A Contestant in the 1997
International Aerial Robotics Competition
Aerospace Robotics Laboratory
Stanford University

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1 Introduction

This paper describes the Stanford Aerospace Robotics Laboratory's (ARL) entry in the 1997 Association for Unmanned Vehicle Systems' 1997 Aerial Robotics Competition. The objective of the competition is to demonstrate a fully autonomous air vehicle which can:

- Take off from a 15' square at a given location.
- Overfly a 120' by 60' grass field without crossing its boundaries.
- Determine the location of five 55-gallon plastic barrels.
- Identify the type of barrel as either biohazard, radioactive, or picric acid..
- Find and retrieve a ferromagnetic disk, located on one of the barrels.
- Return to the take off location and land.

A complete description of the competition and official rules can be found in [5].

2 The Stanford Aerospace Robotics Laboratory

The ARL has been working for many years on technologies relevant to the Aerial Robotics Competition. These technologies include

- "Object-Based Task-Level Control" - allowing the user of an automated system to command a task, rather than be consumed with the low-level control issues of the task.

- GPS for real-time control.
- Vision for real-time control.
- Path planning in structured and semi-structured environments.
- Real-time “on-line” system identification.

The Stanford Department of Aeronautics and Astronautics has several other research laboratories. Relevant to the competition are the the Aircraft and Flight Research Laboratory, and the Global Positioning System (GPS) Laboratory. The members of the Aircraft and Flight Research Laboratory have decades of experience in design and construction of free-flying model aircraft, and their application to flight research. The Global Positioning System Laboratory at Stanford is the Federal Aviation Administration’s center of excellence for GPS technology.

3 Major System Components

3.1 Aircraft Selection

In order to expedite the development of this robotic system, it was decided to utilize an “off the shelf” air vehicle, as opposed to designing and constructing one in-house. The first, second, and fifth competition objectives listed above eliminated the use of any fixed-wing aircraft. A Schluter Futura model helicopter was selected for its low empty weight, its large payload capacity (over 25 pounds), and its 15 minute endurance. This Futura was extensively modified, particularly its powerplant. A two-horsepower single-cylinder engine was replaced by a five-horsepower dual-cylinder engine intended for use on model airplanes. This required the design and construction of a new engine mounting plate and modification of the power transmission devices.

The Futura is equipped with two stabilization devices, “Hiller paddles” and a mechanical rate gyro. The “Hiller paddles” are used to slow the lateral and longitudinal dynamics. The rate gyro is used in a simple electrical feedback loop to slow the yaw dynamics. Both of these devices are standard equipment for helicopter of this size, and are essential to permit manual flight operation.

3.2 Sensor Selection

Sensors that are able to measure attitude are necessary to stabilize the helicopter system. This was confirmed with flight tests, where an unsuccessful attempt was made to stabilize the helicopter without using attitude information. In order to navigate, a three degree of freedom position sensor is required.

Inertial navigation systems were ruled out due to high mass and high cost. Combinations of magnetic compasses, rate gyros (for stabilization), and ultrasonic sensors were eliminated due to weight constraints.

The competition rules specify that the extent of the playing field and the contestant’s position on the field can be determined a priori. Thus a navigation system which gives only relative position (with respect to a known position on Earth) is sufficient to complete the competition objectives. One such system is the Global Positioning System (GPS). This system has several major advantages, including:

- High azimuth angles of the broadcast signals. This avoids occlusion often present in terrestrially based broadcast navigation systems.
- Availability anywhere in the world.
- Integration of all sensors into a single unit.
- Rate information "at no extra charge".
- No moving parts.
- Measurements with respect to the earth fixed reference frame.
- Relatively small size and power consumption.

The use of GPS as the only sensor for the control of an unstable vehicle poses a significant challenge and advancement in the development of GPS as a sensing technology.

GPS was selected as primary sensor for the stabilization of the Stanford ARL's autonomous helicopter. A magnetic pulse counter was also added to measure engine RPM to be used for better control of the collective/throttle altitude subsystem. Due to the unstructured environment of the competition, however, sensing of the external situation around the helicopter was necessary for intelligent navigation. Two on-board video cameras were added to allow stereo calculations and computer vision processing of the helicopter's environment. Wireless video transmitters were mounted on the helicopter so that live information could be sent to a more powerful ground station for processing. Using a modified version of a Teleos vision [6] system, stereo ranging, object motion tracking, and color image processing techniques are possible.

4 System Design

The primary design consideration during the development of the ARL helicopter was to minimize risk of crashing throughout the program testing. The helicopter's controls are configured to permit easy human intervention, in order to deal with unexpected malfunctions.

The helicopter receives GPS signals utilizing four independent antennas. All four of these signals are demodulated by a single GPS receiver, which produces all the information necessary to determine vehicle attitude, and attitude rates. One of the antennas is also fed into a second GPS receiver, which determines approximately half of the information necessary to determine vehicle position and velocity.

On the ground, a fifth (stationary with respect to the earth) GPS antenna receives signals similar to those received in the air. A ground based GPS receiver demodulates this signal, obtaining the second half of the information required to determine vehicle position.

