Merged Vision and GPS Control of a Semi-Autonomous, Small Helicopter

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1 Introduction:

This final report documents the activities performed on NASA Grant #NCC 2-967 during the period 1 April 1996 through 30 September 1997.

2 Attachments:

The work performed in this program and relevant background material are documented in the three papers which are attached to this document.

Carrier Phase GPS and Computer Vision for Control of an Autonomous Helicopter

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BIOGRAPHY

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ABSTRACT

The Stanford University Aerospace Robotics Lab (ARL) has developed a fully autonomous hoverable unmanned air vehicle (HUAV) which uses differential carrier phase GPS (DCPGPS) as the only sensor for both control and navigation. Precision autonomous operation in a structured environment has been demonstrated at the 1995 Aerial Robotics Competition, where the ARL helicopter demonstrated retrieval and transportation of 4 oz objects around a small field.

The ARL has experimentally demonstrated the advantages of combining differential carrier phase GPS for high-bandwidth vehicle control with computer vision to enable the operation of an unmanned, autonomous helicopter in a dynamic unstructured environment. DCPGPS techniques and conventional control methods are used to close a short-period inner loop, stabilizing the helicopter's dynamics and providing a global navigation system. An outer loop is closed using feedback from the vision system to determine the precise location of the ground and other objects in the environment.

This paper examines the combination of differential carrier phase GPS and computer vision techniques to enable an autonomous vehicle to operate in unstructured environments. Experimental results are presented and future work is discussed.

INTRODUCTION

Helicopters have found broad use in many diverse applications, including search and rescue, fire fighting, fine-scale terrain mapping, and agricultural operations. The operation costs of manned helicopters are quite high. It is expected that the operational use of unmanned helicopters could greatly reduce the cost of many of these tasks.

The remote piloting of hoverable unmanned air vehicles is a very difficult task, requiring great operator skill and attention as well as a high-bandwidth, low-delay data link between the pilot and vehicle. Furthermore, most applications require that the pilot maintain visual contact with the HUAV at all times. These requirements limit the applications of HUAVs and prohibit large scale deployment of these systems.

Many airborne applications require operation in dynamic, unstructured environments. Imaging is the most natural method of obtaining information about an unknown environment, and has broad applications in military reconnaissance, agricultural inspection, and mapping. Imaging plays a critical role in the operation of HUAVs, providing information to ground based operators and enabling operation in an unstructured, dynamic environment.

The Stanford Aerospace Robotics Laboratory has been working towards developing prototype HUAV systems which address these issues. This paper examines the combination of differential carrier phase GPS and computer vision techniques to enable an autonomous vehicle to operate in unstructured environments.

EXPERIMENTAL SYSTEM

The HUMMINGBIRD autonomous helicopter was originally constructed for research in the control of an unstable flying machine using Global Positioning System measurements as the only sensor. The hardware system, shown in Figure 1, has now been extended to deal with the combination of GPS measurements with vision system measurements. The basic airframe is a

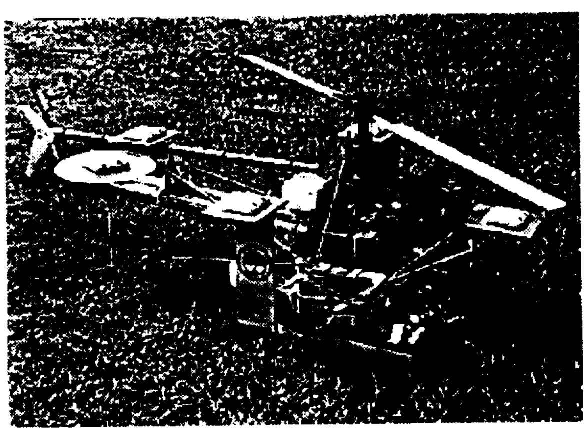

Figure 1: **Current configuration of the Stanford HUMMINGBIRD.**

heavily modified Schluter Futura hobbyist model helicopter. The airframe is capable of carrying twenty-five pounds of experimental equipment. Nominal gross takeoff weight is forty-six pounds.

A plywood plate, clamped to the bottom of the helicopter landing gear, supports the onboard electronics and their power supplies. Four GPS antennae are mounted on the helicopter—the port and starboard antennae are mounted on wooden towers at the extreme aft corners of the plywood plate, the nose antenna is supported by small aluminum tubes, and the tail antenna is mounted directly onto the helicopter tail boom. The electronics consist of a 486-based computer, a wireless ethernet modem, an RS232 radio modem receiver, two GPS receivers (Trimble TANS-Vectors), two color cameras, and one microwave wireless video transmitter. All electronics are shock mounted on closed-cell foam mounts.

