A Fixed-Wing Aircraft for Hovering in Caves, Tunnels, and Buildings

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Abstract

Micro Air Vehicles (MAVs) are small bird-sized aircraft with applications in reconnaissance, search-and-rescue, airborne agent and pathogen detection, and target acquisition. Fixed-wing MAVs cannot hover and thus, are not able to fly in tight, enclosed spaces. Rotary-wing platforms can hover but are limited by endurance. This paper presents a fixed-wing MAV with a secondary flight mode (i.e. hovering) allowing it to fly in caves, tunnels, and buildings. The sensing and control system used to achieve autonomous hovering is also described. This is, to the best of our knowledge, the first documented success of autonomously hovering a fixed-wing MAV in the open literature.

Figure 1: A fixed-wing MAV hovering like a helicopter to stare in a second story window.

1 Introduction

Micro Air Vehicles, or MAVs, are small unmanned aircraft that range from flying insect [3] and bat-sized platforms [10] to slightly larger vehicles such as DARPA's Organic Air Vehicle (OAV). MAV missions, such as target acquisition, airborne agent and pathogen detection, search-and-rescue or hovering outside a second story window to gather intelligence (i.e. hover-and-stare), can take place in a variety of environments. Referred to as near-Earth environments, these low altitude flying areas (e.g. caves, tunnels, in and around buildings) are narrow and cluttered with obstacles. This makes the long term goal of full autonomous flight in these environments very challenging.

MAV research groups focusing on the design of fixed or rotary-wing vehicles have had many successes. In 2000, Aerovironment's Black Widow MAV, with a 15 cm (6 inch) wingspan and a weight of 80 grams, was remotely piloted in "heads-down" mode for 30 minutes [4]. A year later, the Navy Research Lab (NRL) developed a slightly larger prototype with a 46 cm (18 inch) wingspan, capable of carrying a one-ounce camera for 20 minutes [8]. Each of these vehicles have cruise speeds of 7-11 m/s (15-25 mph) which limits the MAV's applicable missions to open, outdoor flying environments. However, there is demand for small unmanned air vehicles that can acquire intelligence, surveillance, and reconnaissance (ISR) in environments where larger UAVs such as the *Predator* and *Global Hawk* cannot. Towards this, the authors were one of the first to develop a platform capable of carrying a wireless camera and flying in a 10 x 10 m^2 area [7]. However, flight in caves and tunnels presents areas much smaller and therefore requires a platform with hovering capabilities. In addition, maintaining the maneuverability and endurance of a fixed-wing aircraft was also desired.

Leveraging a maneuver known as *prop-hanging* from the radio-controlled airplane community, the authors were able to integrate the maneuverability and en-

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durance superiority of fixed-wing aircraft with hovering capabilities of rotary-wing vehicles [5]. During a prop-hang, where the fuselage is completely vertical, the thrust from the motor and propeller balance the weight of the aircraft (see Fig. 1). This is made possible by a high thrust-to-weight ratio ($T/W > 1$) which also allows a quick transition from cruise flight, through the stall regime, and into hovering mode. However, the aircraft is unstable in this configuration and requires an expert human pilot to constantly manipulate the aircraft's control surfaces (e.g. rudder and elevator) in order to sustain a hover. With full autonomous operation in mind, taking the human out of the loop during this difficult and demanding flight mode is a logical first step. An onboard control system was used to acquire data from an orientation sensor to automate the process. To the best of our knowledge, there is no other work in the open literature that shows autonomous hovering of a fixed-wing Micro Air Vehicle.

This paper illustrates the usefulness of a hovering, fixed-wing aircraft for flight in cluttered terrain. Section 2 discusses the evolution of the most recent prototype and explains the transition from cruise to hover flight. Section 3 details the attitude sensor and controller used to achieve autonomous hovering while Section 4 presents the experimental results. The paper finished with sections on future work and conclusions.

2 Platform Evolution

Successfully traversing caves and tunnels demands a small-scale aircraft which is highly maneuverable. The initial prototype weighed 30 grams, had a 46 cm (18 inch) wingspan and could fly for 20 minutes on a 145 mAh lithium polymer battery. It was maneuverable in the sense that it flew so slowly (approximately 2 m/s), oncoming collisions were detected and avoided well before the aircraft got there. With a 15 gram payload, optic flow microsensors [1] were mounted on the front of the plane and were used to achieve autonomous collision avoidance inside an urban structure [6]. However, the small payload capacity of the aircraft was quickly exhausted. Furthermore, the lightweight airframe prevented flight outdoors. As such, the design specifications were modified such that the next generation was

- highly maneuverable
- compact (less than 91 cm, or 3 feet)
- capable of flying 25 minutes or longer
- able to carry a payload of 100 grams
- capable of hovering

The revised design specifications narrowed the list of feasible platforms down to two configurations: fixed and rotary-wing. Neither platform, however, was able to meet all five design parameters. For example, fixed-wing platforms leverage the lift generated from airfoils to provide longer flight times, but are unable to hover. Rotary-wing aircraft, such as helicopters and ducted fans [2] [9], are capable of stationary flight but have limited endurance because the lift is provided directly by electric or gas powered motors. It therefore seemed logical to develop a hybrid in order to meet all of the design specifications.

