From Insects to Machines

Demonstration of a Passively Stable, Untethered Flapping-Hovering Micro-Air Vehicle

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Insects and hummingbirds remain unmatched in their aerodynamic ability to hover in place in addition to other acrobatic feats such as flying backward and sideways by exploiting flapping-wing motion [1]. Although this remarkable ability is key to making small-scale aircraft, flapping-hovering behavior has been difficult to reproduce artificially because of the challenging stability, power, and aeroelastic phenomena involved. Recent interest in small-scale unmanned air vehicles, especially those capable of hovering like insects and hummingbirds, is driven by many potential applications. A number of flapping machines have been developed [2]–[8], but only two are capable of untethered hovering flight [9], [10]. A key challenge is to demonstrate a stable untethered flapping-hovering ability at a weight and power approximating that of insects and birds where flapping-hovering flight is observed in nature. Here we demonstrate, for the first time, a passively stable 24-g machine capable of flapping-hovering flight at a Reynolds number similar to insects ($Re = 8 \times 10^3$). This architecture, particularly the passive stability, may help in the design of insect-sized hovering vehicles as well as shed light on the aeroelastic dynamic principles underlying insect flight.

For the past several decades, researchers have been studying the complex flows form that allow insects to perform such incredible aerial feats, and what effect they have on flight at small scales, with the hope of building a fly-sized flapping-hovering machine. Flapping flight, such as that employed by insects, offers several advantages over ornithoptic flapping flight as seen in larger birds or fixed and rotary wing flight, most notably in scalability to small sizes [11]. This is particularly the case for hovering at low air speeds, where it has been shown that the efficiency of flapping wing flight exceeds both the fixed and rotary wing flight [12]. At smaller sizes, such as that of a fruit fly, fixed wing airfoils become less efficient than flapping flight because of the low Reynolds number. Low Reynolds numbers also appear in thin atmospheres such as that found on Mars [13], where conventional airborne exploration would be difficult. Flapping flight also offers the potential for more agile and robust flight systems, as can be observed in the maneuverability and resilience of insects in tangled and confined environments. With these advantages in mind, and the countless applications ranging from surveillance and exploration to artificial pollination and flocks of rapidly reconfigurable three-dimensional (3-D) airborne machines, there has been a significant effort toward demonstrating a robotic fly.

Current work has focused on thrust mechanisms that produce sufficient lift for hovering flight and that provide a

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future of possible methods for control. Significant work has been done on forward-flying flapping micro-air vehicles, but these cannot hover. Two micro-air vehicles have demonstrated hovering abilities, most notably, Stanford Research Institute International (SRI)/University of Toronto Institute for Aerospace Studies (UTIAS) and Delaurier's Mentor project [10] and the DelFly 2 from Technische Universiteit (TU) Delft [9]. Both these machines take advantage of opposing wing pairs flapping together and rely on vane-type surfaces for control. Fearing and Wood [5] have recently demonstrated a fly-sized flapping machine takeoff but used off-board power and stabilization. The design presented here offers a scalable flapping wing architecture that provides the opportunity for quad-rotor-like active control using flapping wing pairs rather than vane surfaces for control. We further demonstrate that the machine is passively stable, thus eliminating the need for active stabilization control, a property that may help eliminate the need for complex and relatively heavy active stabilization systems in smaller-scale future designs.

Aerodynamics of Flight

The key to building a flapping-hovering machine is understanding the aerodynamic forces involved as well as the wing motions and aeroelastic dynamics required to generate those forces. It has long been established that there must be interactions beyond traditional aerodynamic theory that accounts for insects' ability to actually fly [14]. Scientists have been working on understanding the complex unsteady aerodynamic flows that form in the intermediate Reynolds numbers between 10^1 and 10^4, where insect flight generally falls [15]. Although the precise mechanism that forms and utilizes these flows is still an active research area, underlying theories to explain the phenomena have come a long way.

The first unsteady aerodynamic effect proposed to explain lift enhancement in insects is the Weiss-Fogh Clap and Fling effect, which has been described in detail using both insects and robotic setups [16]. As the wings start to peel apart at the beginning of the fling phase (outstroke), a low-pressure region forms that pulls air into the cleft around the leading edge (Figure 1). This influx of air strengthens the formation of the leading edge vortices, which increase the circulation and thus lift. In Figure 1, the machine is shown under a strobe light during normal flapping at 20 Hz. The image is composed of several individual images to show both the in and out stroke of each wing pair. The inner pair is the outstroke, and the outer pair the instroke. Air drag and momentum bend the wings, providing an appropriate angle of attack, allowing for positive lift generation throughout the entire cycle. The fluid inertia combined with the slowing down and switching direction passively pitches the wings. Similar mechanisms for wing control have been observed in insects (see Figure 2). A similar mechanism, though less pronounced, takes place on the clap, where the air leaving the gap between the two wings helps increase vortex formation [16].

