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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[¶] Doctoral Candidate, Department of Aeronautics and Astronautics, woodley@sun-valley.Stanford.EDU 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

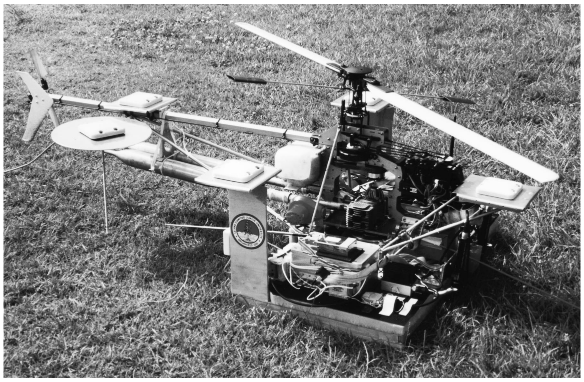

Figure 1: HUMMINGBIRD Helicopter

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.

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-

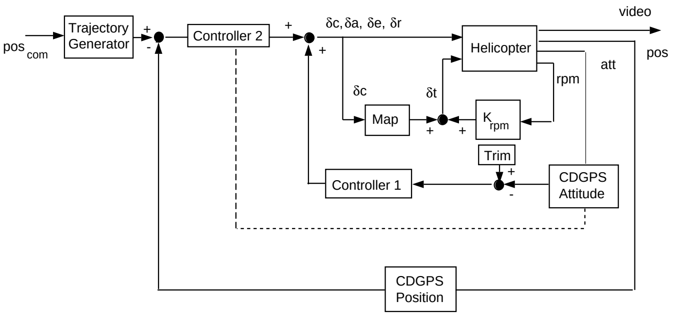

Figure 2: Inner Loop

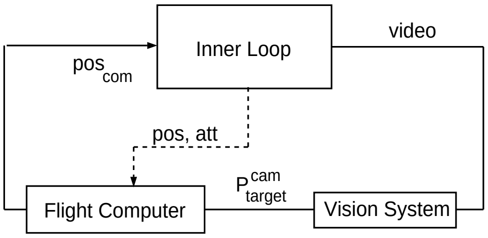

Figure 3: Outer Loop

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

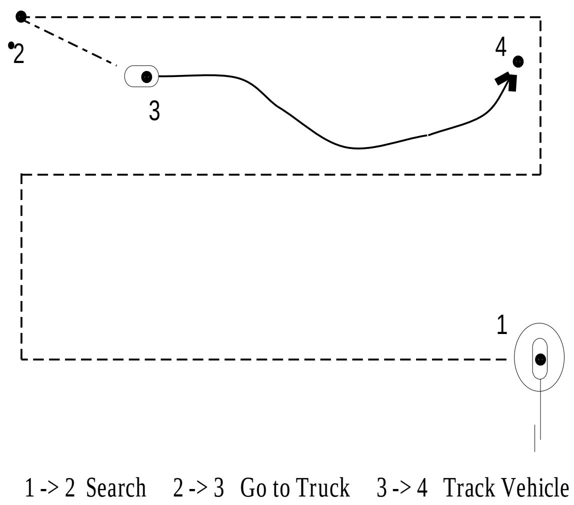

Figure 4: The Demonstration Task

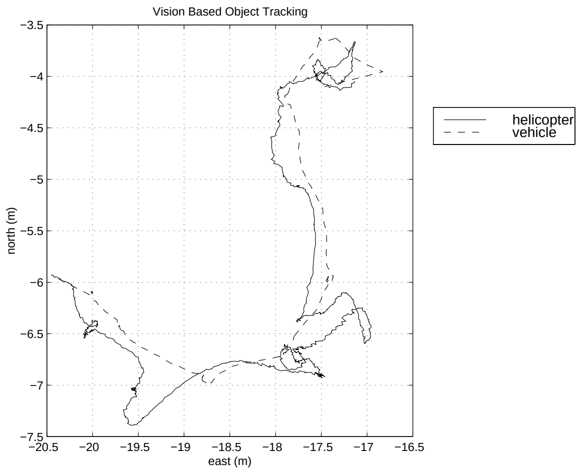

Figure 5: **Groundtrack Performance of Task**

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.