

Optic Flow Based Collision Avoidance on a Hybrid MAV

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Abstract

Recent terrorist attacks on the United States have exposed the need for better surveillance and situational awareness technologies. Organizations created to address these needs are aggressively funding research in the use of Micro Air Vehicles for homeland security missions. Such missions have been occurring in caves, tunnels, and urban areas. By mimicking flying insects which navigate in these complex environments regularly, an optic flow collision avoidance system for a MAV was prototyped. However, there were certain instances (e.g. flying directly into a corner) where this system failed. To address this, a new MAV platform was prototyped which enabled a quick transition from cruise flight into a hovering mode in order to avoid such a collision. The hybrid MAV offers the endurance superiority of fixed-wing aircraft along with hovering capabilities of rotorcraft. This paper details the applications and design of a hybrid MAV in conjunction with sensing and control techniques to perform autonomous hovering and collision avoidance. This is, to the best of our knowledge, the first documented success of hovering a fixed-wing MAV autonomously.

1 Introduction

More often, homeland security and disaster mitigation efforts have taken place in unforeseen environments which include caves, tunnels, forests, cities, and even inside urban structures. Performing various tasks such as surveillance, reconnaissance, bomb damage assessment, or search-and-rescue within an unfamiliar territory is dangerous and also requires a large, diverse task force. Unmanned robotic vehicles could assist in such missions by providing situational aware-

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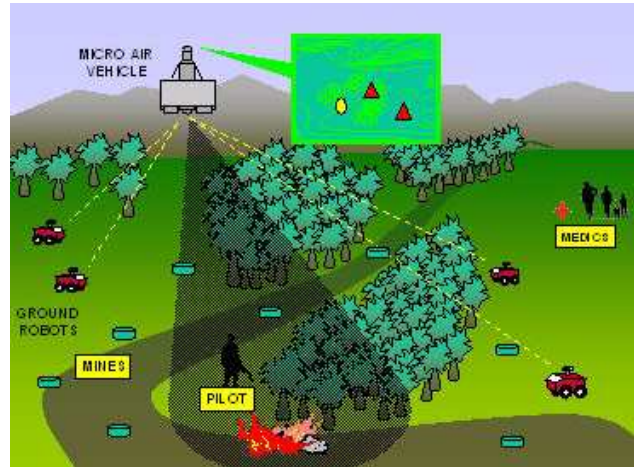


Figure 1: A small UAV is hovering above to acquire and distribute situational awareness to command and control personnel.

ness without risking the lives of soldiers, first responders, or other personnel. While ground-based robots have had many successes in search-and-rescue situations [6], they move slowly, have trouble traversing rugged terrain, and can still put the operator at risk. Alternatively, small unmanned aerial vehicles (UAVs) can provide soldiers and emergency response personnel with an “eye in the sky” perspective (see Fig. 1). On an even smaller scale, tiny bird-sized aircraft or micro air vehicles (MAVs) can be designed to fit in a backpack and can be rapidly deployed to provide “around the corner” or “over the hill” surveillance. Navigating in urban environments, however, remains a challenging problem for UAVs. In [7], promising results are shown for a rotorcraft equipped with a SICK laser scanner. Because lift decreases with platform size, carrying this type of sensor on a MAV isn’t feasible.

For inspiration towards autonomous MAV navigation in and around buildings, the authors looked to fly-

ing insects. Flying insects, such as honeybees and fruit flies, use optic flow to navigate in complex and dynamic environments [8] [2]. By mimicking insect behaviors, the authors were the first to demonstrate tasks such as collision avoidance and landing inside an urban structure [4]. More recently, optic flow has been used outdoors to avoid collisions with a tall building and navigate through canyons [5]. While using optic flow outdoors in rich texture areas seems promising, there are some limitations when using this technique as the only sensing modality inside buildings (e.g. flying directly at a wall with no texture). To address these sensor limitations, the authors prototyped a fixed-wing MAV that is capable of a quick transition into hovering mode to avoid collisions directly in front of the aircraft. This paper illustrates how integrating optic flow sensing for peripheral collision avoidance with a novel MAV platform results in a vehicle that is well suited for flight in urban areas. Section 2 discusses optic flow and reactive control experiments mimicking flying insects while Section 3 talks about the fixed-wing MAV with hovering capabilities. In Section 4, autonomous control of the aircraft’s attitude during a hover is detailed. Section 5 concludes and outlines near-future goals.

