AUTONOMOUS GUIDANCE AND CONTROL OF A BIOMIMETIC SINGLE-WING MAV

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We discuss the guidance and control of the Samarai MAV—a single-winged, wholly rotating, biomimetic micro air vehicle developed at Lockheed Martin Advanced Technology Laboratories. Samarai is inspired by, and named after, the samara or maple seed *Acer diabolicum* Blume. It weighs 200 grams and consists of a single wing of radius 30 centimeters with an electric motor/propeller at the tip and torque-rod driven trailing-edge flap as the sole control surface. One end is attached to a hub containing a full suite of avionics for measuring its states in all degrees of freedom. While Samarai exhibits the passive rotational stability inherent in maple seeds, the onboard avionics and flight controls give it the added capability of powered flight to specific locations—under high-level operator guidance or autonomously. We will discuss the innovations in vehicle modeling, state sensing/estimation and control needed to realize these capabilities. We will also present experimental results.

INTRODUCTION

Micro air vehicles (MAVs) – capable of both indoor and outdoor operation—are getting attention in the unmanned aircraft systems (UAS) community. Further, MAVs that hover and perform vertical takeoff and landing (VTOL) are of added interest. There are numerous civilian and military applications for these capabilities, including operating in confined spaces and surveillance/reconnaissance. Inherent difficulties in achieving viable flight designs at a smaller-scales, including Low Reynolds number aerodynamics, micro-actuation and micro-propulsion, have led researchers to draw engineering inspiration from nature. These biologically-inspired air vehicles attempt to mimic nature’s flyers and gliders. They include flapping wing designs motivated by insect or bird flight and single-winged flyers inspired by fruits and seeds. Winged seeds, called samaras, are perhaps the most-simple, stable and efficient flyers nature has created. Samaras disperse themselves by auto-rotating passively using a single wing as they descend from trees, thereby ensuring they are widely dispersed. Inspired by these flight concepts, Lockheed Martin Advanced Technology Laboratories (ATL) developed the Samarai MAV—a 30 centimeter radius maple seed-like aircraft that can autonomously take-off/land vertically and fly laterally (like a helicopter) to the intrinsic stability of nature’s maple seeds. This is shown in Figure 1.

Similar to the seed, the Samarai MAV is wholly rotating, providing a 360-degree scanning capability to any sensor onboard the vehicle. We will describe the MAV and discuss the approach adopted for modeling, state sensing/estimation and guidance and control.

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Figure 1. The Samarai MAV design is inspired by nature’s maple seeds. In flight, it spins in the same manner as the maple seed, but also adds the ability to fly like a helicopter

Although the MAV flies like a helicopter, its Low Reynolds number aerodynamics, coupled with wholly rotating degrees of freedom, make it impractical to adopt typical high fidelity modeling techniques used for helicopters. Our research methodology begins with an analytical model and then creates empirical nonlinear models from flight test data, which map control inputs (flap and throttle) to rotational/translational motion variables. This flight data is obtained using a high rate Vicon motion capture system. Because the MAV’s entire body rotates, state sensing using common inertial packages is problematic. We created custom avionics packages using sensors that tolerate these rotations when mounted in specific configurations. Signals are then fused and processed through an extended Kalman filter to estimate vehicle states. In the area of guidance and control, the key problem is simultaneously maintaining lift and controlling the MAV’s translation using only a single control surface with limited actuation authority. This and limited processing/computational abilities requires algorithms to be robust and lightweight. Our approach uses a magnetometer to sense the vehicle’s rotational phase/rate. Then its dynamics are transformed to that of a spinning disk able to tilt and translate (similar to a helicopter) by modulating the flap at specific points during the rotation.

Single-wing UAVs such as the Samarai MAV are inherently stable in hover, mechanically simple, have clean aerodynamics and very few moving parts. The control problem for the MAV can be simplified to that of controlling a virtual disk created by the spinning blade. The motion of this disk is similar to, but simpler than, that of a helicopter rotor. It is possible for this type of vehicle to have a wing loading one tenth that of a conventional helicopter or flapping wing design of the same size because, for a dimensional constraint, the greatest Reynolds number for a flight vehicle is achievable with a rotating wing. This reduces the power requirement for a given flight endurance. Recent work has shown that a single rotating wing requires half as much power as a flapping wing to achieve a comparable level of flight performance. Others have reported the development of single-winged vehicles. In these efforts, data collection and sensing of relevant vehicle states are done externally—i.e., “off-board”—typically using a vision based motion capture system. The Samara MAV features a complete suite of avionics and sensors, enabling state sensing during flight experiments to be done on-board the vehicle. This key feature enables completely autonomous operation requiring no off-board sensing or computation.
We also provide a description of the MAV followed by a discussion of the modeling and simulation approach. The sensor suite and associated state estimation approach are briefly discussed followed by guidance and control. An example flight experiment demonstrating autonomous control is then described followed by concluding remarks.

