DESIGN AND IMPLEMENTATION OF A GPS-BASED NAVIGATION SYSTEM FOR MICRO AIR VEHICLES

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Abstract

Micro Air Vehicles (MAVs) are becoming vastly popular in the areas of surveillance and reconnisance for military and civilian use, however, their instability due to their small size renders them useful to only a handful of pilots. We propose implementing a GPS-based navigation system for use in autonomous flight of micro air vehicles. Previous efforts in this area have produced a vision-based horizon tracking algorithm capable of sustained level flight with user input. Our goal is to improve on this flight system using information from a GPS receiver. In this paper we first introduce MAVs and the current vision-based navigation system. We next discuss the integration of the GPS navigation system by describing the design of the hardware system and software algorithms for navigation and control. The GPS and vision-based navigation system has been successfully built and integrated, and is currently in the test phase of development.

1. Introduction

MAVs hold a great potential for use in the surveillance field. Equipped with small video cameras and transmitters, they can be used in areas too remote or dangerous for a human counterpart. Their small scale and low noise enables them to blend in with the sky and surroundings, rendering them unnoticeable. Even at low altitudes, their strong resemblance to insects and birds enables MAVs to operate unnoticed. This trait lends itself well to unobtrusive wildlife surveillance as well as a variety of military applications.

The small size requirements of MAVs generate a variety of challenges in development not seen in their larger wing counterparts. These challenges fall into three broad categories: (1) aerodynamic efficiency, (2) increased wing loading, and (3) stability and control [2]. Solutions for the first and second challenges are currently being developed in the Micro Air Vehicle Laboratory at the University of Florida in the form of innovative designs incorporating advanced materials [3]. In this paper we propose solving the third challenge of stability and control. We plan to implement a GPS-based navigation system into the existing vision-based navigation system to solve this challenge. The resulting flight control system will be capable of achieving fully autonomous flight, removing the human component from the control loop.

The current GPS constellation which began operation in the early 1990's allows for accurate land based navigation with meter accuracy [1]. This system is widely becoming the standard for land and air based navigation [9]. Within the United States, GPS has been approved as an IFR supplemental navigation system for domestic en route phases of flight, and as a primary means for oceanic navigation. [5].

Presently, GPS is being added to the primary computer systems of large aircraft, increasing their navigation abilities. We feel GPS can also greatly alter the usability of MAVs. The lack of stability and control inherent in MAVs renders them useful to only a handful of skilled pilots. With the proper navigation system the MAVs can be telecontrolled by a computer, eliminating the major stability challenges of flight, allowing any pilot to focus simply on altitude and direction. With a GPS-based navigation system the pilot can be further removed from the control loop. This system could fully control the flight of the aircraft allowing any person to operate the MAVs by simply programming a flight path.

2. Overview of System

In developing MAVs we look to nature for the biological MAV counterpart, the bird. Most large winged aircraft are designed with rigid fixed wings to avoid catastrophic failures due to structural dynamics. Birds on the other hand do not have rigid wings, and instead exhibit a great deal of flexibility in their wings. The design of MAVs makes use of this flexible wing design to produce a passive mechanism called adaptive washout to suppress wind gusts' effects on their stability. To implement this flexible wing concept, we make use of carbon fiber construction techniques to produce lightweight durable aircrafts.

The planes developed for use in this research have wingspans from 24in to 5in. For initial tests a 24in MAV, shown in Figure 1, will be used since it has the highest payload capacity. The 24in plane is capable of carrying 150g in addition to its primary flight systems including servos, a motor, receiver, and batteries. Using a standard configuration, the

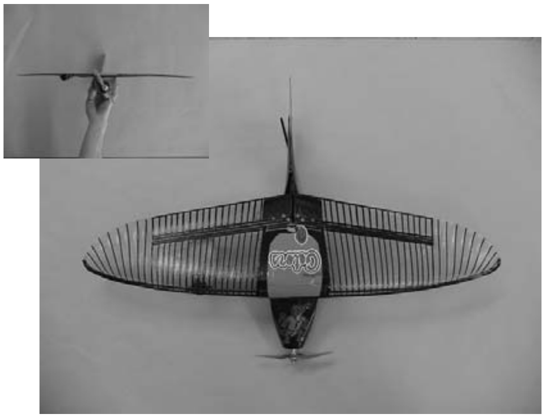

Fig. 1: Example MAV with 24in wingspan

MAV is capable of sustained flight for up to 45min. This flight time is essential for close-range surveillance missions.