Critical to the safe flight testing of the helicopter is a fully manual flight mode. An independently powered radio receiver, with computer override capability, can be used to take manual control of the helicopter at any time. Flight testing is always performed under the direct supervision of a skilled RC pilot.

Ground station equipment consists of a dual-processor Pentium computer (coupled to the wireless ethernet network), a single antenna GPS receiver, an RS232 radio modem transmitter, and a microwave wireless video receiver. The GPS receiver on the ground receives signals from up to six satellites. Carrier phase measurements are uplinked to the helicopter directly through the single direction dedicated RS232 link. No GPS processing is performed on the ground.

The helicopter receives GPS signals from three sources—the ground station (via the RS232 link), from a local "position" GPS receiver which produces raw carrier phase signals from one antenna, and from a local "attitude" GPS receiver which produces differential measurements between a master antenna and each of three slave antennae. The helicopter's on board 486 then applies algorithms as described in Conway [1] to determine the vehicle attitude, attitude rate, position, and velocity. No real-time computation using the video information is currently done onboard the helicopter.

Before the helicopter begins flight, the planned trajectory is determined and uploaded to the onboard computer. During flight, the ground station computer receives and stores video images marked with the corresponding GPS-determined helicopter position and attitude. After landing, the ground station downloads all data taken by the onboard computer during flight and begins a post-flight analysis. The video data is then tested for validity and the final processing is performed.

The wireless ethernet communciation between the helicopter and the ground-based Pentium system allows the helicopter to utilize these off-vehicle computer resources. In the near future, it is envisioned that real-time vision algorithms could be applied to direct the control of the helicopter at a high level.

DIFFERENTIAL CARRIER PHASE GPS

Key to the success of the HUMMINGBIRD platform has been the use of GPS as a sensing technology for closed loop control of an unstable air vehicle. GPS attitude and position sensing has several distinct advantages, including:

- no moving parts
- very little calibration required
- drift-free in both position and attitude
- future promise of reduced size, power consumption and increased reliability associated with electronic parts.

A major achievement of this project is the fully autonomous flight of a helicopter using GPS as the *only* sensor for both attitude and position stabilization and control. A 10 Hz update rate for all 6 DOF is sufficient to ensure stable flight of our test vehicle. No other rate gyros, compasses, et cetera were used. For a complete description of the algorithms used in this work see Conway [1].

The ability to fly pre-programmed paths was demonstrated in the 1995 International Aerial Robotics Competition, where our helicopter was the first—and to date only—air vehicle to pick up and move a small ferromagnetic disk fully autonomously. The trajectory flown is shown in Figure 2.

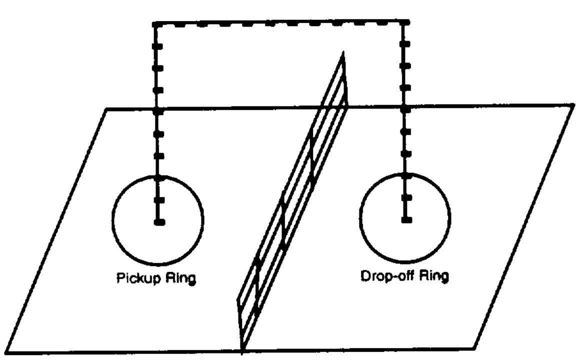

Figure 2: **Competition flight trajectory**

The helicopter autonomously retrieved a disk in the Pickup Ring, crossed the 1-m barrier at an altitude of six meters, and delivered the disk to the Drop-off Ring.

Further work has begun to extend the GPS sensing system to become an integral part of a computer vision system. The mixing of the two technologies seems appropriate since GPS provides an excellent sensor for position, while vision provides a large amount of local information about the surrounding environment but provides little information about the global position of various objects.

GPS-AUGMENTED VISION

As previously stated, DCPGPS techniques and conventional control methods are used to close an inner loop, stabilizing the helicopter's dynamics and providing a global navigation system. An outer loop is closed using feedback from the vision system to determine the precise location of the ground and other objects in the environment.

The precision available using DCPGPS is useful when it is coupled with traditional computer vision techniques. Many such techniques exist for localizing objects within a scene relative to the camera. If one can directly measure the position and orientation of a camera, one can then determine the location of sensed objects in global coordinates.