2 Optic Flow

Insects perform tasks such as collision avoidance and landing by perceiving the optic flow of their surroundings. Optic flow refers to the apparent motion of texture in the visual field relative to the insect’s body. Through several experiments with honeybees [9] and fruit flies [10], it is suggested that flying insects avoid collisions by turning away from regions of high optic flow (see Fig. 2). To mimic these navigation techniques, a 30 gram flying testbed was prototyped. Fig. 3 shows this prototype which was designed to be small and fly at 2 m/s for extended reaction times in order to avoid detected obstacles.

2.1 Collision Avoidance

Mimicking behaviors of flying insects required optic flow to be measured in front of the aircraft to detect oncoming collisions (see Fig. 4). Fig. 5 shows a one-dimensional optic flow sensor, developed by Centeye, that was used in the experiments. It is comprised of a mixed-mode “vision chip” which images the environment and performs low-level processing using analog VLSI circuitry [1]. Then an off-the-shelf microcontroller performs mid- and high-level processing using standard digital techniques. The resulting sensor, in-

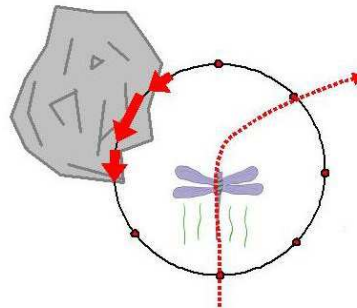


Figure 2: Dragon fly saccading away from regions of high optic flow in order to avoid a collision.



Figure 3: Our 30 gram prototype with 60 cm wingspan flies at speeds of 2 m/s.

cluding optics, imaging, processing, and I/O weighs 4.8 grams. This sensor grabs frames at up to 1.4 kHz and measures optic flow up to 20 rad/s.

Using two of these sensors angled at ± 45 degrees from the fuselage, optic flow fields were detected on each side of the aircraft. Optic flow is measured in rad/sec and is a function of the MAV’s forward velocity, V , angular velocity, ω , distance D from an object, and the angle, α , between the direction of travel and the sensor’s optical axis (see Fig. 6). The formula, originally derived in [12],

$$OF = \frac{V}{D} \sin \alpha - \omega \quad (1)$$

was used to set an optic flow threshold that corresponded to D being twice the turning radius of the aircraft. The threshold assumed cruise conditions (i.e. $V=\text{const.}$ and $\omega=0$) and was preset experimentally.

The aircraft was then flown towards different obstacles and an approaching object on either side of the MAV would generate an increase in optic flow as seen in (1). The output of each of these sensors was fed

