Modeling of Dive Maneuvers in Flapping Wing Unmanned Aerial Vehicles

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Abstract—For certain autonomous applications, flapping wing unmanned air vehicles (FWUAVs) provide a desirable balance between fixed wing and rotary air vehicles because they are fast, quiet, and maneuverable. Combined with autonomous stabilization and navigation, these platforms have the potential to allow close up chemical and visual inspections of areas using a dive maneuver. FWUAVs are good platforms for this task because they use limited wing motion and do not have to utilize propellers and rotors that would disturb the surrounding air. In this work, the diving behavior of a FWUAV is characterized and modelled. This model is then used in real time during flight to project dive paths and trigger an autonomous dive to descend to inspect an area.

I. INTRODUCTION

There are many advantages to flapping wing unmanned aerial vehicles (FWUAVs). Fixed wing UAVs fly at high velocities, making them less maneuverable than helicopters or quadrotors, while rotary wing platforms are loud due to high motor speed, slower, and less energy efficient. FWUAVs provide a balance between the two because they are fast, quiet, and maneuverable.

FWUAVs can be used as mobile scarecrows, crop examiners, or weather monitors, as well as recon for soldiers on the battlefield. FWUAVs look like natural creatures from a distance, so they are ideal for recon as enemy soldiers would not notice them as easily as something like a loud quadrotor darting around.

Previous work at the University of Maryland includes the Small Bird [1-2], Big Bird [3], Jumbo Bird [4-6], and Robo Raven [7-10] platforms. The first three each use one motor to drive both wings, while Robo Raven has independent wing control. One version of Big Bird featured folding wings enabling static lift generation in addition to aerodynamic lift [14], helping increase the payload capacity. The Robo Raven platform has programmable control over each individual wing’s position using high power servo motors and a microcontroller [7-8]. It has a wingspan of approximately 1 meter and weighs 290 grams. It flies in winds up to 10-15 mph, and its programmable individual wing control enables it to perform aerobatic maneuvers including dives, backflips, and tight turns. Robo Raven III is identical to Robo Raven except for the wings, which have integrated solar cells. These solar cells are used to charge the battery the FWUAV uses to fly [9]. Robo Raven IV uses an IMU, GPS, and PID control to autonomously stabilize and loiter in a given radius of a point [10]. Robo Raven V has the sensor capability of Robo Raven IV and has added thrust from two propellers at the rear of the platform [11].

There are many other avian inspired flapping wing platforms that are single motor driven. Two examples are Festo’s Smartbird [12] and Aerovironment’s Nano Hummingbird [13-14]. There are also many flapping wing insect and bat inspired platforms of note including Harvard’s RoboBees [15-16], the MicroBat [17], the BATMAV [18], Festo’s BionicOpter [19], and the Delfly series [20-23]. Most notably, the Delfly Explorer runs on one motor and uses an onboard gyroscope, barometer, and stereo vision camera to detect and avoid obstacles in its path. Finally, there are many single motor off the shelf hobby FWUAVs [24-26].

Controlled aerobatic maneuvers are mostly limited to fixed and rotary wing MAVs like UPENN’s quadrotors [27] and a fixed wing MAV at UIUC that can land on a human hand [28]. The two exceptions to this are the Robo Raven platform and Bat Bot, a bat inspired robot with multiple articulated degrees of freedom in each wing capable of flight without a conventional tail, hovering, inverse perching, and quick turning [29]. FWMAVs like the Robo Raven and the H² Bird have also been launched off of moving RC cars and hexapedal robots [30].

Aerobatic maneuvers are useful in many ways, specifically for close up inspection of an object or area. While fixed and rotary wing MAVs or UAVs would disturb the environment with a close up inspection, FWUAVs would not because they are much quieter and displace less air. This is useful if an unknown object must be identified up close at a given location, or if there is a chemically affected area that needs to be inspected without disturbing the air.

The motivation of this work is to characterize and model the dive behavior of a FWUAV so that dives can be executed in flight in a controlled fashion for search and rescue missions, and for more inconspicuous surveillance. For example, distressed individuals may seek to hide within secluded and obscured environments where a conventional quadrotor drone may be noticed by them and cause them to become harder to locate. A dive maneuver is used because it is a useful maneuver for quick descent and is often used by...
real birds. Making this maneuver autonomous makes flight adjustments quicker and more refined and eliminates the need for a pilot to have visual contact during the dive. There are potential applications in search and rescue robotics including close up inspection of damaged or delicate structures and examining potentially dangerous areas.