In the first set of experiments performed using the HUMMINGBIRD helicopter, the UAV was maneuvered over a grass field upon which many distinctive objects were placed. Assuming the field is level, and given the camera's height above the ground (measured with GPS), a single image is sufficient to determine the location of a target in global coordinates.

It is possible to extend this technique to provide a crude "mosaicking" capability by capturing successive images, each with corresponding DCPGPS position and attitude. By appropriate image transformations, a large image can be constructed from many, possibly overlapping, images.

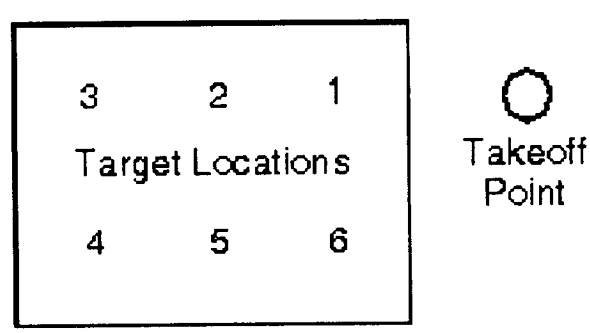

Figure 3: **Test Field**

Figure 3 shows a typical test setup for the object location algorithm. The test field measures 15 meters by 9 meters, with a known take-off point five meters outside the surveyed area. Targets, which were black plastic barrels or 4-inch metal disks painted orange, were placed at presurveyed target locations within the field.

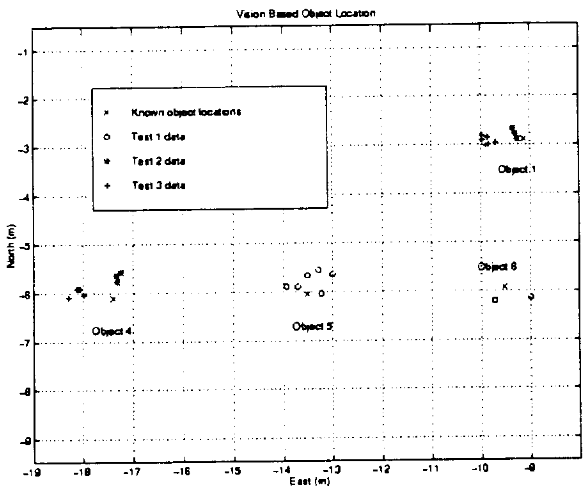

Figure 4: **GPS-Augmented Vision - Experimental Results**

Figure 4 presents the results from three test flights over the field. In each test, objects were placed on two of the six possible target locations, and HUMMINGBIRD then proceeded to survey the disk locations from an altitude of about three meters. Each data point corresponds to a single photograph of the field.

Table 1: **Vision Based Object Location**

Test Number	*Target Number*	*Position Error (m)*	
		Mean	*Standard Deviation*
1	5	0.27	0.39
1	6	0.31	0.52
2	1	0.21	0.12
2	4	0.46	0.11
3	1	0.75	0.13
3	4	0.73	0.14

As Table 1 shows, our accuracy at locating the disks is quite good. The mean location is generally within 0.50 meters, and the standard deviation usually under 15 centimeters. The data clearly indicates that the greatest error sources are constant offsets, which will be eliminated in the future with better algorithms and improved equipment calibration. Closer synchronization between the GPS attitude solutions and the camera images should also help to reduce the small amount of data scatter present.

FUTURE RESEARCH

The ARL is currently working on several additional projects to further implement vision with the HUMMINGBIRD helicopter. These include stereo imaging, motion based stereo, servoing off of camera inputs, and mobile object tracking and following.

In many computer vision applications, target objects are not located at known distances from the camera. In these situations a single image is not sufficient to determine the location of the object. HUMMINGBIRD employs a pair of stereo cameras to enable it to determine the range to target objects. This will help facilitate the retrieval of objects from on top of obstacles, or when the altitude of the target object is not known beforehand.

Conventional stereo vision is only effective out to a limited range determined by the baseline distance between cameras. Because HUMMINGBIRD is capable of determining the locations and pointing angles of its onboard cameras quite accurately using GPS, it is able to perform motion based, or long-baseline, stereo. This involves taking two images from different locations and then triangulating to determine the global location of the object. Eventually, this could provide the capability to perform accurate stereo mapping of objects kilometers away.