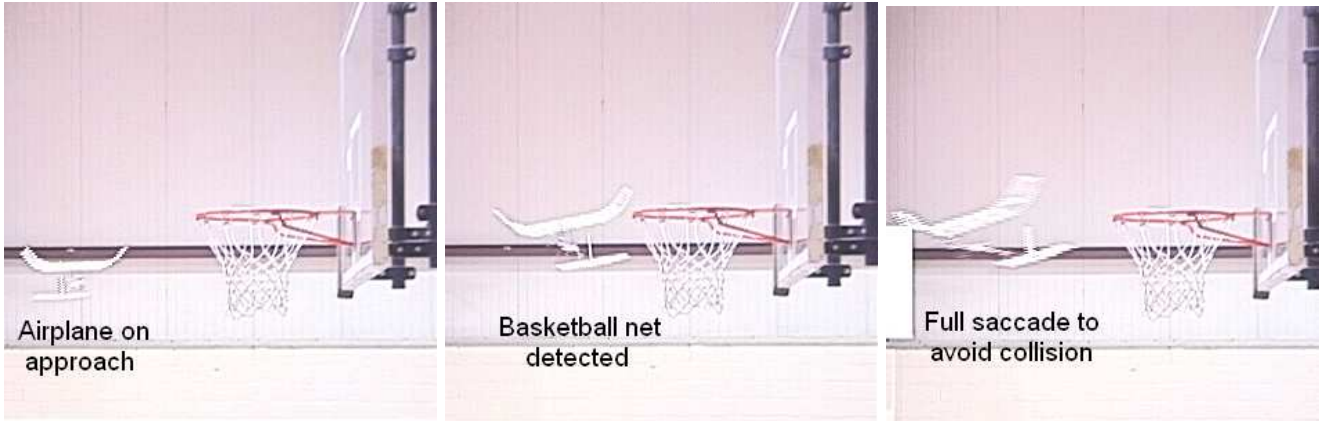


Figure 7: Optic flow is used to sense when an obstacle is within two turning radii of the aircraft. The aircraft avoids the collision by fully deflecting the rudder.

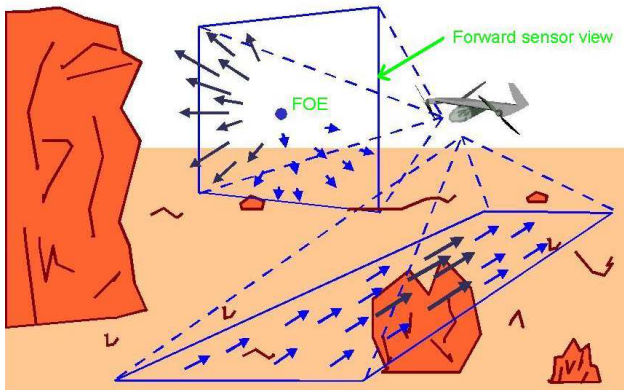


Figure 4: Optic flow as seen by aerial robot flying above ground.

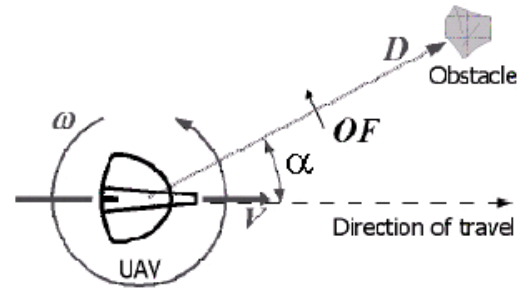


Figure 6: 1D optic flow during MAV steady, level flight.

into an onboard microcontroller. If the values from either of the sensors exceeded the threshold, the processor would apply full deflection to the rudder to avoid the collision. By implementing this reactive-based method, autonomous collision avoidance was successfully demonstrated (see Fig. 7).

2.2 Optic Flow Limitations

The proof-of-concept experiments showed promising results for using optic flow for peripheral collision avoidance, however, there are some limitations when flying directly towards an object. For example, when two optic flow sensors are aligned at 45 degrees from the fuselage like in the experiments above, smaller objects such as poles could remain outside the sensor's field of view (see left part of Fig. 8). This is most likely why honeybees never fly a straight line towards a target, but rather make a slight zigzag pattern. This generates an artificial parallax that will yield optic