In this paper, the Robo Raven V platform is described, its dive mechanics are characterized and modelled, and the autonomous dive algorithm is described and used to trigger an autonomous dive towards an inspection area.

II. PLATFORM OVERVIEW

A. Hardware and Control Architecture

Robo Raven V (Figure 1) is a FWUAV constructed of Delrin®, carbon fiber tubes and rods, and Mylar. A laser cutter is used to manufacture 2D parts from Delrin® sheets, and these parts are then connected to create parts of the frame. Carbon fiber tubes form the main structure of the frame and fit into the laser cut parts with interference fits.

The wings are built using carbon fiber tubes and rods with Mylar stretched across them. They are attached to the platform by sliding the main front carbon fiber rods at the front of the wings into laser cut Delrin® parts that fit over the aluminum servo horns on the main drive servos. These main servos are rated for high torque and high speed and are used to drive the wings and tail. An ArduPilot 2.5 microcontroller is used to control the platform.

Two props on the back (Figure 2) give added thrust to the platform to increase the payload. These motors are placed on the ends of laser cut parts or "arms" connected to the frame. These arms are controlled by servo motors and can be moved up and down above the center axis of the platform. The added thrust of these propellers significantly increases the lift generated by the wings because of the increased speed of the bird.

The Robo Raven V platform has a payload of 212 grams in addition to its weight of 450 grams. It flies at about 9 m/s and about a 20° angle of attack and flaps at 4 Hz.

Figure 3 shows the control architecture of Robo Raven V. The remote sends commands to the onboard receiver which is connected to the ArduPilot that controls the wing and tail servos, and props. PID control is incorporated for roll stabilization with the tail as the actuator. Finally, switches on the remote are used to switch between autonomous and manual control modes.

III. DIVE CHARACTERIZATION AND MODELING

Diving is initiated by moving both wings to a specified degree dihedral and holding for as long as the dive command is given. Airspeed increases during the dive motion, reminiscent of an attacking bird of prey. Flapping is resumed at the end of the motion to allow recovery and continued flight (see Figure 4). During the dive, the motors are turned off and generate no forward thrust.

In this section we characterize Robo Raven V’s diving and develop a model to predict its dive path based on initial conditions. We create the dive model by summing forces to solve for the horizontal and vertical accelerations, velocities, and positions as a function of time using Forward Euler Integration. We then compare this model to actual position information extracted from video footage of 20 dive tests with the Robo Raven V (5 tests at each dihedral of 30°, 35°, 40°, and 45°). A least squares error fit is used to optimize the
drag and lift coefficients to minimize error across all of the tests.

\[
\begin{align*}
\alpha_x &= -\frac{1}{2m} \rho_{air} C_D [A_h \cos(\theta_p) + A_v \sin(\theta_p)] V_y^2 \\
\alpha_y &= g + \frac{1}{2m} \rho_{air} \left( A_v \cos(\theta_p) + \sin(\theta_p) A_h \right) C_D V_x^2 + C_L A_w \cos(\theta_p) \cos(\theta_d) V_x^2 
\end{align*}
\]

where \( A_h \) and \( A_v \) are the horizontal and vertical cross sectional areas in the horizontal and vertical directions, \( C_D \) and \( C_L \) are the horizontal and vertical drag coefficients and the lift coefficient, and \( \theta_p \) and \( \theta_d \) are the pitch and dihedral angle. \( m \) and \( \rho_{air} \) are the mass and air density. Shear drag is ignored. The lift force is included because the wing deforms into an airfoil shape during normal flapping, and it is unclear how much of an airfoil develops during diving when the wings are held still. \( x \) and \( y \) refer to the global frame and \( h \) and \( v \) refer to the FWUAV frame.

