 International Aerial Robotics Competition, the Rose-Hulman Robotics Team has made significant improvements to the onboard computer system, control system, and to the vehicle itself. These improvements yield a more stable flight system with increased computing bandwidth all bundled into a highly modular system. A dedicated hardware flight controller allows additional resources to be allocated for various subsystems such as navigation, communication, and computer vision. A modular cPCI computer system provides high bandwidth for image processing and the ability to easily add and remove components. An adaptive hierarchal fuzzy control system will provide stable flight despite physical changes in the flight system. Finally an onboard generator coupled with a larger engine will provide power to all electrical systems while the helicopter is running.

1 Competitive Strategy

The team's goal for the 2003 IARC is to demonstrate an adaptable robust autonomous flight platform capable of long-range operation. Our strategy is to focus on the fundamental requirement of the mission, autonomous operation at speeds upwards of 30 km/hr at an extended distance from the base station. The first component of our goal is to demonstrate autonomous, semi-adaptive flight including takeoff, hover, in-flight maneuvering, and landing. The second part is to demonstrate waypoint navigation capability by flying a predetermined 3 km path. The third component is to further integrate navigation along with a more advanced adaptive flight control system allowing the helicopter to execute intelligent maneuvers, such as coordinated turns, to provide higher speed and more efficient autonomous flight. This strategy will yield a dependable robust autonomous platform which can demonstrate sophisticated flight behavior when integrated with additional subsystems in the future.

The continuous evolution of the design of the helicopter aids to a successful competitive strategy. Eventual completion of the current mission may require higher flight speeds and greater maneuverability than in previous missions. In last years competition a flat Kevlar mounting system was replaced with two versatile, yet large, carbon-fiber enclosures on both the front and back of the helicopter. This year, advances in technology have allowed the team to miniaturize many of the components on the helicopter thus the large enclosures are now obsolete.

Previously, the computer enclosure in the back of the helicopter housed the Pentium II SBC (single board computer), wireless Ethernet, and servo controllers in a PC-104 stack. This configuration albeit small, was difficult to service as all cards on top had to be removed to reach one on the bottom. Additionally the small surface area of a PC-104 card made it difficult to place large components such as DSPs or FPGAs on a single card. These flaws, combined with obsolete digital I/O boards, prompted the team to investigate various alternatives. In searching for alternative systems several factors were considered as described in the hardware subsystem section below. The industrial standard 3U cPCI (compact PCI) was chosen as the best solution. A small cPCI cage with room for additional non form factor boards was mounted to the chassis on the rear of the helicopter. In this configuration all computing hardware including the NovAtel GPS is housed inside the cage protecting them from various hazards including EMI and reduces the number of exposed cables. The new front of the helicopter will contain the power supply hardware, servo battery backup, kill switch, sensor system, and in the future the two cameras needed for stereoscopic vision.

The team is continuing to use the Linux software platform developed last year with a few exceptions. The modular communication protocol CORBA was replaced with a light-weight custom protocol the team developed. The new protocol still serves all the same functionality as CORBA but is better suited for the mission objectives and our hardware system. The original fuzzy controller was further expanded upon and developed as well as ported to a FPGA to serve as a dedicated hardware controller. The controller was refined into a three level hierarchal system with an adaptive controller at its lowest level. With this approach the highest level serves as a command interpreter accepting commands similar to “make a coordinated 90 degree turn with radius 10m at 2 m/s”. The upper level then instructs the middle level with more defined commands and sequences such as defining a yaw rate, roll angle, and pitch required to execute the maneuver. The middle level then blends and switches between a collection of low level controllers. When the target position is relatively far away, it will select a velocity controller to obtain a desired speed at which to approach its target position. As the helicopter approaches this position, a slow down controller is activated, followed by a position controller which will hold its designated position until the next command is issued. All lower level controllers will exhibit some level of intuitive adaptation to allow for changes in the dynamics of the helicopter both in the air and between flights. Initially, the adaptation will be in the form of adjusting trim settings on all controller outputs to correct for steady state errors. Future revisions will include adaptive gains, positions, and widths of fuzzy members, insuring that the system is critically dampened.