SAMARAI MICRO AIR VEHICLE

The Samarai MAV is a 30 centimeters radius; 200 gram single-bladed air vehicle that rotates at 600 revolutions per minute. A motor driving a small propeller is mounted on the tip of the blade to provide propulsion. A portion of this blade is cut out to act as a trailing-edge aerodynamic flap driven by a servo torque-rod assembly mounted at the root end of the flap. This is the sole control surface for the MAV. The other end of the blade is attached to an avionics/payload pod through adjustable spars that enable its angle of inclination relative to the pod to be adjusted as needed. A pair of music wire bent into a skid extending about 2-3 centimeters in front of the wing leading edge act as landing gears. These features are shown in Figure 2.

To estimate the performance of the MAV, we use a helicopter performance method based on momentum theory model for induced power, a profile power model for rotor drag and a parasitic model for forward flight power. Figure 3 shows the mechanical power delivered to the airframe from the propeller (broken down into induced, profile and parasitic power) as a function of forward flight speed.

This shows that the power required to hover is ~7.5W, decreasing to ~6W when the MAV is flying at a speed of 4 meters per second. Speeds above this ~8m/s would require more power than needed to hover.
Figure 3. Flight power breakdown for the Samarai MAV. This power contribution from the various elements of the aircraft’s flight was obtained using modified momentum theory analysis.

OVERALL MAV SYSTEM

The overall closed loop MAV system is implemented as a MATLAB® /Simulink® end-to-end simulation outlined in Figure 4. In operation, the vehicle receives high-level operator commands or flight plans which the guidance and control subsystems transform into flap deflections and throttle commands applied to the MAV. As flight proceeds, sensors packaged in a suite of avionics measure the vehicle’s states. Estimates of the vehicle’s true states are then made and packed in a state vector that the guidance and control subsystems use to compute the set of desired throttle and flap commands. The Guidance, Control and State Estimation subsystems are auto coded and downloaded to the flight computer onboard the MAV for flight experiments. Each of these subsystems is described next.

THE MAV MODEL

To model the MAV, we begin with an analytical model developed from first principles. The procedure is to use a CAD model of the vehicle that captures its blade geometry and inertia distribution. The model receives flap deflections and engine throttle via revolutions per minute setting as input. These are then mapped to forces (F) and moments (M) acting on the body through tables of aerodynamic and propulsion coefficients. The response of the vehicle to these inputs is encapsulated in the state vector $X= [P \ V \ \omega \ q]$, where $P= [P_x \ P_y \ P_z]$ is the position vector of the center of gravity, $V= [V_x \ V_y \ V_z]$ is the translational velocity, $\omega= [\omega_x \ \omega_y \ \omega_z]$ is the angular velocity vector and $q= [q_0 \ q_1 \ q_2 \ q_3]$ is the attitude quaternion. Vehicle state evolution is governed by the 6DOF rigid body equations of motion (EOM) given by Equation (1).

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\begin{align*}
\dot{P} &= RV_b \\
m\dot{V} &= \sum F - \dot{\omega} \times (mV) \\
I\dot{\omega} &= \sum M - \dot{\omega} \times (I\omega) \\
\dot{q} &= \frac{1}{2} \dot{\Theta}q
\end{align*}
\]
Figure 4. Main components of the MAV System Simulation. Vehicle dynamics are embedded in the MAV subsystems; sensor models in the Sensors subsystem; an extended Kalman Filter in the State Estimator subsystem, and Guidance and Control algorithms in similarly named subsystems. For flight experiments, the state estimator, guidance and control subsystems are auto coded and downloaded to the MAV’s onboard processor.

where \( V_b \) is the body frame velocity, \( m \) is the mass of the vehicle, \( \omega \) is the skew symmetric matrix of angular velocities, \( I \) moment of Inertia, \( R \) the rotation matrix from body to inertial frame and \( Q \) is the quaternion wedge matrix. This approach produces a comprehensive high fidelity vehicle model (represented by the MAV sub-system in Figure 4). However, it is too complex for use as an onboard model for state estimation and feedback controls. Therefore, we also developed a simpler model based on empirical flight data.