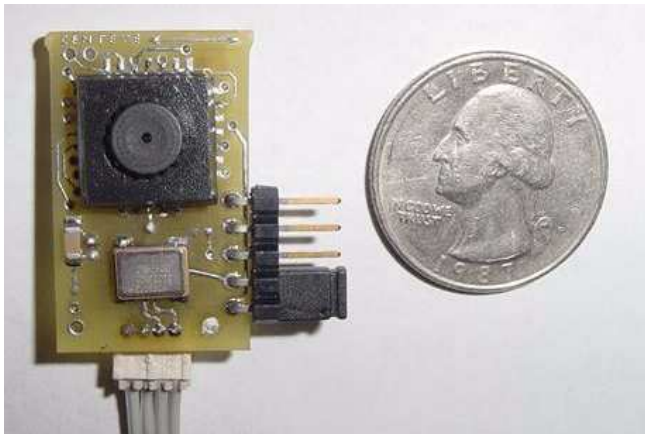


Figure 5: mixed-mode VLSI optic flow microsensor is slightly bigger than a US quarter.

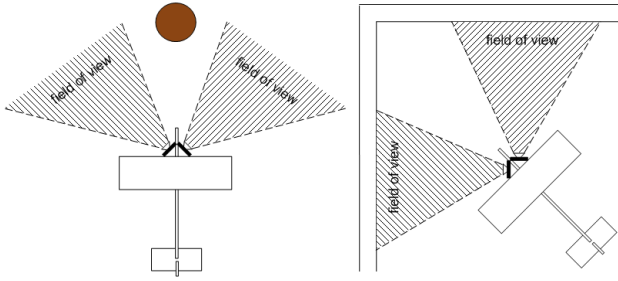


Figure 8: Limitations of using optic flow for navigation.

flow values for smaller oncoming obstacles.

Similarly, optic flow-based collision avoidance is also insufficient when flying directly towards larger obstacles such as walls. The right half of Fig. 8 shows an example of this scenario. In [13], the diverging optic flow field generated by the wall was used to trigger a warning two meters before the collision. However, the experiment was performed in an artificially textured environment (i.e. alternating white and black sheets were used as walls). Realistically, walls are often homogeneous and have little texture. Therefore, this method will most likely fail especially since the wall will be the only object in the sensor’s field of view. It has been shown in [11] that when fruit flies are presented with this scenario, they stick out their legs in preparation for landing. Landing on a wall is obviously not feasible for a MAV, however, a quick transition to a stationary attitude is. That is, a fixed-wing MAV can be designed to quickly transition to a hover in order to avoid collisions in these instances.

3 Fixed-Wing Hovering MAV

Integrating the endurance of fixed-wing aircraft with hovering capabilities of rotorcraft have recently been realized in the radio-controlled (RC) community through a maneuver known as *prop-hanging*. During a prop-hang, the longitudinal axis of the fuselage is completely vertical and the thrust from the motor balances the weight of the aircraft. Leveraging this maneuver, the authors were able to prototype a fixed-wing platform with an additional flight mode for hovering [3]. Fig. 9 shows the prototype in its hovering attitude. The prototype is constructed with a 3 mm depron foam core laminated with carbon fiber cloth. It has a 1 meter wingspan, weighs 600 grams, and could fly in cruise mode for 30 minutes on a 11.1 V, 1320 mAh lithium polymer battery. With a 6.6:1

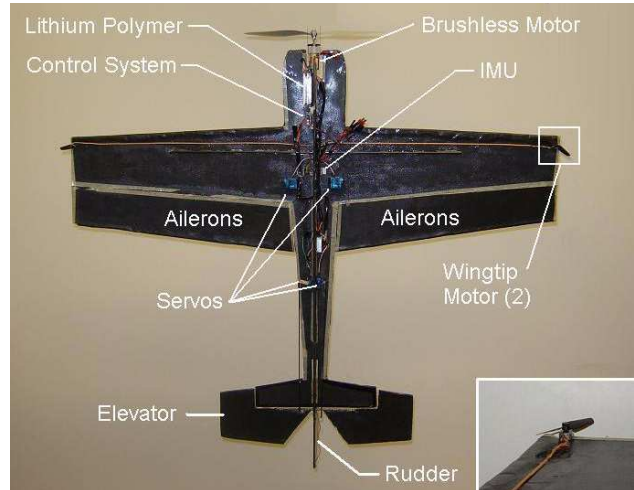


Figure 9: Our hybrid prototype weighs 600 grams, has a 1 m wingspan, and has a speed range of 0 to 20 m/s. *Inset*: wingtip motors are added to counter the rotation about the roll axis during a hover (i.e. torque roll).