Additional changes to the helicopter include a higher power engine, new servo suite and onboard generator. With the previous hardware setup, the helicopter was operating at near 90 percent throttle during hover. The addition of a ground vehicle and vision system would add additional weight to the platform and continue to strain the engine. Fortunately, Bergen helicopters manufactures a larger, 8hp engine for the helicopter. Additional maintenance on the helicopter included replacing the old servos that were beginning to show sings of wear. The team took this opportunity to purchase a set of digital servos which are currently leading the state of the industry for RC hobbyists and professionals. The old servo set operated off of a 50Hz PWM signal, used plastic drive gears, and had a relatively slow reaction rate. The new servos operate at 175Hz and use metal drive gears. These servos offer higher torque needed for the new engine, faster response, and a quicker update rate. With new computing hardware and the expected power draw of the vision system, a larger capacity power system was required. A custom generator was installed to utilize the increased horsepower of the engine and to provide power for all electronics while the engine is running. This eliminates the need to cycle batteries between flights and provides up to 750 watts of power at full throttle, eliminating insufficient power issues for any future additions.

2 System Overview

The aerial vehicle is composed of mechanical, electrical, sensor, hardware, software, and safety sub-systems. The 2003 vehicle includes many modifications in these systems from the 2002 vehicle design. The system overview shown in Figure 1 shows the main subsystems and their components.