This model, shown in Figure 5, maps flap and throttle control inputs through empirical models of the actuators to climb/descent rates and translational velocities with simplifying assumptions on aerodynamic loading. Observe that the state vector for the empirical model specifies vehicle attitude in Euler angles rather than quaternions.

Experimental data is collected by using a Vicon motion capture system and manually flying the MAV in ways that excite each degree of freedom by using a combination of throttle setting and control surface deflections. Separate models are created for the vertical and horizontal degrees of freedom based on experimental data. See our earlier work for examples of the results from the empirical modeling process\textsuperscript{13}. The MAV subsystem in Figure 4 is typically the analytic model given by Equation (1) while the vehicle model used in the state estimator and controller is the empirical model described by Figure 5.
Figure 5. The empirical modeling approach uses experimental data to model the flap actuator and throttle dynamics as well as flight test data that represents mapping from vehicle rotation rate and cyclic/collective flap to forward flight speed and climb rate. The quaternions in the analytical model are converted to Euler angle representation to match the empirical model in the simulator.

SENSING AND STATE ESTIMATION

The avionics suite onboard the Samarai MAV packages a number of sensors in an atypical configuration designed to ensure accurate measurements for state estimation without a significant impact from the vehicle’s whole body rotation. The avionics package, shown in Figure 6, contains sensors that enable measurements of all of the vehicle’s rotational and translational states. These sensors are identified in Table 1.

Figure 6. The avionics package onboard the Samarai MAV features a suite of sensors arranged in non-traditional configurations that enable accurate measurement of full vehicle state.
Table 1. MAV sensors and their function

<table>
<thead>
<tr>
<th>Sensor</th>
<th>State Measured</th>
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<tbody>
<tr>
<td>Magnetometer (3-axis)</td>
<td>Rotational phase and rate; attitude refinement</td>
</tr>
<tr>
<td>Accelerometer (Tangential)</td>
<td>Roll, pitch, lateral acceleration, vibration</td>
</tr>
<tr>
<td>Accelerometer (Vertical)</td>
<td>Total tilt angle, climb acceleration, vibration</td>
</tr>
<tr>
<td>Gyro</td>
<td>Vehicle pitch/roll, vibration</td>
</tr>
<tr>
<td>Static pressure sensor</td>
<td>Pressure altitude, climb rate</td>
</tr>
<tr>
<td>Dynamic pressure sensor (pitot)</td>
<td>Relative wind speed/direction</td>
</tr>
<tr>
<td>GPS</td>
<td>Position, ground speed, altitude</td>
</tr>
</tbody>
</table>

Each sensor measures a specific component of the state vector for the onboard vehicle model shown in Figure 5. State estimation is accomplished in two steps. First, low-level filters are applied to the raw sensor data. Then true vehicle states corresponding to these filtered measurements are estimated using an Extended Kalman Filter that runs on the vehicle’s main processor. The MAV also uses an onboard Avionics Processor to interact directly with sensors and vehicle control components (flap and throttle).

GUIDANCE AND CONTROL

The main control challenge for a wholly rotating vehicle such as the Samarai MAV is how to simultaneously maintain lift and control translation to specific points using only a single control surface with limited authority. To solve a similar problem in a conventional helicopter, the angles of the rotor blade are adjusted in flight using a device called a “swashplate.” The swashplate’s action has the effect of changing the direction of thrust generated from the blade. Although the MAV is similar to a helicopter in many respects, it does not possess a swashplate. Therefore, our approach is to solve this problem by creating a virtual swashplate that consists of the entire rotor disk whose attitude is controlled using a single flap. In this scheme, flap deflections are modulated at precise rotational phase angles to generate forces/moments needed to sustain lift and also tilt the rotor disk by an appropriate amount in the desired direction of flight. This has the desirable effect of causing the vehicle to fly in that direction. In Figure 7, we compare the action of a physical swashplate to that of a virtual swashplate.

**Figure 7.** The virtual swashplate control methodology essentially attains the same functionality as a helicopter’s complex mechanical swashplate using only a single flap and rotational phase sensed by a magnetometer. (Details are not included due to a patent pending on this technology.)
The virtual swashplate approach is at the heart of our guidance and control scheme (Figure 8). It is designed using an inner-outer loop decomposition that maps desired motion to actual flap and throttle commands to the MAV. Guidance commands are specified in terms of two autonomously controlled flight modes: Waypoint mode and Velocity mode. In waypoint mode, the vehicle flies to specific North, East, and height (N-E-H) coordinates relative to a reference point. In velocity mode, the vehicle flies at a specified speed in a commanded direction using commands specified as speed, heading, and height.