gear ratio and a brushless motor which yielded 900 grams of thrust, the MAV has a thrust-to-weight ratio of 1.5. This high T/W ratio was required in order to balance the weight of the aircraft and an extra 100 gram payload when in hover mode. In cruise flight (i.e. wings parallel to the ground), it has a speed range of 5-20 m/s.

3.1 Transition Between Flight Modes

The most critical aspect of the hybrid design is the transition from cruise to hover flight, which will be used as a secondary collision avoidance maneuver (see Fig. 10). During this phase, there exists an angle-of-attack, α , for which the wings are no longer a contributing factor to the lift component (i.e. stall). To achieve the transition, the aircraft has to leverage its momentum and essentially overpower its way through the stall regime. This requires a high thrust-to-weight ratio so the momentum is not lost through the transition. Furthermore, as the aircraft is transitioning from cruise flight (minimum thrust) to the hovering flight mode, the throttle must be increased to balance the weight of the aircraft. The transition back to cruise mode is less complex. Vertical acceleration is first required to give the plane some momentum and then the elevator is deflected to pitch the aircraft forward into cruise mode.



Figure 10: Our MAV prototype with a 1 meter wingspan manually transitions from cruise flight (top left) through the stall regime (top middle) and into a hovering position (top right) to avoid a collision with a basketball net.

3.2 Hovering

After transitioning into the hovering mode, the attitude must be sustained by constantly adjusting four channels of a radio-controlled transmitter (see Fig. 11). Assuming the aircraft is in or close to the hovering attitude (i.e. fuselage is vertical), an expert human pilot must: (1) increase/decrease the throttle if the plane begins to lose/gain altitude, (2) apply left/right rudder deflection if the plane begins to yaw to the left/right, (3) administer up/down elevator if the aircraft starts to pitch forward/backward from the “nose-up” position, and (4) counter the moment created by the motor torque by deflecting the ailerons. Steps 1-3 can be seen in more detail in Fig. 12, which shows the forces acting on the MAV during a hover. The forces generated by the rudder and elevator deflection angles regulate the aircraft’s attitude while the thrust force balances the aircraft weight. Summing the forces in the vertical direction yields

$$T \cos \psi \cos(\theta - 90) - D \cos \psi \cos(\theta - 90) - F_E \sin \delta_E \cos(\theta - 90) - F_R \sin \delta_R \cos \psi - W = ma_z \quad (2)$$

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 . When the aircraft is in a perfect hover (i.e. $\theta = 90$, $\psi = \delta_E = \delta_R = a_z = 0$) the thrust must equal both the weight and drag forces.

4 Autonomous Hovering

In order to autonomously avoid a collision by transitioning into hover mode, both the transition into hover and the hover itself must be automated. To reg-

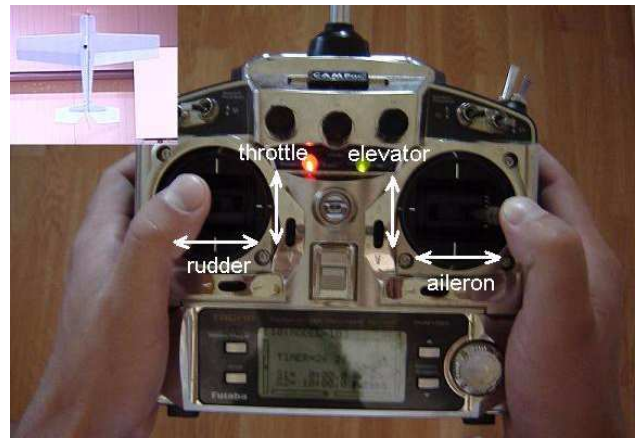


Figure 11: Manual hovering demands control of all four transmitter channels.

