A Contestant in the 1995 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 1995 Association for Unmanned Vehicle Systems' 1995 Aerial Robotics Competition. The objective of the competition is to demonstrate a fully autonomous air vehicle which can:

- Take off from a specified location.
- Fly to a second location.
- Pick up a small ferromagnetic disk.
- Place the disk at a third specified location.
- Return to the original location and land.
- Repeat the transfer for a total of six disks.

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 competition rules specify that

- the vehicle must take off and land within a 15' square.
- the vehicle must not leave a 120' by 60' arena at any time during the competition.
- the vehicle must pick up a small ferromagnetic object.

These requirements eliminate the use of any fixed wing aircraft. An Excel 60 Pro model helicopter was selected for its low empty weight, its large payload (approximately 12 pounds), and its 15 minute endurance.

The Excel 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), ultrasonic sensors, and vision were eliminated due to weight constraints.

The competition rules specify that all waypoint locations necessary to complete the tasks can be determined a priori. Thus a navigation system which gives only absolute position (with respect to the 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 are with respect to the earth fixed reference frame.
- Size and power consumption are relatively small.

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 the only additional sensor for the stabilization and navigation of the Stanford ARL's autonomous helicopter.

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 one way wireless 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.

Figure 1: Photograph of the helicopter

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 independent microprocessors to handle the interface between the manual controller and the 486 computer. The code on these microprocessors was developed and carefully tested prior to any flight testing, and has been not modified since this rigorous verification.

Two 68HC11 microprocessors are used in this interface. They provide analog to digital and digital to analog conversion of eight standard model aircraft channels.

In order to ensure a reliable power source, an independent battery is used to power the 68HC11s and the manual controller. A second battery powers the 486 computer, and all equipment associated with automatic control. A third battery is used to power the helicopter's servos. The third 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.

In compliance with competition rule 11, a ninth channel of the manual controller is connected directly to a fuel shut off servo. This allows the helicopter's engine to be shut down should the microcontrollers, or any other system become inoperative, rendering the helicopter a hazard.

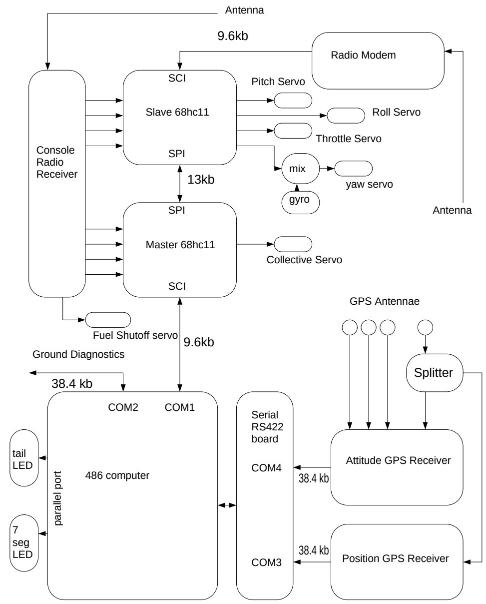

Figure 2: Schematic diagram of helicopter's electronics

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 antenna occlusion, 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 the 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 antennas are mounted on aluminum tubing to the left and right of the main rotor mast.

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 axis (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 68HC11 microprocessor. The 68HC11s command the helicopter's servos in turn.

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 stored in computer memory, and upon the termination of a flight, downloaded to a laptop computer for later analysis. 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,

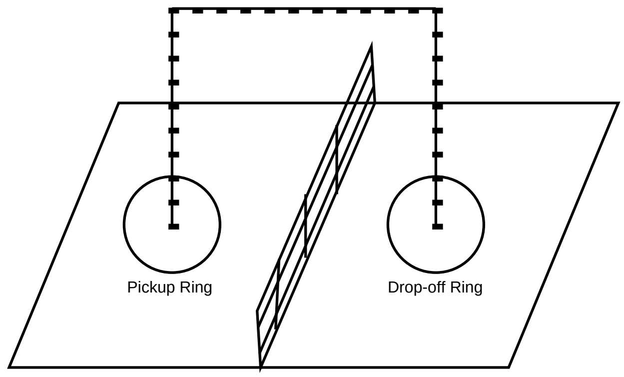

Figure 3: Sketch of the contest course

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 two types of trajectories - travel and search. Due to the structured nature of the competition, the GPS coordinates of all trajectories are known a priori.

Travel patterns like the one illustrated below will be employed. The search pattern will be a spiral centered over the pick-up ring.

As a result of the short trajectory lengths, the competition's tasks 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 (see figure 3).

7 Disk Retrieval System

An electromagnet suspended from the bottom of the helicopter has sufficient force to capture and carry a single contest disk. As illustrated, the magnet housing will be lined with a contact switch. The magnet is suspended inside the housing by weak springs. When the outside

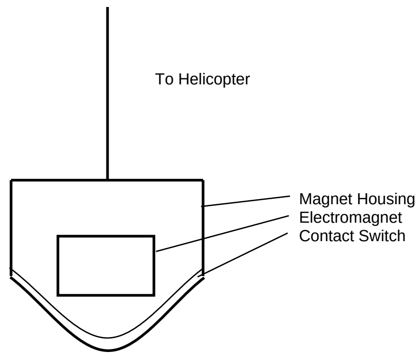

Figure 4: Magnet and housing

of the housing contacts a disk the magnetic force presses the magnet against the contact switch. This signals the helicopter to begin a travel pattern to the drop-off zone.

The simplicity of this disk retrieval mechanism is possible due to the accuracy of the GPS navigation system.

8 Conclusions

This research demonstrates the first fully autonomous control of an unstable air vehicle using GPS as the only sensor. 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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