The vision-based system takes advantage of the surveillance capabilities of MAVs. With a color camera and transmitter already included in the payload, the system does not rely on any additional payload to control the MAV. All the vision-based control work is done off-board using a base station computer on the ground.

The vision-based system derives its control using a direct measurement of the aircraft's orientation with respect to the ground. The two degrees of freedom critical for stability in this measurement are the bank angle (Φ) and the pitch angle (Θ). These two angles are determined directly from the horizon estimate of an image from a forward facing camera on the aircraft. The bank angle is determined as the inverse tangent of the slope of the horizon line. The pitch angle is estimated to be closely proportional to the percentage of the image above or below the line.

The horizon estimation algorithm begins with a course search of the image, fitting horizon estimates based on previously defined search parameters. The various sky and ground regions resulting from this search are modeled as a Gaussian distribution in RGB space. Using the Gaussian model, the mean and covariance matrices of the two distributions are calculated and used in the cost function equation below

$$F = \begin{bmatrix} |\Sigma_G| + |\Sigma_S| + \\ (\lambda_{G1} + \lambda_{G2} + \lambda_{G3})^2 + \\ (\lambda_{S1} + \lambda_{S2} + \lambda_{S3})^2 \end{bmatrix}^{-1} \tag{1}$$

where Σ_G denotes the covariance matrix for ground pixels, and Σ_S denotes the covariance matrix for sky pixels. This cost function is used for computing the line with the highest likelihood of being the best-fit horizon [2].

3. Light-Weight GPS Navigation System

The integration of GPS navigation into the MAV control system consists of developing hardware and software layers. When designing the hardware system we must consider the payload requirements of the MAV. This requirement is the main restriction as to what processing is done on the MAV.

The on-board hardware enables the system to directly determine the GPS coordinates of the MAV using a GPS receiver and antenna mounted on the plane. This system does not perform any navigation processing and is only used to gather data. The system is responsible for collecting GPS data and transmitting it to the base station. The base station hardware is responsible for receiving the GPS data transmissions, and making them available for to the computer.

3.1 Hardware Description

To meet the small payload requirements of the MAV we searched for a small lightweight GPS receiver with standard functionality and limited user dependence. To satisfy these requirements, we used the *Royaltek REB-2000* GPS receiver. This unit is an 11-channel GPS receiver, transmitting NMEA update messages at 1HZ through a local serial port. The unit operates on 3.3V at less than 170mA and weighs 8.6g. The weight of this receiver falls well within the payload requirements of the MAV.

The documented error of the GPS receiver is in the range of 15m. The typical observed drift is around 7m to 10m. These error measurements might seem too large for raw navigation purposes, however, they are within control limits. The MAV must maintain considerable speed to stay airborne for proper operation. The average speed during test flights is around 40mph to 50mph. This amounts to around 20m of ground coverage per second. With GPS data updating at 1Hz, the drift due to error becomes tolerable since the MAV will always be outside the range of error by the time the next data set arrives. While this is not precise navigation, it is sufficient for following a general flight path based on waypoints.

An equally small GPS antenna was needed to interface with the GPS receiver. When shrinking the size of a passive GPS antenna, signal degradation becomes large, and it is difficult to produce usable satellite transmissions. We determined we would need an active antenna with a sizable gain that consumes minimal power. The GPS antenna that meets our requirements is the *Tri-M Micro Skymaster*. This antenna has a 24dB gain with a maximum of 12mA current consumption. For the purposes of this project the antenna cable was shortened from 3ft. to 14in to reduce extra payload.