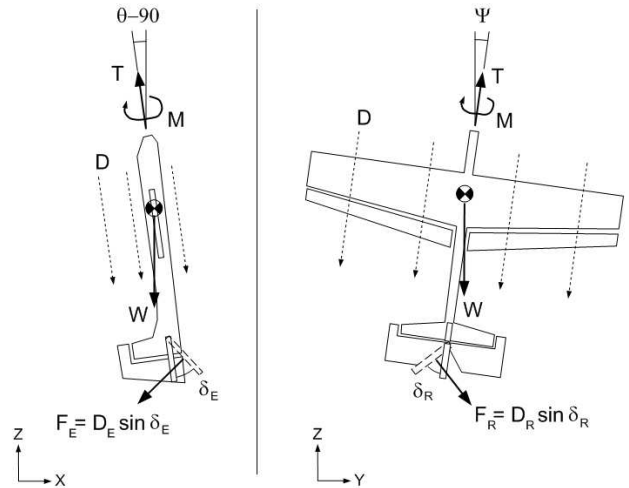


Figure 12: When in a hovering attitude, the elevator and rudder control surfaces are used to regulate the pitch and yaw angles, respectively.

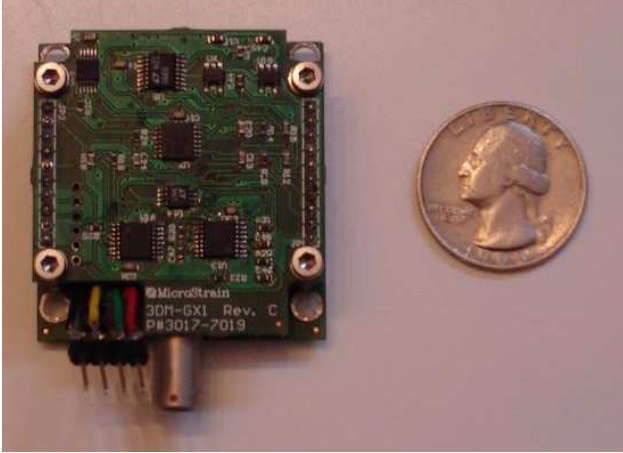


Figure 13: Microstrain’s 30 gram IMU sensor was used to feedback attitude information to the onboard control system.

ulate the attitude during a hover, data from a small and lightweight inertial measurement unit (IMU) is fed into an onboard control system. This data is captured during both manual and autonomous hovering and used to compare the controller performance to that of an expert human pilot.

4.1 Sensing and Control

Autonomous attitude control of this aircraft requires a sensor that can measure the vehicle’s orientation when pitch angles approach and exceed ± 90 degrees. Fig. 13 shows an IMU by Microstrain which outputs a gyroscopically stabilized four component quaternion describing the MAV’s orientation with respect to the fixed earth coordinate frame. It weighs just 30 grams (out of its protective casing) and is comprised of three triaxial accelerometers and angular rate gyros as well as three orthogonal magnetometers. The IMU, using RS232 communications, will transmit orientation data to the host computer at a clock cycle of around 10 ms. Therefore, embedding the sensor on the MAV platform will enable an onboard microcontroller to obtain the aircraft’s orientation at a rate of 100 Hz.