In addition, three more general mechanisms for lift enhancement beyond traditional aerodynamic theory (including airfoils and drag induced lift) have been established: delayed stall, rotational circulation, and wake capture [14]. Delayed stall is a translational mechanism by which leading edge vortices are formed, resulting in a higher circulation about the wing, increasing net lift. Rotational circulation is a mechanism whereby the rotating surface of the wing nearing the end of its half stroke pulls air in the boundary layer along with it, increasing the circulation, and thereby the lift. Wake capture is also a rotational mechanism whereby the wings recapture the wake from the previous half stroke on their return, taking advantage of the energy already spent to generate the vortex wake [14].

Passive Wing Pitching

An important factor in controlling the formation and utilizing these aerodynamic processes is the precise control of the wing. Using a robotic setup, Dickinson proposed that by carefully

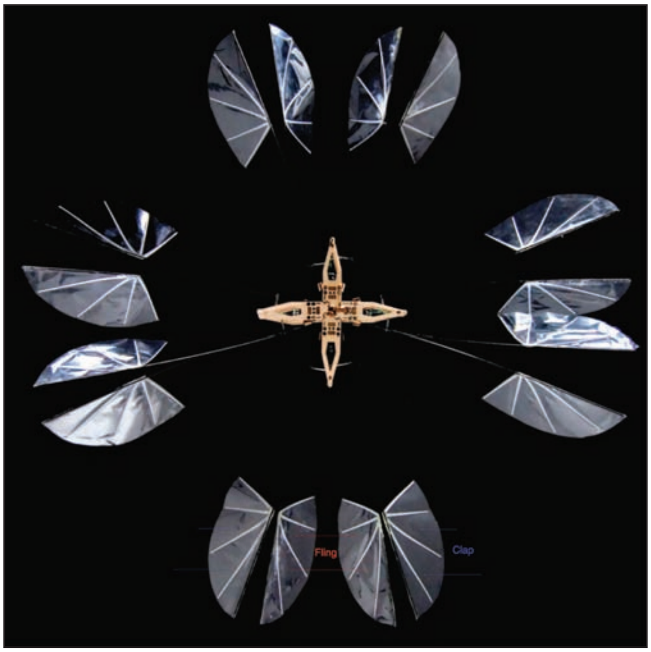

Figure 1. *Aeroelastic wing bending (top view).*

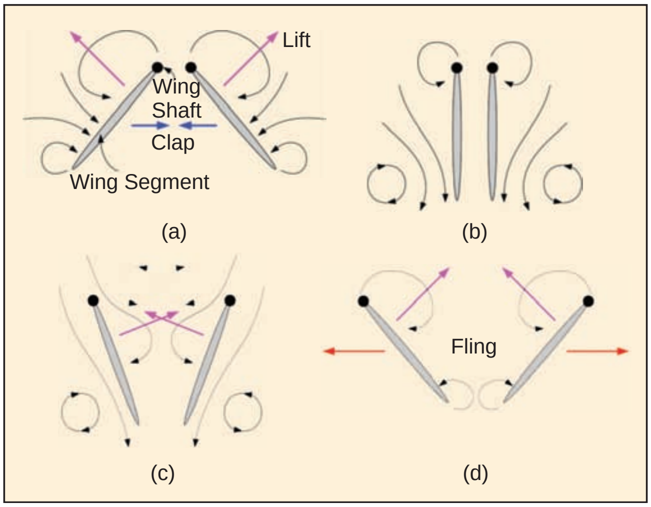

Figure 2. *Aeroelastic wing bending and vortex formation, side view. Diagram depicting vortex formation and shedding throughout the cycle. As the wings come together, (a) vortices are formed at the trailing and leading edges, and (b) these are then shed and (c) recaptured during the fling phase. (Image adapted from [16].)*

controlling the timing of the wing pitch and delayed stall, the insect could theoretically increase its lift by 35% during peaks [14], but this comes at a cost of increased drag and reduced efficiency [15]. Recent work on insect flight dynamics has shown that energy efficiency is improved through the use of wing dynamics to help pitch the wing [17]. Studies on the hawk moth have shown that wing bending is even largely independent of fluid dynamics, suggesting that complex stroke patterns can be designed purely through wing architecture and careful design of the wing's moment of inertia [18]. Further work on drosophila wing stroke patterns has shown that it is likely that the majority of the pitching occurs passively [19]. Nearly all successful small-scale flapping-based machines that have been demonstrated have made use of aeroelastic pitching, either through baggy wing skins or an elastic skeleton [2]–[10].

Using such a passive mechanism to control the wing motion drastically reduces the complexity of the design by eliminating the need for a second actuator to actively control the wing pitch. A single actuator can be used to flap the wings, while a combination of air drag and the wings' moment of inertia and elasticity bends the wing plane such that it provides a positive lift force on both the in and out strokes. The timing of the rotation, extent to which the wings bend, and, thus, the lift coefficient are controlled by the material properties of the wings. This aeroelastic bending is shown in Figure 2. The mechanism shown in the figure provides a substantial increase in lift production.