In the future, HUMMINGBIRD will be able to servo off of its vision system by working to keep a target object centered in its field of view and at a constant range. This will greatly facilitate object retrieval or manipulation and allow for greater resolution when performing aerial surveying tasks. HUMMINGBIRD will also be able to track and follow moving objects, improving its ability to work in dynamic environments.

References

[1] Andrew Conway. *Autonomous Control of an Unstable Helicopter Using Carrier Phase GPS Only.* PhD thesis, Stanford University, 1994.

[2] K M Black, R G Martinez, W Page, and J Fitzer. Evolution and design of the 1993 university of texas at arlington autonomous aerial vehicle. In *Proceedings*, June 1993.

[3] Clark Emerson Cohen. *Attitude Determination Using GPS.* PhD thesis, Stanford University, Department of Aeronautics and Astronautics, Stanford, CA 94305, December 1992.

[4] P. Y. C. Hwang. Kinematic GPS: resolving integer ambiguities on the fly. In *IEEE PLANS*, pages 579–586, March 1990.

[5] M. Anthony Lewis, Andrew H Fagg, and George A Bekey. The USC autonomous flying vehicle: An experiment on real-time behavior control. In *IEEE 1993 International Converence on Robotics and Automation*, pages 422–429, May 1993.

[6] Paul Y Montgomery, Hirohiko Uematsu, and Bradford W Parkinson. Analysis of angular velocity determination using GPS. Sep 1994. Salt Lake City.

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

[1] K M Black, R G Martinez, W Page, and J Fitzer. Evolution and design of the 1993 university of texas at arlington autonomous aerial vehicle. In *Proceedings*, June 1993.

[2] Clark E. Cohen. *Attitude determination using GPS : development of an solid-state guidance, navigation, and control sensor for air and space vehicles based on the Global Positioning System.* PhD thesis, Stanford Univ., 1992.

[3] Andrew R. Conway. *Autonomous Control of an Unstable Model Helicopter Using Carrier Phase GPS Only.* PhD thesis, Stanford Univ., 1995.

[4] M. Anthony Lewis, Andrew H Fagg, and George A Bekey. The USC autonomous flying vehicle: An experiment on real-time behavior control. In *IEEE 1993 International Converence on Robotics and Automation*, pages 422–429, May 1993.

[5] Robert C. Michelson. Official competition rules for the 1995 international aerial robotics competition. Technical report, Association for Unmanned Vehicle Systems, 1994.

[6] Teleos Research. AVP-100 Documentation. 2464 Latham Street, Suite 101, Mountain View, California, 1996.

Combined CDGPS and Vision-Based Control of a Small Autonomous Helicopter

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1 Abstract

Recent results in merging Carrier-Phase Differential GPS (CDGPS) sensing with vision-based sensing to control a small autonomous helicopter are presented. The helicopter is a heavily modified yet low-cost kit helicopter that includes a full on-board CDGPS system, stereo video cameras, and sufficient computational capabilities to perform fully autonomous missions. The demonstration mission presented here is a search of a field to find an object followed by the tracking of that object (using the vision system) as it moves around the field. The helicopter system is described and the performance in accomplishing the task is presented.

2 Introduction

The control of autonomous unmanned aerial vehicles (UAVs) has become a topic of considerable interest in recent years. The availability of these vehicles will enable tasks to be accomplished with greatly reduced levels of pilot workload (e.g. when teleoperation is used) including complete autonomy in the execution of a mission. Possible applications include remote surveying and aerial mapping, power line inspection, crop dusting, fire fighting, and movie filming. In order to accomplish these missions, however, progress needs to be made in the areas of navigation and position control, attitude sensing and stabilization, sensing of the surrounding environment, and autonomous task execution strategies.

Since 1995 the Stanford Aerospace Robotics Laboratory (ARL) has been operating a small, fully autonomous helicopter, HUMMINGBIRD, as part of a program of basic research to develop these basic capabilities for autonomous operation of UAVs. Previous work in this program focused on demonstrating the feasibility of using Carrier-Phase Differential GPS (CDGPS) as a sensor for attitude and position control as well as for navigation. Using this system alone (i.e. as the only sensor on board the helicopter), an autonomous control system was implemented that stabilized and controlled the helicopter with performance matching or exceeding that of an expert human pilot. Precision flight was experimentally demonstrated by performing autonomous hover, automatic retrieval of a ferromagnetic disk using a magnet-tether manipulator, and autonomous landing tasks [1], [2].