An onboard control system was designed using a PIC16F87 microcontroller and a RS232 converter chip to communicate serially with the IMU. The microcontroller pings the IMU for the current quaternion, q_c , which corresponds to the MAV’s attitude at that instant. The desired quaternion, q_d , which describes the MAV’s orientation during a hover, is

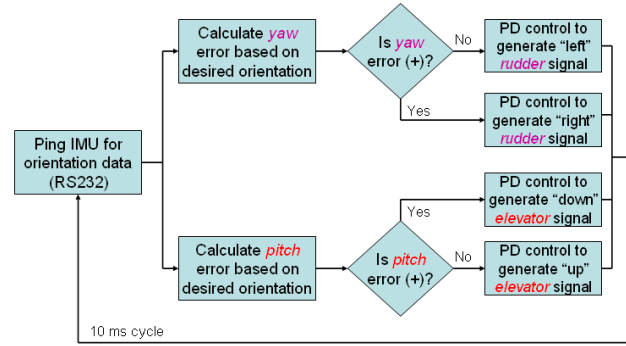


Figure 14: Flow chart describing the autonomous hovering code.

$$\begin{aligned}
 qw_d &= \cos(\theta/2) = 0.707 \\
 qx_d &= e_1 \sin(\theta/2) = 0.000i \\
 qy_d &= e_2 \sin(\theta/2) = 0.707j \\
 qz_d &= e_3 \sin(\theta/2) = 0.000k
 \end{aligned}$$

The error quaternion can be found using the following formula

$$q_e = q_c^* * q_d \quad (3)$$

where q_c^* represents the conjugate of the current quaternion. The yaw and pitch error can be extracted from q_e and proportional-derivative (PD) control is used to send pulse-width modulated (PWM) signals to the rudder and elevator servos. This, in turn, drives the aircraft orientation back to the hovering attitude. Fig. 14 shows the control loop which repeats continuously and is synchronized with the IMU clock cycle (i.e. every 10 ms).

4.2 Experiments

The first autonomous hovering experiments were conducted inside an urban structure with limited flying space (i.e. 3m x 3m area) to demonstrate that hovering can be sustained within small areas. The MAV’s attitude is under full autonomous control through rudder and elevator inputs while the height is adjusted manually through throttle commands via the pilot until the aircraft’s weight is balanced. Initial experiments demonstrated that the MAV was able to successfully hover in “hands-off” mode for several minutes before draining the battery (see Fig. 15).



Figure 16: A skilled 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).

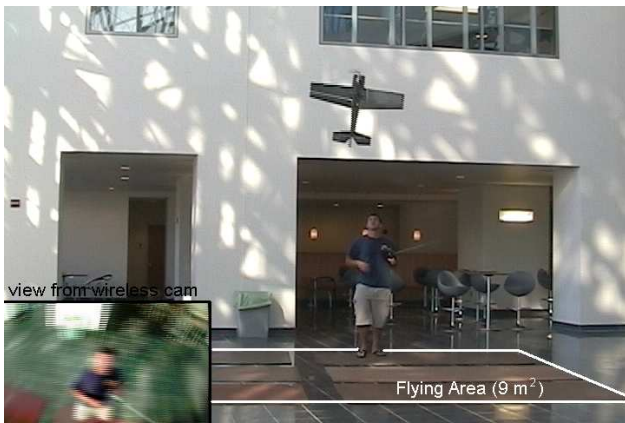


Figure 15: MAV performing a *hands-off* autonomous hover in an urban structure. *Inset*: also, a shot from the MAV's bellycam is shown.

Another experiment was performed to contrast hovering under both manual and autonomous control. The metrics used were duration of the hover before losing control and stability of the aircraft while in hovering mode. A skilled human pilot was initially given control of the aircraft and was instructed to fly around a gymnasium in cruise configuration, then transition from cruise to hover flight and attempt to hover the aircraft for as long as possible. The video stills¹ in

¹The video sequence shows three images extracted once a second for a period of three seconds. With the plane rotating

the top of Fig. 16 show the pilot struggling to keep the fuselage vertical, but is able to keep the aircraft positioned over a small area. Out of a few trials, the human pilot was able to sustain a hover for several minutes before draining the battery. However, the aircraft's pitch and yaw angles oscillated significantly as the pilot tried to maintain the hover. This is supported with a portion of the captured flight data, labeled *human-controlled*, in Fig. 17. Next, the pilot was instructed to again fly in cruise configuration and manually 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 control system. This time, the aircraft is fixed in a vertical position and is able to hover for more than 5 minutes before exhausting the battery (see bottom of Fig. 16). Again, the flight data was captured and a fraction of it is shown in Fig. 17.