2.1 Hybrid Platform

With a maneuver adopted from the radio-controlled airplane community known as prop-hanging, adding an additional flight modality to a fixed-wing aircraft was realizable. Prop-hanging is the aircraft's ability to balance its weight with the thrust generated from the propeller. This requires a large thrust to weight ratio (T/W > 1). Also, the airflow over the control surfaces is limited during a hover (i.e. propeller wash). To compensate, increased rudder and elevator surface areas are needed.

Entering the hovering orientation from cruise flight requires the aircraft to successfully transition through the high angle-of-attack (AoA) regime, which typically causes the wings to stall. During this phase, there is an angle for which the wings are no longer a contributing factor to the lift component. To achieve the maneuver, the aircraft has to leverage its momentum and overpower its way through the stall regime. The high thrust-to-weight ratio helps to maintain the momentum so it is not lost through the transition. Fig. 2 shows the prototype as it transitions from cruise flight to the hovering orientation.

2.2 Sustaining a Hover

Manual controlled hovering of a fixed-wing aircraft requires an expert human pilot to continuously manipulate four channels of a radio-controlled transmitter. Fig. 3 shows the throttle, rudder, elevator, and aileron control sticks which are used to control the aircraft's altitude, yaw, pitch and roll respectively. During a hover, the position of the elevator and rudder control surfaces are the most critical. With no aileron control, the plane will rotate about the vertical axis (as a natural reaction to the torque created by the high-powered

Figure 2: Our MAV prototype with a 91 cm (36 inch) wingspan transitions from cruise flight (top left) through the stall regime (top middle) and into a hovering position (top right).

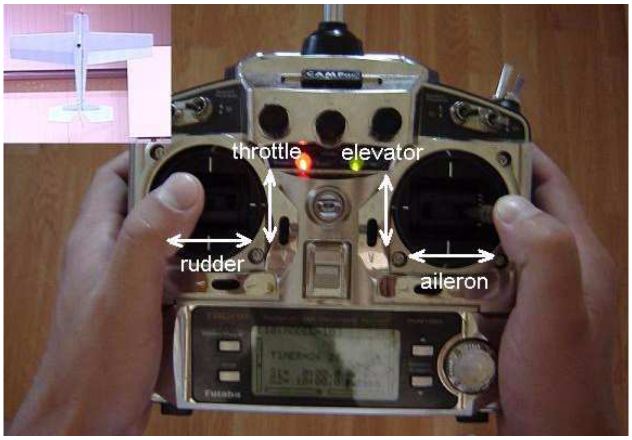

Figure 3: Manual hovering demands control of all four transmitter channels.

brushless motor), but will have no translational velocity and will therefore remain in a hover. Similarly, the throttle requires minimal control input because it is an electric aircraft. That is, the aircraft will not lose weight in mid-flight by expending fuel and therefore results in a fixed throttle position to balance the aircraft's weight and drag in a hover. This is shown in the analysis below.

Figure 4 shows a free-body diagram of the forces of flight acting on the aircraft during a hover. Summing the forces in the vertical direction yields

$$\Sigma F_{z_{elevator}} = 0 \Rightarrow T cos(\theta - 90) - D cos(\theta - 90) \\ - F_E sin\delta_E cos(\theta - 90) - W = 0 \quad (1)$$

$$\Sigma F_{z_{rudder}} \Rightarrow T cos\psi - D cos\psi - F_R sin\delta_R cos\psi \\ - W = 0 \quad (2)$$

where F_E and F_R are the elevator and rudder restoring forces, respectively, and are functions of the drag force, D, and control surface deflection angle, δ. It can be seen from (1) and (2), that when the aircraft is in a perfect hover (i.e. $\theta = 90$, $\psi = 0 \Rightarrow \delta_E = \delta_R = 0$), the thrust must equal both the weight and drag forces.