While significant, the autonomous capabilities of the helicopter demonstrated previously were limited to missions that could be expressed entirely in a GPS frame. That is, commands to fly trajectories, retrieve objects, or land were all possible only if the location of the paths, points or objects could be expressed as GPS coordinates (known apriori). Many tasks of current and future interest require, however, that the helicopter be able to sense the presence of objects-of-interest in the environment whose GPS coordinates are unknown. An obvious example is a search-task in which the objective is to find and then track or retrieve an object. Accomplishing these types of tasks requires that the helicopter also be equipped with sensing systems that can detect the presence of the objects-of-interest.

Described below are the results of current research activities in the Stanford ARL that have addressed

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these issues. This research has involved the development of a small autonomous helicopter, HUMMINGBIRD, and the demonstration of its use in performing tasks that combine both vision and GPS based control modes.

3 Related Research

Several other researchers have explored the development of autonomous helicopters. The earliest successful work was in the early 1990's by Michio Sugeno at the Tokyo Institute of Technology [3] using a Yamaha R-50 helicopter. The TIT helicopter used gyroscopes, accelerometers, and a laser altimeter as sensors and implemented a fuzzy logic controller. The helicopter was able to use image guidance to find a landing spot and land on the stationary target. More recent work includes that of Stanford, MIT and CMU all of whom have won the Association for Unmanned Vehicle Systems International aerial robotics competition. Stanford won in 1995 using a precursor to the HUMMINGBIRD helicopter described in this paper that flew a predetermined trajectory and retrieved an object successfully from the ground. This helicopter demonstrated the feasibility of using CDGPS as the only sensor for both attitude stabilization and navigation. In 1996, a team from MIT, Boston University, and Draper Labs [4] won with a helicopter that used an inertial navigation unit for attitude and Carrier-Phase Differential GPS (CDGPS) for position. This MIT helicopter carried a camera onboard and was able to map the location of objects on the ground. Finally, Carnegie Mellon University won in 1997 flying a Yamaha R-50 [5] that mapped and identified ground targets. In each of these cases, the ground target was stationary throughout the helicopter flight.

4 Helicopter Testbed

The HUMMINGBIRD helicopter used for these experiments is a heavily modified Schluter Futura model helicopter (Figure 1). It was selected for its low empty weight, its large payload capacity (over 25 pounds), and its 15 minute endurance. The modifications included stiffening of the structure to accommodate the mounting of the video and electronic components, and the replacement of its standard two-horsepower single cylinder engine 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 helicopters of this size, and are essential to permit manual flight operation.

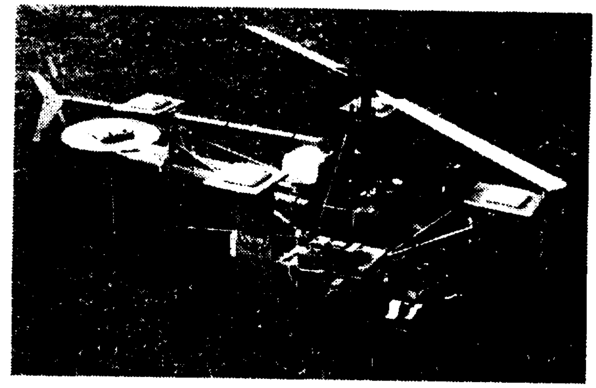

Figure 1: HUMMINGBIRD Helicopter

The computing and sensing components onboard the HUMMINGBIRD vehicle include two GPS receivers, 4 GPS antennae, two video cameras, a wireless video link, a wireless ethernet link, a 9600 baud com link, a 486 class computer and two HC11 computers. The supporting ground station includes a GPS antenna and receiver and a dual-Pentium computer (for the vision data processing).

5 GPS Sensing System

The HUMMINGBIRD helicopter uses the Global Positioning System (GPS) as its primary sensor, both for navigation and stabilization. This is a satellite-based navigation system which offers absolute positioning in a world-fixed reference frame anywhere on the globe. GPS offers many additional advantages for an airborne navigation system, including (1) integration of all sensors into a single unit; (2) drift free rate information; (3) no moving parts; and (4) relatively small size and power consumption.