![Figure 8. Autonomous Guidance and Control scheme for the MAV features a cascade of position and velocity control subsystems that map desired commands to flap deflections and throttle setting](image)

For waypoint mode commands, the position control loop uses a simple linear control scheme to compute the desired velocity to attain these positions. The velocity loop then generates control commands that control translational and rotational velocities. Rotational rate is controlled within the engine control loop also using linear controller. A proportional controller with feed-forward terms controls vehicle climb rate by determining the required throttle setting to sustain lift. If only small changes in vehicle climb rate are desired, the throttle is used exclusively to control vehicle height. Otherwise a combination of collective flap and throttle percentage are used. If the required waypoint includes translational motion segments, cyclic flap commands are also computed within the velocity control loop.

Velocity mode commands bypass the position control loop and directly drive velocity control loop. In response, the controller regulates collective flap up and down positions and throttle setting in response to vertical motion commands. Based on the commanded forward speed and direction, cyclic flap commands are computed corresponding to specific rotational phase of the wing to cause a disk tilt and translation in the desired direction. In this way, our approach essentially synthesizes a virtual swashplate.

**EXPERIMENTS AND RESULTS**

We have successfully flown the Samarai MAV in multiple indoor and outdoor flight experiments, demonstrating autonomous flight to waypoints, higher-level operator directed flights and
automatic tracking of speed and heading commands. Videos of some of these flights are available on YouTube†.

Results from a typical autonomous flight carried out in an indoor field are shown in Figures 10 – 12. The mission profile for this experiment required the MAV to:

a) Take off and hover at a height of 3 meters above ground level (AGL) until t=10s

b) Fly at a speed of 2 meters per second (m/s) in a direction corresponding to a heading of 116 degrees until t=35s. Note that the coordinate frame is defined such that a heading angle of 0 degrees corresponds to flight due East while due North corresponds to 90 degrees.

c) Hover at this location for 10s

d) Fly at a speed of 1.25 m/s with desired heading of 310 degrees until t = 65s

e) Hover at this location for 10s

f) Descend to land

Figure 9 shows the MAV flying the desired trajectory with these motion segments identified by the labels (a) - (f).

![Figure 9. Overall flight path of the MAV showing autonomous flight in response to time-parameterized speed and heading commands.](image-url)

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† http://www.youtube.com/watch?v=5LqSWiatV0Q&feature=related
† http://www.youtube.com/watch?v=Pbegin59K6s&feature=related
For additional insights into the MAV’s flight performance for each motion segment, we show state variables and controls for the vertical and translational motion. In Figure 10, the MAV quickly ascends to the commanded height of 3 meters with ~0.5 meters error (top plot in Figure 10). It essentially holds this height until mission conclusion and then lands. Note that the initial downward dip in the climb rate (middle plot in Figure 10) occurs before the control law is engaged (at t=5s). Once this happens, there is a downward collective flap of 20 degrees (bottom plot) that generates a lifting force resulting in positive climb rate. This causes the MAV to lift off and hover at the commanded height. Observe the transients in collective flap deflections each time the motion segment changes.

![Figure 10. The MAV’s height (top), climb rate (middle) and collective flap deflection (bottom) for the flight profile. Downward collective generates lift that causes the vehicle to ascend to the desired height. This height is maintained using a collective offset until the collective flap deflects upward to push the vehicle down at t=75s.](image)

In Figure 11 we show the translational motion variables. The MAV tracks the speed commands with some transients during changes in the motion segments (second plot from bottom). Cyclic flap deflections are also timely and appropriate for the desired speed.

**CONCLUSION**

This work has described the Samarai Micro Air Vehicle (MAV) and discussed the approach taken for modeling; state sensing and estimation; and guidance and control. Results showed
Figure 11. The MAV’s North and East position coordinates (top); total distance traveled (second from top); speed (second from bottom) and cyclic flap deflections (bottom). Observe that cyclic deflections begin promptly at t=10s when the first translation motion segment starts and decays to zero during hover at t=35s to t=45s. Also note that the amplitude of the cyclic flap deflections is proportional to the desired speed; ~5 degrees for a 2m/s desired speed and ~3.3 degrees for 1.25m/s.

successful autonomous flight with all sensing and computation completely onboard the MAV. We are continuing to perform flight experiments with this vehicle to evaluate appropriate payloads, missions and concepts of operation for which it will be of utmost utility to users. We are also developing schemes to improve the MAV’s wind and gust tolerance.

REFERENCES