To satisfy the data transmission requirements, a system was designed using the *TX1\RX1* FM serial data transmit-

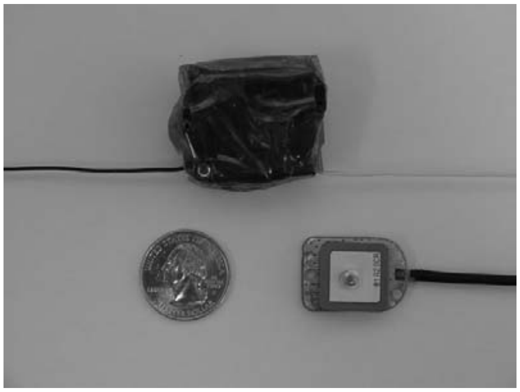

Fig. 2: GPS receiver and data transmitter package

ter/receiver pair designed by *Radiometrix*. These units operate on the 173.25MHz FM band and can transmit at data rates up to 10 KBps. The overall range of the system can approach 10Km with the proper antennas and data rate. The *TX1* and *RX1* operate at 3.3V and have internal regulators. They consume 10mA on average. These properties of the *TX1/RX1* make them suitable for use in MAV applications.

3.2 Software Description

The software package for the GPS-based navigation system consists of three main control structures: (1) data input and extraction, (2) control system, and (3) vision system interface. These systems interact to gather data from the GPS receiver on the MAV, determine proper flight control changes to achieve the desired mission goals and interface with the current vision system. The software is based on the flow diagram in Figure 3.

The data input and extraction system is the first step in the program flow. The system is designed to directly interface with the GPS receiver and the base station data receiver. The GPS receiver is initialized to transmit NMEA GPS sentences at 4800 Bps with a 1Hz update frequency. The data input and extraction software reads these NMEA sentences from the RS-232 port and decodes them for use in the other parts of the software package. The system is extremely robust to account for invalid data due to signal degradation when flying at large distances from the base station.

Included in the data input and extraction system is the data display console. This section provides the user with all the data transmitted from the GPS receiver as well as the current navigation data being used in the flight control system. It also enables the user to make changes to the flight path on the fly.

The software control system is the next step in the program flow. This system first takes the raw GPS data and converts it into the proper units for use in the flight controller. It then uses the desired flight plan to determine the necessary navigation controls for achieving autonomous flight. The flight plan consists of a number of waypoints for the MAV to traverse. The user designs a course based on latitude, longitude and altitude measurements at discrete points on the path. The system is designed around central PID controllers using two individual PID systems to control the direction or bearing and the altitude.

The errors for the PID system are determined from the current GPS position data and the predetermined flight plan. The altitude is taken directly from the GPS GPGGA NMEA sentence. The position and course data are taken from the GPS GPRMC NMEA sentence. The bearing controller is updated using the error between the current bearing to the desired point and current course as shown in Figure 4. The altitude controller is updated using the error between the current and desired altitude.

The bearing error is based on the current course and the bearing to the next requested waypoint in the predetermined flight path, and is calculated using the Great Circle equations for navigation in a three dimensional environment. The bearing to the next requested waypoint is calculated by first determining the distance to the next waypoint

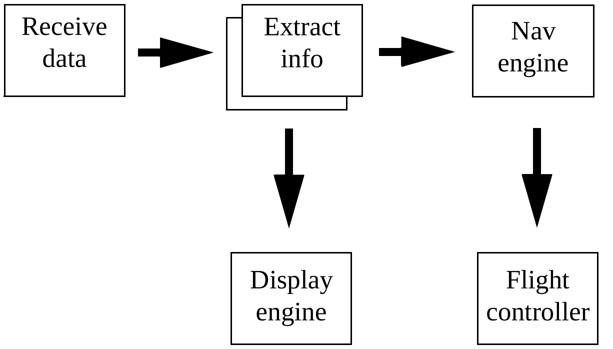

Fig. 3: Software flow diagram

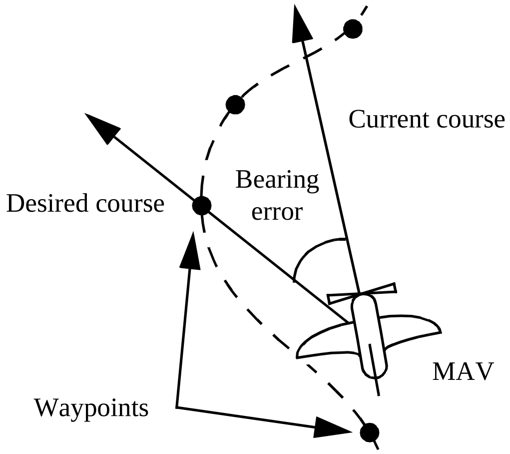

Fig. 4: Flight path bearing error illustration

using equation (2). This distance is used in equation (3) to determine the absolute bearing off north. The resulting bearing is used as the desired bearing in determining the PID error measure [4].