The GPS technology employed by the ARL is called Carrier-Phase Differential GPS (CDGPS) since it uses the carrier signal rather than the GPS code to compute position. This carrier wave has a wavelength of 19 cm and can be tracked very precisely. The HUMMINGBIRD helicopter employs an algorithm which examines the raw phase measurements taken at two non-collocated receivers and computes the relative (differential) position between them in a world-fixed reference frame to an accuracy of 2-3 cm.

The GPS receivers used on HUMMINGBIRD are Trimble TANS Quadrex units. These receivers are well suited to attitude determination, since they can take in multiplexed signals from up to four antennas. In addition the TANS outputs raw phase measurements at 10 Hz, which is fast enough for the stabilization of the helicopter dynamics.

5.1 Attitude Sensing

The GPS attitude sensor consists of a single on-board GPS receiver and an array of four active GPS antennas. These antennas are arrayed in an upward-facing diamond configuration just below the main rotor disk: one (master) antenna mounted on the tail boom, one mounted on the fuselage forward of the main rotor mast, and two lateral antennas mounted on towers attached to the electronics payload plate. This placement is intended to minimize occlusion of the satellites by the helicopter airframe. Since the rotor blades are constructed of wood, have a small cross section (6 cm) when compared to the wavelength being considered (19 cm), and are spinning rapidly, there is little interference as a result of the antennas being below the rotor disk.

GPS signals from the four antennas are multiplexed into the receiver. The receiver takes carrier phase measurements of these signals and outputs these results at 10 Hz to the on-board computer through a 38400 baud serial communications link. The computer then computes the difference in position in world-fixed coordinates between all four antennas on the helicopter. Since CDGPS difference measurements are accurate to 2-3 cm, and the baselines between antennas are about 1 meter, these algorithms can compute the helicopter attitude to an accuracy of 1-2 degrees. Attitude rate measurements are accurate to about 1 degree per second.

5.2 Position Sensing

The GPS position sensor consists of two parts. The on-board section includes a second GPS receiver and the master antenna. This receiver computes GPS phase measurements and sends them directly to the on-board computer. The second section is the GPS ground reference station, which is composed of a fifth GPS antenna located on the ground (usually near the take-off point) and a third GPS receiver. GPS carrier-phase measurements and timing information is sent from this GPS ground station to the helicopter computer at 10 Hz via a 9600 baud wireless 461 MHz modem with an RS-232 interface. The helicopter then computes the differential position between the ground station antenna and the master antenna on the tail boom, giving a relative position measurement accurate to 2-3 cm. Velocity measurements are accurate to better than 10 centimeters per second.

In order to make this position sensor robust to failures, several steps were taken. First, the differential GPS ground reference station is independent of the computer performing the vision processing, so a computer failure on the ground will not affect the GPS navigation. Second, all processing of GPS data is done on-board the helicopter, minimizing the need to transfer data over wireless links. Third, the position and attitude algorithms are independent of each other. If the GPS ground station and the helicopter were to lose contact, the helicopter would still be attitude stabilized and is thus easily recoverable.

6 Vision System

The HUMMINGBIRD vision system consists of a pair of downward pointing Sony XC-999 color cameras mounted on the front of the helicopter. Due to the weight constraints of the vehicle, the vision processing is done on an off-board ground station computer. Two wireless video transmitter units are used to send the color images from the helicopter to a dual Pentium computer. After processing, the information is telemetered back to the on-board computer via a wireless Ethernet link.

The vision processing is performed by a Teleos Corp. (now a division of Autodesk) Advanced Vision Platform (AVP) system. This system is capable of performing YUV color segmentation and signum-of-Laplacian-of-Gaussian (SLoG) filtering and correlation at 30 Hz. The current system uses the color segmentation ability of AVP to identify objects. The segmented UV images correspond closely to red and blue color components and test objects of these colors are used in order to simplify processing. The color segmented images are thresholded, and then objects are defined (as regions of a specified size). The optimal threshold values vary due to the current lighting conditions. They are selected by a human operator, not the vision system, and can be adjusted in real time. The AVP system has been used by a related project to perform texture-based mosaicking and object tracking and their algorithms are being brought into this project [6].