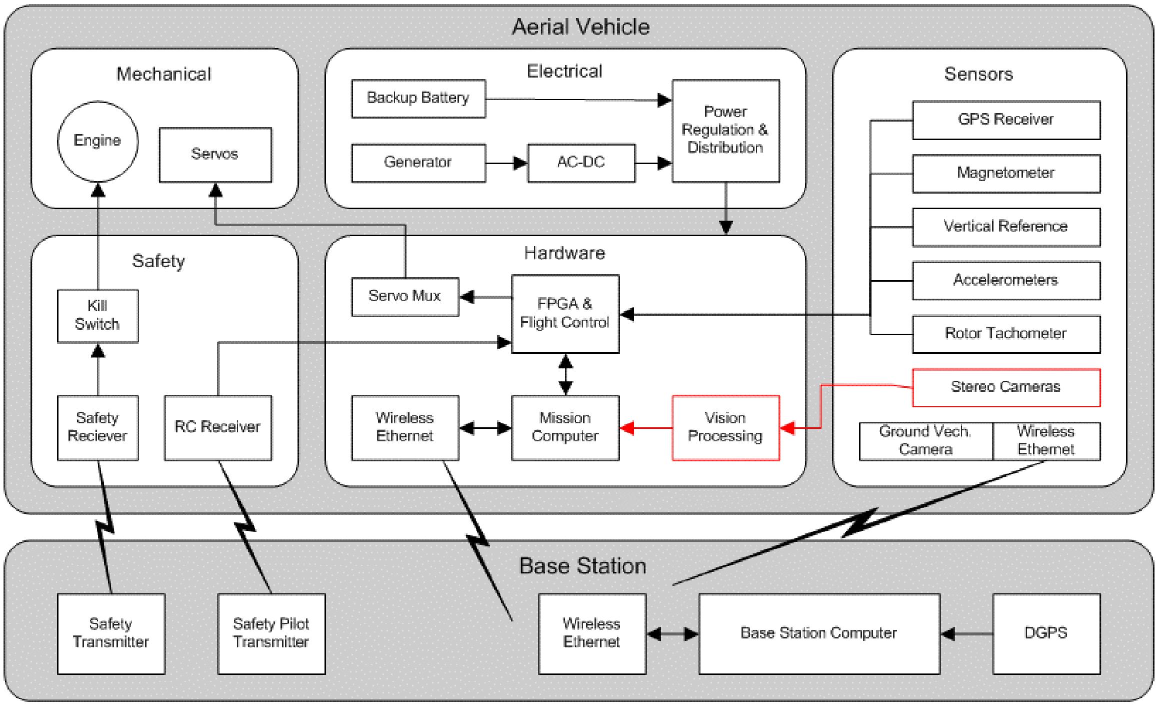

Figure 1: System Overview Diagram

3 Mechanical Subsystem

3.1 Primary Vehicle

The primary aerial vehicle is a highly modified Bergen Industrial Twin model helicopter. Previous modifications to the helicopter include 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, and a durable custom landing gear. Modifications to the vehicle this year include the replacement of the dated 4.5 hp engine with a more powerful 8 hp power plant, a new servo suite, and an onboard generator. The larger engine insures that the additional weight of the ground vehicle, vision system, and generator loading will not impact the maneuverability of the helicopter. New servos compliment the new engine by offering higher torque and metal drive gears which will improve their reliability.

3.2 Secondary Vehicle

The secondary vehicle is a four wheeled ground vehicle that will be delivered to the target building via a launching mechanism underneath the helicopter and between the legs of the landing gear. This vehicle is designed as self-righting upon entry and landing inside the building. The proposed ground vehicle carries a commercial, off-the-shelf wireless web cam. With the wireless web cam as the base, the ground vehicle can easily send images to other devices or computers on the wireless network when the helicopter acts as a wireless relay, forwarding packets from the ground vehicle's relatively weak wireless link through the helicopter's amplified wireless link to the base station. All computers connected to the base station’s network will be able to simultaneously browse to the built in web server on the web cam and view the images it receives in real-time. The vehicle itself will use a series of infrared range finders to exhibit a simple wall following behavior, allowing it to travel through all the rooms in the building. The ground vehicle is currently in a prototyping stage with both the chassis and microcontroller under development.

3.3 Mounting System

The mounting system has been redesigned to allow for higher integration, more modularity, and support for several smaller replacement components. Upgrading the Watson vertical reference sensor to a Microstrain MEMS device left a large amount of room in the forward mounting bay. Additionally, converting the computer system to the cPCI form factor required revamping of the rear mounting bay as well. An industrial cPCI mounting cage was mounted to the rear of the helicopter. In this fashion, it would be relatively difficult to remove the cage; however, individual cards can easily be removed via a tool-less locking clamp. This allows the team to integrate the RC receiver into the cage and create a more rugged wiring system. Currently, the sensor package and power system are housed in the front of the helicopter. The forward mounting bay is still under development, pending creation of a rigid camera mounting system.

4 Electrical Subsystem

With the new mounting system, the wiring system has again been modified to simplify the wiring and reduce the length of cables. The rear computer cage contains 3 primary connectors mounted directly to the cage and a few peripheral connectors on a removable metal plate on the front. The three permanent connectors include a power connector, servo connector, and a high capacity data connector. The power connector contains the necessary voltages for the computer components with ample current supply for future additions. The servo connector contains all signals necessary for the five servos required for flight. The additional data connector will be used for the sensor package and any additional I/O that may be required. All connectors are ruggedized and are of different form factors to prevent misconnections.

With new computing hardware and the expected power draw of a computer vision system, the previous Lithium Ion battery system was insufficient. Taking advantage of the new engine, the team selected an onboard generator solution. This generator produces approximately 75 Watts at idle, enough power to run the computers but not the servos, and upwards of 750 Watts at hover. In the generator configuration, power drawn from the engine is proportional to the amount of load on the generator. With minimal electronics, the engine will experience minimal loading. This also allows for seemingly limitless upgrading of electronics as the generator will be able to support high powered components. One disadvantage of a generator power source is that, in the event of engine failure, all power is lost, including power to the servos, preventing a controlled decent. As a solution to this problem, a backup battery for the servos and RC receiver is included in the power management system. An additional trade-off of the generator is that the power system weighs slightly more than the equivalent Lithium Ion system. However, a generator does not need to be recharged, the computer has power as long as the engine is running, and flight time is only limited by the capacity of the fuel tanks.