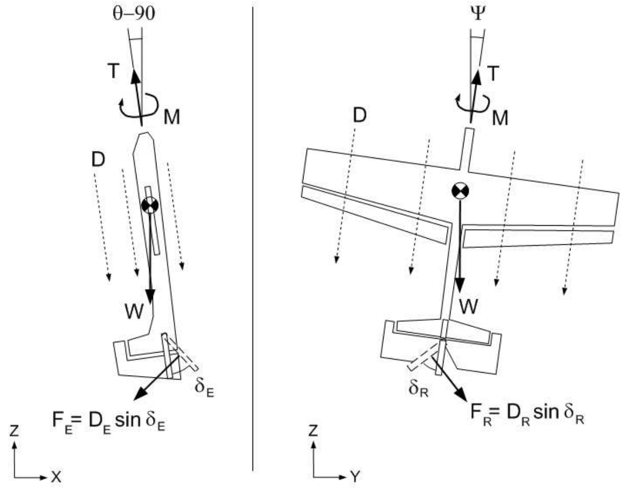

Figure 4: When in a hovering attitude, the elevator and rudder control surfaces are used to regulate the pitch and yaw angles, respectively.

3 Sensing and Control for Automation

Automating the hovering flight mode requires that the aircraft attitude be measured. Furthermore, because the MAV pitch angle will approach ninety degrees during the transition from cruise to hover flight, conventional Euler angle notation will yield erroneous data due to gimbal lock. To avoid this phenomenon, an alternative method must be employed.

3.1 Inertial Measurement Unit

One method of avoiding the singularities present at pitch angles of ± 90 degrees is through the use of quaternions. Quaternions are four-dimensional vectors[1]

$$q = w + xi + yj + zk \tag{3}$$

where x, y, and z are complex numbers defining the axis of rotation and w is the angle of rotation about that axis. A desired Euler angle orientation during a hover (θ=90 and ψ=0) corresponds to a ninety degree rotation about the y axis. In quaternion form, this yields

$$\begin{aligned} w &= \cos(angle/2) = 0.707 \\ x &= e_1 * \sin(angle/2) = 0i \\ y &= e_2 * \sin(angle/2) = 0.707j \\ z &= e_3 * \sin(angle/2) = 0k \end{aligned}$$

This is the desired attitude quaternion, q_d, during a hover. The measured attitude quaternion, q_m, is acquired using Microstrain's 3DM-GX1 inertial measurement unit (IMU). Fig. 5 shows the IMU, which directly outputs a gyroscopically stabilized four component quaternion describing the orientation with respect to the fixed earth coordinate frame. It weighs just 30 grams and is comprised of three triaxial accelerometers and angular rate gyros as well as three orthogonal magnetometers. The IMU, using RS232 communication protocol, transmits orientation data to the control system at a rate of 100 Hz.

3.2 Onboard Processing and Control

Using a PIC16F87 microcontroller and a RS232 converter chip, the onboard control system pings the IMU for the measure quaternion every 10 ms. The software embedded on the micro computes the error quaternion

$$q_e = q_d * q_m^* \tag{4}$$

and the angular error about the roll, pitch, and yaw axes is extracted from it. The angular errors are then fed through a PD controller to determine the pulse-width modulated (PWM) commands to the rudder and elevator servos. This, in turn, drives the aircraft orientation back to the hovering attitude. Fig. 6 shows the control loop which repeats continuously and is synchronized with the IMU clock cycle (i.e. every 10 ms).

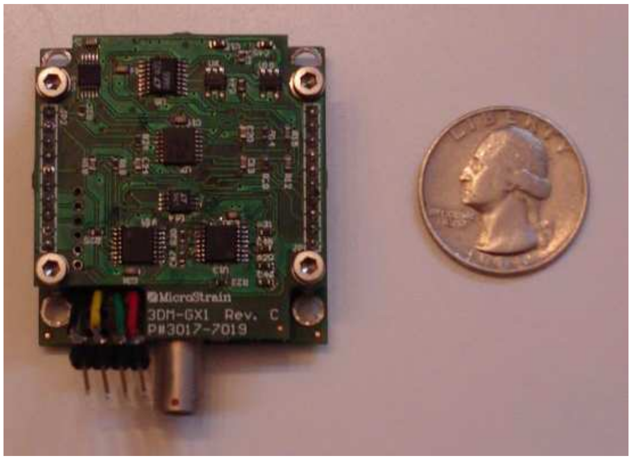

Figure 5: Microstrain's 30 gram IMU sensor was used to feedback attitude information to the onboard control system.

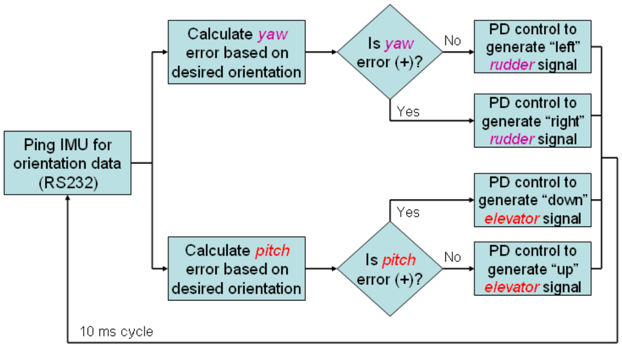

Figure 6: Flow chart describing the autonomous hovering code.