An on-board 486 computer receives all information from the three GPS receivers via serial communication links. The serial link between the helicopter and the ground is made via a two-way radio link. The 486 computer completes the calculation of the vehicle position, velocity, attitude, and attitude rate, and then determines an appropriate control output. These outputs are then fed through the manual control system to the helicopter's servos.

4.1 Reliability Considerations

In order to permit rapid human intervention, all commands sent to the helicopter's control servos pass through a reliable, independently- powered manual control system. A human pilot can override automatic operation in one of two ways:

- Toggling a switch on the control panel returns the helicopter to complete manual control.
- Disturbing the controls causes the manual control inputs to be algebraically summed to the autonomous control inputs.

A design objective of the ARL helicopter was to permit frequent and rapid modifications to the computational algorithms, without adding significant risks to the survivability of the helicopter. It was decided to utilize a timer card to handle the interface between the manual controller and the 486 computer. The code on this card was developed and carefully tested prior to its use in flight, and has not been modified since this rigorous verification. One QUARTZ-MM timer card, attached to the 486 computer, is used in this interface. It converts pulse-width modulation of eight standard model aircraft channels to digital signals and vice versa.

In order to ensure a reliable power source for the most vital systems, an independent battery is used to power the fuel shut-off servo, the manual controller, and an independent ground-controllable multiplexer. A second battery powers the helicopter's servos. A third battery group consists of two subgroups of 6 and 10 cells, which power the 486 computer, a wireless Ethernet modem, the GPS receiver, cameras and video modems, and all other equipment associated with automatic control. The second battery was added in order to decouple electrical noise from the manual controller, to increase endurance, and to decouple the (critical) servo system from the often modified automatic control electronics. The third group was split to provide unregulated 7.2 and 12 volts to the electrical components.

In compliance with Air Vehicle Attribute 3, a ninth channel of the manual controller is connected directly to the fuel shut off servo. The ground-controllable multiplexer combines the signals produced by the computer with those sent manually, including the signal to shut off the fuel, to present a consistent input to the helicopter servos. Should any system become inoperative, rendering the helicopter a hazard, the ninth channel will allow the helicopter's engine to be shut down.

4.2 GPS Antennas

Maintaining GPS signal integrity during flight operations is critical for successful flight operations. Issues addressed in design of the antenna system were multipath interference, the relative geometry of the antennas, and satellite visibility.

One of the major drawbacks of GPS signals is the line of sight propagation characteristics. In order for a signal to be received by a GPS antenna, an unoccluded line of sight (roughly speaking) must exist between each antenna and the various satellites broadcasting relevant signals.

The initial GPS attitude determination algorithm invented by Cohen [2] required that the four antennas be mounted in a non-coplanar fashion, and that the antennas have unoccluded lines of sight to the identical constellation of satellites. In an aircraft application, these conditions are maintained by by mounting the antennas high on top of the fuselage, wings and tail.

With a helicopter, it is difficult to mount the antennas above the main rotor. Work by Conway [3] extended attitude algorithms to include coplanar configurations, and configurations where some satellites are occluded when viewed from individual antenna.

As a consequence of this extension, the ARL helicopter is able to mount the four antennas nearly in a plane, just below the main rotor disk. This provides nearly clear view of the sky by all antennas, with only a small occlusion by the main rotor mast. Since the rotor blades are constructed of wood, have a small cross section (6 cm) when compared to the wavelength being considered (19.2 cm), and are spinning rapidly, there is little interference as a result of the antennas being below the rotor disk. The small amounts of interference induced are eliminated by the phase lock loops in the GPS receivers. One antenna (the master antenna) is mounted on the tail boom, one is mounted on the fuselage forward of the main rotor mast, and two antennae are mounted to the plate holding the electronics.

4.3 GPS Receivers

At the time of selection, few receivers were available which were capable of computing aircraft attitude as well as position, with relatively low total mass. The Trimble TANS Quadrex was selected as the best candidate in this regard. In order to maintain compatibility with this system, the Trimble 16248-50 antennas were selected. These antennas have crystal RF filters which provide good frequency domain side-lobe attenuation, while providing approximately 50 dB gain from built in amplifiers. These antennas are somewhat heavier than other available antennas; however, the superior in-band gain and out-of-band attenuation of these antennas justified the weight penalty.

An RF splitter allows the tail boom's antenna (the master antenna) to be distributed to both the attitude GPS receiver and the position GPS receiver. The receivers are electrically identical but have significantly different software operating on their local microprocessors.

The interface between each GPS receiver and the 486 computer is made through 38400 baud serial communication links. Configuration commands are sent to the GPS receivers upon system start up, after which position and attitude information is made available to the 486 computer ten times per second. Information from the ground station is also received by serial link, in this case a 9600 baud, wireless 461 MHz modem with an RS-232 interface.

4.4 Main Computer

Some processing is performed by the 486 computer in order to resolve the GPS information into earth fixed coordinates (for position), and locally level (for attitude). These calculations result in vehicle position, attitude, velocity and attitude rate ten times per second. Position is accurate (RMS values) to approximately 3 centimeters in all three axes (depending on satellite geometry), and attitude to about one degree (which is a function of antenna geometry). The velocity is accurate to about 10 centimeters per second, and attitude rate to about 1 degree per second.