5 Sensor Array Subsystem

The onboard sensor array consists of a NovAtel differential GPS receiver, one dual-axis Analog Devices accelerometers, a Microstrain 3DM-G gyro enhanced orientation sensor, and a custom hall-effect main rotor tachometer. The Watson vertical reference, magnetometers, and accelerometers were replaced this year by the Microstrain integrated sensor. The 3DM-G is a MEMS device which has drastically reduced the weight and volume of the sensors it replaced. These sensors are sampled by a Virtex II Pro FPGA. The Virtex also serves as a dedicated flight controller for the helicopter as well. The FPGA inputs the sensor data into its hardware Kalman filter on which the dedicated fuzzy control system acts.

6 Hardware Subsystem

The hardware system consists of a commercial cPCI computer board, a PMC (daughter board for a cPCI carrier) Virtex II Pro FPGA, and an Orinoco wireless Ethernet card with external antenna. For 2003, the team moved from PC-104 hardware to cPCI hardware. Fueling this decision were several factors. Commercial, off-the-shelf components were desirable because they implement proven technology and allow a greater degree of repeatability on new or different flight platforms. Larger form factor boards allow more devices to be integrated into a single board. Modular boards with state of the art components allow for additional features to be implemented and expanded upon with minimal changes to the computer system. A PCI backplane provides adequate throughput for image processing and future additions. The onboard computer is a 1 GHz Pentium III single board computer made by Inova Computers. The board is a tightly integrated package that has allowed us to consolidate several pieces of hardware into a smaller and lighter package. The board has more processing power than currently required, but we down-clock it to an adequate speed to conserve power, while allowing more computational power as our software requires. This board is used primarily for mission control and making decisions based on the vehicle's environment, but it will also serve as a development platform, as it is faster to implement and debug new ideas on the target hardware system. The Virtex II board manufactured by Alpha Data serves as a dedicated flight controller and I/O platform. Everything needed for autonomous flight---sensor sampling, Kalman filtering, fuzzy logic, and PWM output for the servos---is hard coded into the FPGA. External to the FPGA is a protection board that buffers connections between the FPGA and external devices. Included in this board is a servo multiplexer to switch between computer and human control of the vehicle. Since the Kalman filter uses extensive amounts of vector math which can tax a general purpose CPU, the move to a dedicated hardware implementation reduces the power requirements while freeing up the general purpose CPU for mission control. Additionally, a hardware system could be ported to smaller vehicles to provide an “always on” system. Should the mission controller fail, the flight controller would execute the last command and terminate in a hover at the last coordinates requested. The Orinoco 11MB/s 802.11b wireless Ethernet card with external antenna has enabled a data link with bandwidth sufficient for transmitting telemetry data, control commands, and images from the sub-vehicle. Starting this year, the wireless Ethernet card will also serve as a wireless bridge between the ground vehicle and the base station, allowing communication with the ground vehicle.

7 Software Subsystem

The software sub-system has been redesigned using a modular approach to facilitate faster development and to encourage software reusability. The software has been made more mission-independent by generalizing the main software components and allowing independent client applications to be added to provide specialized functionality. This way, mission dependent functionality is isolated from the basic autonomous platform. This has been done by repartitioning the responsibilities of the onboard and base station applications to remove mission specific functionality from potentially reusable code. Figure 2 below shows the relationship between the main applications that make up the new software architecture.