We perform numerical integration to obtain the velocity and position of the FWUAV throughout time.

\[
\begin{align*}
V_{x_{i+1}, y_{i+1}} &= V_{x_i, y_i} + \alpha_{x, y} \Delta t \\
P_{x_{i+1}, y_{i+1}} &= P_{x_i, y_i} + V_{x, y} \Delta t + \frac{1}{2} \alpha_{x, y} \Delta t^2
\end{align*}
\]

The error function is given by

\[
E = (x_{model} - x_{actual})^2 + (y_{model} - y_{actual})^2
\]

The initial condition \( V_{x_0} = 0 \) for each test. \( V_{x_0} \) is extracted from video footage along with pitch information for each test. The bird’s position is measured in pixels from the video frames (sampled at 10 Hz) and converted to meters. The frame resolution is 720p. Figure 5 shows an example of what this position data looks like, plotted on one figure. The data integrity is checked using GPS position to make sure the FWUAV dive path is perpendicular to the camera view.

Figure 5 - Aerobatic dive sequence with the wings at a 45 degree dihedral. Frames in this image are 1/15 seconds apart.

IV. AUTONOMOUS DIVE TRIGGERING ALGORITHM

A. Preparation

To effectively execute a dive, the Robo Raven must first navigate to the diving location. For this task, Robo Raven V uses a GPS, compass, the angle its heading makes with the vector from its current position to the goal point, and roll data for PID stabilization. The tail is used to turn the platform and is the actuator for roll stabilization. See [10] for more details on this algorithm.

B. Algorithm

The dive is triggered during the navigational algorithm as shown in the function block diagram in Figure 6. The FWUAV will always choose the smallest dihedral during the
dive to make the smoothest and safest dive. If it is close enough to the desired inspection area such that a dive with the current selected dihedral would overshoot, the dihedral is automatically increased by 5 degrees until the projected dive ends within the inspection area.

The dive will only trigger if (1) the horizontal component of the projected dive places the FWUAV within a 5 meter radius of the inspection area and (2) the FWUAV is higher than 7 meters in the air.

Because future pitch information is not available, the code uses the current pitch of the bird as constant pitch during each dive projection. This is a source of error in the dive modelling and execution. The dive projection is updated at 4 Hz (the update rate of the GPS, which is used for velocity information in the dive projection). While the dive is triggered autonomously, recovering from the dive is currently done manually.

V. RESULTS AND DISCUSSION

A. Dive Model

Treating the drag and lift coefficients as constants and varying each from 0 to 1.5 (as opposed to functions of the dihedral angle), the minimum error was found to occur at $C_{Dx} = 0.859$, $C_{Dy} = 0.857$, and $C_L = 0$. The error value at this point was found to be $E = 288.6 \text{ m}^2$.

These values make sense. Drag coefficients of flat plates vary between approximately 0.4-1.6 depending on the angle of the plate and Reynolds number [31], and a lift coefficient of 0 indicates that the wings are not deforming into an airfoil shape. This makes sense because force of the air on the wings in the horizontal direction likely flattens them during the dive, resulting in minimal deformation.

Figures 7 through 10 show comparisons of the video data with the optimized model for dihedrals of 30°, 35°, 40°, and 45°. These are typical results, with variation in the final horizontal and vertical positions generally less than 1-2 meters. The initial horizontal velocity varied between tests. Weather conditions were calm during flight testing, with an occasional breeze of 1-2 mph.

Sources of error include limited video definition, manual dive control, and the occasional breeze during testing. The final model can be used to predict the dive path as a function of dihedral angle (see Figure 11). As expected, increasing the dihedral angle increases the dive steepness.
**B. Autonomous Dive Triggering Algorithm**

To verify the algorithm, the FWUAV was flown outside in an open field with the autonomous dive triggering code. Onboard data logging of the platform’s position and height allow for a 3D plot of its path. Figures 12 and 13 show the flight path of the platform from isometric and top views. In these figures, the red dot is the desired inspection point at coordinates of $(0, 0, 0)$ and the blue dots are the flight path.

These figures show that the platform was able to trigger an autonomous dive towards the inspection area. Figure 12 shows that the dive triggered at 19 meters from the target and the nadir of the dive was located 2 meters from the target.
VI. CONCLUSION

In this paper, dive behavior of a FWUAV was characterized and modelled by fitting a physics model with optimized drag and lift coefficients to video data. This model was used to do real time dive path projection to trigger autonomous dives toward an area. Future work includes adding pitch estimation, external wind conditions, autonomous dive recovery, and comparing video data to data from the onboard IMU.

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REFERENCES