As originally thought, the torque-roll did not effect the stability of the aircraft during a hover. That is, the MAV was still able to remain in the vertical position despite the rotations resulting from the motor torque. However, if this MAV were to be used in the field for surveillance and reconnaissance purposes, the view from the wireless camera onboard would have a dizzying effect as the plane was rotating at a rate of 15 at a rate of 0.25 revolutions per second, this is enough to show two quarter rotations.

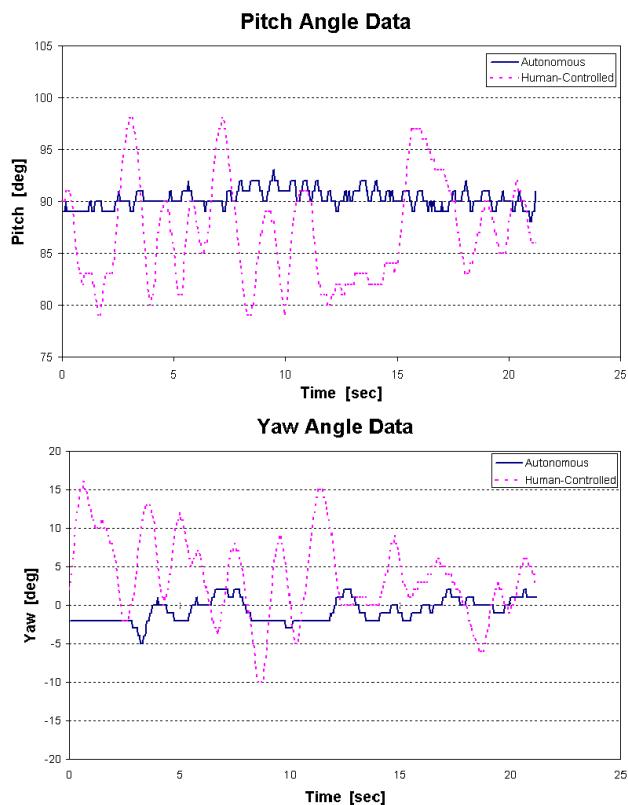


Figure 17: Pitch and yaw angles captured during both human-controlled and autonomous hovering.

rpm. Since the original aileron surface area did not create enough torque to counter the rotation, other alternatives had to be investigated. The first and most obvious is to increase the aileron surface area by lengthening them in the direction of the wing chord. However, this did not work because one, the prop wash during a hover only flowed over about 30 percent of the aileron and two, a longer aileron when fully extended caused some airflow to completely miss the tail which greatly effected attitude regulation during a hover. The second approach was to mount miniature DC motors on each wingtip, blowing in opposite directions to create a rotational force opposite that of the motor torque (see Fig. 9). Original experiments showed promising results as the torque rolling rate was decreased by more than 75 percent. Slightly more powerful motors are currently being investigated.

5 Conclusions

Flying in and around caves, tunnels, and buildings demands more than one sensing modality. This paper presented an optic flow-based approach inspired by

flying insects for avoiding peripheral collisions. However, there were a few real world scenarios where optic flow sensing failed. This occurred when obstacles on approach were directly in front of the aircraft. Here, a simple sonar or infrared sensor can be used to trigger a quick transition into hovering mode to avoid the otherwise fatal collision. Towards this, the authors have demonstrated a fixed-wing prototype capable of manually transitioning from conventional cruise flight into hovering mode. The prototype was then equipped with an IMU and flight control system to automate the hovering process. The next step in this research is to automate the transition from cruise to hover flight.

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