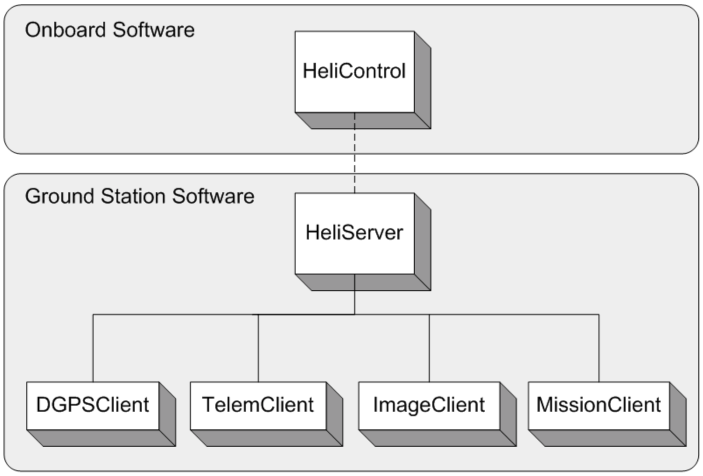

Figure 2: 2003 Software Architecture

HeliControl is the main program that executes onboard the helicopter's computer. HeliControl's responsibilities include obtaining sensor data for logging, reading the state of the helicopter from the FPGA, and issuing commands to the FPGA to navigate the helicopter. An important part of HeliControl is a reusable component called the registry which provides a hierarchical index of data and functions made available to ground station applications. Ground station applications can subscribe to any parameter or invoke any function made available through the registry. HeliControl communicates through a 11MB/s wireless Ethernet link to HeliServer. A suite of client applications then connect to HeliServer and subscribe to data made available through the registry and can invoke methods remotely. Ground station client applications include DGPSClient, TelemClient, MissionClient, and ImageClient. The DGPSClient forwards differential GPS correction logs from the DGPS base station to the helicopter. TelemClient is a GUI application that allows the user to dynamically view and log selected sets of data from the onboard system registry in real-time. MissionClient is the application that is aware of mission specific functionality and provides high-level mission status information. ImageClient will initially allow remote viewing of digitized images from the helicopter.

8 System Operation

8.1 Propulsion

The primary propulsion system is based on a Bergen Industrial Twin model helicopter. The helicopter, equipped with a new 8 horsepower 46cc Zenoah two cylinder engine, weighs approximately 18 pounds and has a maximum takeoff weight of more than 55 pounds. The custom fuel tanks allow the vehicle to carry nearly a liter of fuel for a sustained flight time of approximately 1.5 hours. This helicopter has been a dependable aerial platform that has allowed the team to focus on designing a control system rather than perfecting the flight platform itself.

8.2 Stability Augmentation

Helicopters are inherently unstable systems that require constant monitoring to achieve even simple behavior such as a hover. In order to attain stable control of the helicopter, the onboard computer samples data from six onboard sensors at rates of up to 150Hz and drives servos at 175Hz. Using this raw sensor data, a state model of the helicopter is developed. The helicopter control system understands the state of the helicopter in terms of 17 critical state variables. These variables are the position, velocity, and acceleration in the world, orientation with respect to the Earth's surface, rates of change of the orientation, and the main rotor speed. The navigation system attempts to minimize the error between the current state and desired state by modifying the servo outputs. As in the previous year, the helicopter control system is based on a fuzzy logic control system recommended by Michio Sugeno [1] for a model helicopter. New additions to the controller include a hierarchal structure which is still under development. With a hierarchal architecture, we can issue more advanced flight maneuvering commands, such as a coordinated turn. The lowest level controllers feature a small degree of adaptability through adjustable trim settings that eliminate steady state error. Additional adaptive features---such as online adaptive fuzzy member modification, changing various members' position, width, and gain---are being considered.

8.3 Navigation

The current navigation behavior is based on following waypoints entered into the flight plan before or during flight. Motion between waypoint goals is built out of simple flight modes such as hover, forward flight, ascent/decent, lateral motion, or rotation. In order to reach a waypoint, the navigation system transitions through the appropriate flight modes, or combinations of flight modes, to reach the desired state. For example, to fly to a waypoint directly ahead of the current position, the navigation system starts out in hover mode, transitions to forward flight mode, and then gradually transitions back to hover mode as the vehicle approaches the desired waypoint position.

8.4 Risk Reduction & Threat Avoidance

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.

9 Conclusion

The Rose-Hulman aerial vehicle for the 2003 International Aerial Robotics Competition has undergone major modifications since the previous competition. Modifications have included a highly integrated computing system, a dedicated flight controller, onboard generator, and a new sensor package. Our strategy for the 2003 International Aerial Robotics Competition is to demonstrate an autonomous platform capable of fulfilling the fundamental mission requirements, including an autonomous high-speed flight across three kilometers to the target structure. This strategy will provide the team with a proven autonomous platform from which further mission objectives can be achieved.

References

[1] Sugeno, M. 1995. "Development of an Intelligent Unmanned Helicopter." Tokyo Institute of Technology. Yokohama, Japan.