4 Experiments

The first autonomous hovering experiments were conducted inside an urban structure, with limited flying space, (i.e. 1 x 1 m^2 area). Also, an experiment was performed to contrast the differences in stability between manual and autonomous hovering.

4.1 Autonomous Hovering

The aircraft was released in near-hovering orientation (i.e. the fuselage is close to vertical) and manually given enough throttle to balance the aircraft weight. The controls are simultaneously handed off to the onboard control system. Initial experiments demonstrated that the MAV was able to successfully hover in "hands-off" mode for 35 seconds (see Fig. 7). It should be noted that the aileron control surfaces re-

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[1] Orientation matrices can also be used to avoid gimbal lock, but require 9 bytes of storage as opposed to 4.

mained in the neutral position (i.e. no deflection) throughout the flight. This was to purposefully allow torque roll so the MAV's bellycam could acquire panoramic footage of the flying area.

Figure 7: MAV performing a *hands-off* autonomous hover in and urban structure. Also, a shot from the MAV's bellycam is shown in the bottom left.

4.2 Manual vs. Autonomous Control

The last experiment was performed to visually contrast hovering under both manual and autonomous control. The metrics used were (i) duration of the hover before losing control and (ii) stability of the aircraft while in hovering mode. The human pilot was initially given control of the aircraft and was instructed to fly around the gymnasium in cruise configuration. Then, make the transition from cruise to hover flight and attempt to hover the aircraft for as long as possible. The video stills[2] show the pilot struggling to keep the fuselage vertical, but is able to keep the aircraft positioned over a small area (see top of Fig. 8). Out of a few trials, the human pilot was able to sustain a hover for about 30 seconds before losing control and transitioning back to cruise flight to regain stability. The main cause of this was that the human pilot was not able to correct the error fast enough. Once the aircraft, which was much heavier than conventional RC planes, pitched more than 20 degrees forward it was impossible to bring it back to a hovering orientation without a tremendous amount of overshoot. This process continued until the error started escalating.

Next, the pilot was instructed to, again, fly in cruise configuration and manually make the transition from cruise to hover flight. However, instead of trying to hover the aircraft manually, the pilot flicked a switch on the transmitter which enabled the onboard controller. This time, the aircraft is fixed in a vertical position and is able to hover for more than a few minutes before exhausting the battery (see bottom of Fig. 8).

5 Future Work

The ultimate goal of this research is to develop a fully autonomous MAV to fly in caves, tunnels, and buildings. Autonomous hovering was a major milestone towards this, but the aircraft must also be able to perform other tasks autonomously. For example, the MAV's sensor suite and control system must be capable of obstacle detection in unstructured lighting, precise path planning, and localization. Leveraging previous research, collision avoidance will be accomplished my mirroring Mother Nature. In particular, using optic flow to mimic flight stratagems of flying insects [11].

Furthermore, a second-generation fixed- and rotary-wing hybrid will be developed. This model will be scaled down to a smaller, backpackable version. This will also enable flight in tighter, more confined areas. The future prototype will be used to demonstrate hover-and-stare capabilities (i.e. flying up to a second story window or rooftop and hovering there to collect reconnaissance). Therefore, countering the effects of the motor torque through aileron deflection will be incorporated into the controller.

Finally, the transition from the primary to secondary flight modes must also be made autonomous. This is the more imminent task and must be implemented through the use of quaternions. This is more difficult than autonomous hovering because of the fragile transition through the high angle-of-attack stall regime.

6 Conclusions

Patrolling caves, tunnels and buildings demands a vehicle that can hover. Furthermore, other MAV missions such as gathering reconnaissance inside a cave a few miles ahead requires high endurance. Designing an aircraft for such missions demands a vehicle that is compact, able to fly for extended periods, and most importantly, capable of hovering.

A fixed-wing MAV with hovering capabilities offers

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[2] The video sequence shows three images extracted once a second for a period of three seconds. With the plane rotating at a rate of 0.25 revolutions per second, this is enough to show two quarter rotations.

Figure 8: A human pilot hovers a fixed-wing aircraft in a small gymnasium and struggles to keep control (top). Under autonomous control, the same aircraft is able to sustain a hover for more than 90 seconds (bottom).

the benefits of stationary flight coupled with longer flight times. Furthermore, these unconventional flying environments are usually enclosed and thus degrade GPS signals. Therefore, autonomous flight requires that all processing be done onboard the aircraft. The 15 gram processing and control system reads attitude information from the IMU at a 100 Hz rate, and implements PD control on the rudder and elevator control surfaces to achieve autonomous hovering with a fixed-wing MAV. This research is the first to document autonomous hovering of a fixed-wing aircraft in the open literature.

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