The color based object identification is performed on both the left and right camera images. The correspondence problem is solved by using objects of unique color. By only looking at a single red and a single blue object, it is straightforward to locate the projection of each object in the two different images. With the co-

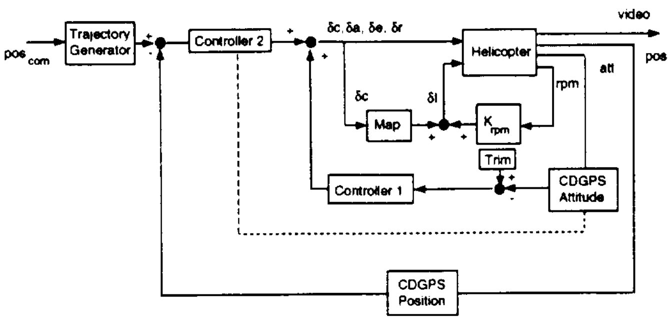

Figure 2: Inner Loop

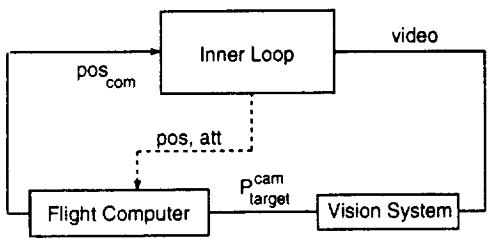

Figure 3: Outer Loop

ordinates of the object in both images, basic stereo triangulation is used to calculate the location of the object relative to the fixed camera reference frame. This information is then sent through the Ethernet link to the on-board flight computer, which transforms the object location into the proper helicopter reference frame. This system has an accuracy of approximately 5 cm in range and 2 cm in location at a range of 2 m. The object tracking algorithm runs at 10 Hz.

7 Control Logic

Two control loops comprise the control system for the HUMMINGBIRD helicopter (Figures 2 and 3) A high-bandwidth inner loop provides attitude stabilization and vehicle position control based entirely on the CDGPS system. A low-bandwidth outer loop provides position commands to the inner loop based on the vision data. In its current form, the merger of these two loops is accomplished by converting the locations of objects-of-interest observed by the vision system (i.e. relative to the helicopter) into global GPS coordinates that can be processed by the inner loop.

The function of "Controller 1" indicated in Figure 2 is to regulate the helicopter attitude. It generates effective aileron, elevator and rudder commands in response to errors in the vehicle trim condition. That is

$$\begin{bmatrix} \delta_a \\ \delta_e \\ \delta_r \end{bmatrix} = [K_1(s)] \begin{bmatrix} \phi_o - \phi \\ \theta_o - \theta \\ \psi_o - \psi \end{bmatrix}$$

The function of "Controller 2" indicated in Figure 2 is to regulate the helicopter position. It generates effective aileron, elevator, rudder and collective commands in response to errors in where the vehicle is compared with the position commands generated by the Trajectory Generator. That is

$$\begin{bmatrix} \delta_a \\ \delta_e \\ \delta_r \\ \delta_c \end{bmatrix} = [K_2(s)] \begin{bmatrix} x_o - x \\ y_o - y \\ z_o - z \end{bmatrix}$$

where x, y and z are expressed in body coordinates. In these controllers, $K_1(s)$ and $K_2(s)$ represent a matrix of controller transfer functions. (Note that rate information is provided by the CDGPS system.)

The Trajectory Generator shown in Figure 2 creates position time history commands for the inner loop to track. It has two basic modes of operation: a GPS-based mode and a Vision-based mode. In GPS-based mode, the Trajectory Generator's function is to create a time history of (x, y, z) the vehicle is expected to fly. Typically, this has been done by preprogramming a series of way-points connected in time by constant velocity trajectories (other trajectories, e.g. optimal, could be implemented as well). An example application of this mode is the programming of a predefined search pattern in GPS coordinates. The second, Vision-based, mode is used when objects or locations are being tracked using the vision system. In this mode, the output of the Trajectory Generator is simply the error signal generated by the "Vision System" shown in the Outer Loop block diagram (Figure 3). In the current implementation of this mode (also shown in Figure 3), the relative target position error is converted into GPS coordinates by the Flight Computer. This allows the feedback loops active in the Inner Loop Control to be the same for both modes of operation.