$$d = \operatorname{acos}\begin{pmatrix} \sin(lat_1) \cdot \sin(lat_2) + \\ \cos(lat_1) \cdot \cos(lat_2) \cdot \\ \cos(lon_1 - lon_2) \end{pmatrix} \tag{2}$$

$$c = \operatorname{acos}\left(\frac{\sin(lat_2) - \sin(lat_1) \cdot \cos(d)}{\cos(lat_1) \cdot \sin(d)}\right) \tag{3}$$

The final phase of the program flow is the vision system interface. The vision system was designed around user input to determine the desired pitch and bank angles. Without user input, the system would continue to fly on a level straight course. The GPS vision system interface take the place of this user input.

The interface provides the desired pitch and bank angles based on the GPS system PID controllers. The control output from the altitude PID system is used in determining the desired pitch percentage for the vision interface. The control output from the bearing PID system is used in determining the bank angle for the vision system interface.The vision system uses the desired GPS pitch and bank angles in the main flight controller to determine the proper control surface changes. This enables the system to maintain the main flight control interface in the vision system for ease of integration. It also allows the vision system to continue legacy support for user input when GPS is unavailable.

3.3 PID Controller Tuning

The difficulty in tuning the PID controller is the potential for a catastrophic crash due to non-dampening control. The MAV can not be flown directly by the autonomous navigation system until this controller is properly tuned, however, tuning the controller requires flying the MAV.

To properly tune the PID system while maintaining stability of the MAV we developed a process where a pilot flys the MAV through a predetermined course using the vision-based system and the joystick. The GPS-based system suggests a horizon location based on the course as shown in Figure 5. Observations are made as to the instability of the PID system, and the proper gains are changed. The system is then be reset to observe the changes.

Tuning of the PID system using this method is not as difficult as initially expected. Slight changes to the gain values result in a suggested horizon location similar to the user's input. As long as the output values of the PID controller are within the range of joystick values, the system can not become unstable. This is due to the original design of the flight controller, which was based solely on user input. The specifications of the flight controller enable any pilot to indirectly fly the MAV. The pilot's input, while used as the basis for navigation, is not allowed to cause instability in the MAV's flight. These same specifications are used when processing GPS suggested horizon locations. If the GPS desired navigation updates cause any instability in the MAV's flight, they will be ignored until stable horizon locations are achieved.

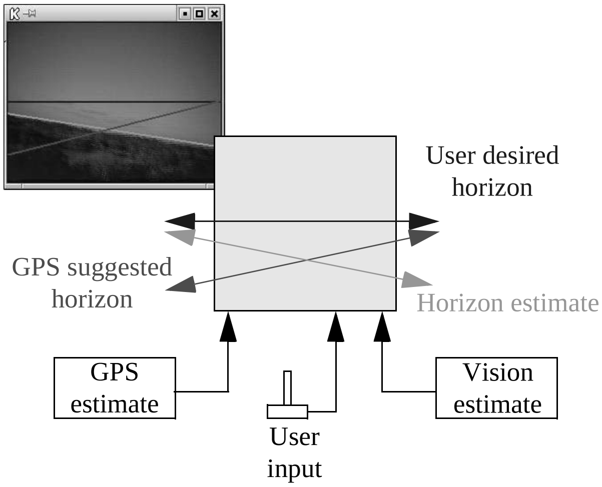

Fig. 5: PID controller tuning method

4. Conclusion

The GPS-based navigation system described in this paper has been constructed. Its reliability has been verified in multiple ground-based tests involving varying courses. Integration of the vision system and the GPS has been successfully completed. Currently, we are in the process of begining aerial testing of the complete autonomous navigation system.

5. References

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