Once the 486 computer has calculated both position and attitude, an appropriate control signal is determined and sent to the timer card for conversion to pulse-width modulation signals. These signals are combined in the on-board multiplexer with any manual inputs before being sent to the helicopter servos.

All information received by the 486, including information received from the GPS receivers and all information sent to the manual controller is logged throughout each flight. The data is sent down to the ground station via wireless Ethernet and stored there on hard disk. Any measurement made during the flight can be reproduced in the lab for system debugging, system identification, and control law development.

5 Control Laws

One control law has been developed - a robust hover control. The ARL's approach to control development has been largely experimental. No cross couplings between the yaw, vertical, lateral, or longitudinal dynamics have been modeled.

The yaw dynamics are controlled using only heading information. The heading rate information is ignored as the existing gyroscope provides negative feedback of yaw rate at a higher update with less delay than possible with GPS yaw rate information.

Altitude is controlled by feeding back both altitude and altitude rate (PD feedback).

The lateral and longitudinal dynamics require a more complex control strategy. Design was based on successive loop closure, where an inner "attitude loop" was first closed, followed by closure of outer "position" loops.

The first level of feedback is provided by the Hiller paddles, inherent in the helicopter's basic design. Since the paddles provide attitude rate feedback, the GPS attitude rate signals can be ignored. The second loop closure feeds back roll and pitch information. The outer loops feed back vehicle position and velocity.

6 Navigation

The competition objectives can be achieved with four types of trajectories - search, travel, retrieval, and inspection. Commands to switch trajectory modes will be made autonomously.

Due to the structured nature of the competition field, the GPS coordinates of the initial search trajectory is known a priori. This search will be conducted in a back-and-forth, lawn mower-like pattern. The search will end once the entire field has been surveyed or all five barrels have been definitively located.

As a result of the relatively short trajectory lengths, travel can be completed with a quasi-static control system about hover. The helicopter can be made to follow trajectories by quantizing the trajectory and commanding the helicopter to hover at each successive point along the path.

Once the ferromagnetic disk has been found (see below), the retrieval trajectory will yield control to the computer vision system. As explained below, the vision algorithm produces the relative location of the disk. The retrieval trajectory will ensure that the helicopter does not exceed position or velocity limits during disk acquisition.

If conditions at the contest site require that pictures of the barrel emblems be taken from a different altitude than that used for normal flight, the inspection procedure will command the helicopter to hover over a barrel and slowly descend or ascend to this new altitude. After a sufficient amount of time to insure that a quality image has been taken, the helicopter will slowly resume its original altitude.

7 Drum Identification

There is some known information about the drums, including:

- There are five 55-gallon black plastic drums.
- They are within the boundaries of the field, and are no closer than three meters to any arena boundary.
- The drums will appear to be either fully exposed or partially buried, either standing up or on their sides.
- The label will be visible from directly above.
- One of the barrels will have a ferromagnetic disk resting on it.

Two on-board video cameras pointing straight down provide stereo range information which is used to find these drums. Because the field is effectively flat, any large increase in the local ground level of the helicopter can be assumed to be a barrel. A wide camera angle provides a large stereo field, allowing filtering processes to find barrels not only directly beneath the helicopter but also to its front and sides. When coupled with the accurate GPS knowledge of the location of the helicopter when each image was taken, a complete map of the field can be constructed that locates the barrels to within one meter. Overlapping video images serve to eliminate noise and faulty readings by looking at each point from several different angles.

8 Disk Detection and Retrieval System

Because the exact location of the ferromagnetic disk is not known, an adaptive system was developed to pick out the disk from its surroundings and retrieve it. The video image from one of the cameras is analyzed using a variety of color processes. The first algorithm breaks down the image into its red, blue, and intensity components. Because the disk is the object with the highest red component on the competition field, only the red information is retained. A Gaussian filter then suppresses almost all the noise resulting from the grass and the wireless transmission. Finally, a threshold filter produces a final black-and-white image that is entirely black except for the disk. The centroid of the disk in the camera field of view can then be easily ascertained.

Using the accurate position and attitude information provided by GPS, the location of the disk is computed and then compared to the determined locations of the barrels. If a match is made, control of helicopter position is given to the vision system, which attempts to place the disk in the center of its image (the approximate location of the disk retriever magnets.) The retriever, made up of four permanent magnets mounted on a wooden frame, needs to be within one inch of the disk to attract and grab it. Once the disk is secured, the helicopter proceeds to the starting area for landing.

9 Conclusions

This research is a continuation of previous work which demonstrated the first fully autonomous control of an unstable air vehicle using GPS as the only sensor. The main advancement of this work is the incorporation of real-time vision into the planning of the vehicle path and the use of video within the position-controlling loop to locate and interact with an object. In the future, the ARL helicopter will continue to serve as a testbed for integrating GPS with other sensing and control technologies. As the mass, size, and power consumption of GPS receivers is reduced, it is expected that GPS will become an important sensing technology for future autonomous systems.

References

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