8 Demonstration Task

In order to demonstrate the ability of the HUMMINGBIRD helicopter to perform a task that involved the integration of CDGPS-based control and vision-based control, the task identified in Figure 4 was performed. It consists of three main segments. In the first, the vehicle is commanded to fly a "lawnmower" pattern over the field as it searches for the target vehicle. This is indicated as the dashed line in the figure between

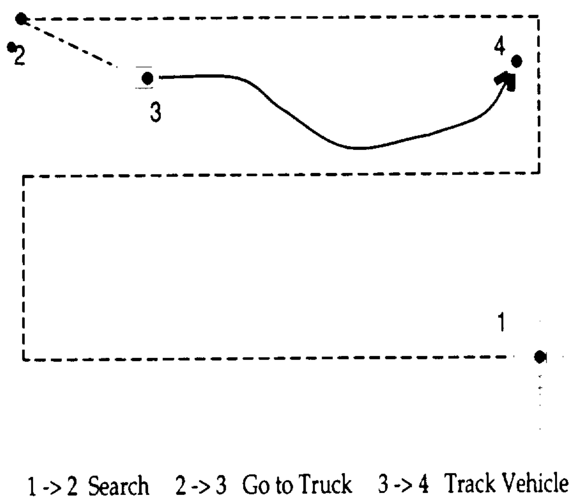

Figure 4: The Demonstration Task

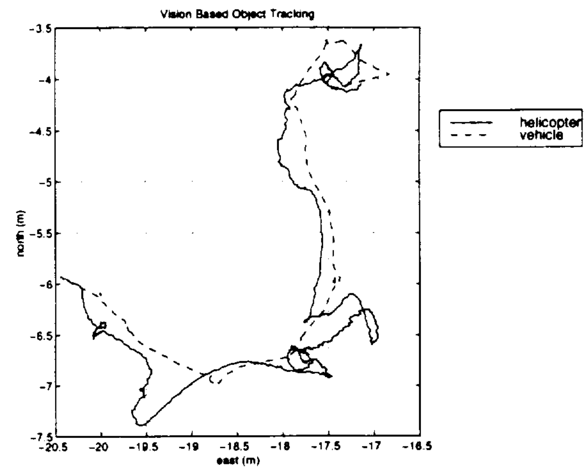

Figure 5: **Groundtrack Performance of Task**

points 1 and 2. During this first phase of the flight, the vision system is on but is not part of the control system. Rather, if the target vehicle is detected (the vehicle has an orange target on its back for this test), its position is computed in GPS coordinates and saved. At the end of the search phase, the helicopter enters the second phase where it is commanded to fly from point 2 to the stored location of the target (point 3). Once there, the control system switches modes to closing a vision-based tracking loop that causes the helicopter to hover directly over the target vehicle. Once in this state, the target vehicle is then driven around the field and the helicopter holds station directly over it. Note that the control loops active in this task were preliminary and therefore of relatively low bandwidth compared to what is achievable with this system.

The performance achieved in accomplishing this task is presented in Figure 5. It clearly shows the ability of the helicopter to track the target vehicle.

9 Conclusions

The ability to merge CDGPS-based control and vision-based control to control a small helicopter has been demonstrated. Further, the capabilities enabled by this integration have been used to demonstrate a fully autonomous search and tracking mission with the helicopter.

References

[1] Woodley, B.R., Jones, H.L, LeMaster, E., Frew, E. and Rock, S.M., "Carrier-Phase GPS and Computer Vision for Control of Autonomous Helicopters," Proceedings of the 9th Intl. Meeting of the Satellite Division of the Institute of Navigation, ION GPS-96, Sept. 1996, pp. 461-465.

[2] Woodley,B., Jennings, C., Conway,A. and Rock, S.M., "A Contestant in the 1995 Aerial Robotics Competition: Aerospace Robotics Laboratory Stanford University", Proceedings Manual. AUVS '95 Technical Papers, Washington DC, July 1995, pp.669-76.

[3] Sugeno, M. et al., "Development of an intelligent unmanned helicopter", *Proceedings of 1995 IEEE International Conference on Fuzzy Systems*, Yokohama, Japan, Mar 1995, vol.5, pp. 33-4.

[4] DeBitetto, P., and Johnson, E.N., and Lanzilotta, E., and Trott, C., and Bosse, M., and Draper (C.S.) Lab., Cambridge, MA, USA, "The 1996 MIT/Boston University/Draper Laboratory autonomous helicopter system", AUVSI '96 Proceedings, Orlando, FL, July 1996, pp. 911-20.

[5] Murphy, R.R., "1997 International Unmanned Aerial Vehicle Competition", Journal of Robotics and Autonomous Systems, Vol 21, Issue 3, Oct 1997.

[6] Marks, R.L., Rock, S.M. and Lee, M.J., "Real-Time Video Mosaicking of the Ocean Floor," *IEEE Journal of Ocean Engineering*, Vol. 20, No. 3, July 1995, pp 229-241.