Machine Design

With the natural inspirations from insect and hummingbird flight in mind, we have designed an 18-g machine (excluding batteries, 24 g including batteries) capable of flapping-hovering flight. The design consists of four pairs of wings; each is independently powered by a small dc motor and designed to act in a similar manner to an insect, taking advantage of passive wing bending, the clap-and-fling effect, as well as the other unsteady aerodynamic effects, with a single active degree of freedom. The machine we present here is entirely passively stabilized (Figure 3); yet, the presence of four independent pairs allows for future implementation of active control. The hovering machine has thrust exactly equal to its weight. Small perturbations will cause an imbalance in forces, and the machine may begin to rotate and drift. The top and bottom sails act as dampers, producing a restoring force in the presence of a drift or rotational velocity. These two dampers determine a rotation point for the machine. If the rotation point is above the center of mass, the machine will be stable, similar to a damped pendulum. A damping along the axis is due to a damping factor from the flapping wings.

Materials and Construction

The structural components of the hoverer were made of 2.4-mm Balsa sheets laser-cut into interlocking components. The wings comprised a 13-μm polyethylene terephthalate (PET) film welded to a laser-cut vein pattern made of 250-μm PET. Wing pairs were attached to the flapping mechanism using 21-cm-long, 0.9-mm-diameter carbon fiber rods. The flexible carbon fiber allows the wings to bend during flapping, increasing the amplitude of the flap (Figure 4). The elasticity of the wings allows some of the energy to be stored from one stage of the cycle and transferred to the next. Wing shafts were connected to the structure with a PET flexible hinge joint to constrain motion to the desired plane. Minimum distance between static wings was designed to be 0.2 of the chord length to maximize the benefits from clap and fling effect. Flapping motion of each wing pair was generated by a separate 1.2-g geared (25:1) dc pager motor (GM15, distributed through Solarbotics, Calgary, Canada). The motor turned a hand-bent 0.6-mm-diameter steel crankshaft, which was connected to the wings with connecting rods and ball joints (steel tube and fishing line knots on either end). Motors were powered in parallel by two 3.1-g, 3.7-V, 90-mAh Li-poly batteries in series (available through plantraco.com). Batteries were connected to the structure with a 24-cm-long, 0.4-mm steel rod, reinforced by 0.2-mm fishing line to ensure rigidity. Top and bottom sails were constructed from lightweight semi-rigid packing foam, reinforced by balsa struts at the top. Total weight of the machine, including sails and both batteries, was 24.2 g (Figure 5). The dc motor is connected to the wing shafts with a crankshaft and connecting rods. As the crankshaft

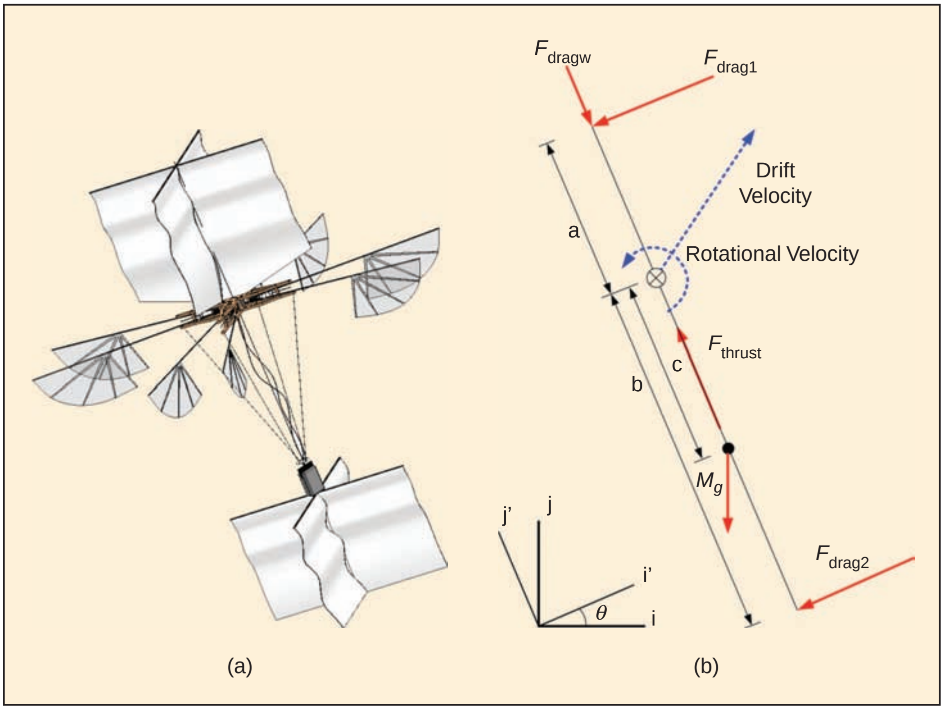

Figure 3. *Passive stabilization mechanism. (a) CAD diagram. (b) Free body diagram of perturbed system.*

turns, the wings flap in and out, nearly symmetrically. Opposite wing pairs are reversed to reduce effects of the slight asymmetry.

Passive Stability

Although the primary goal of this article is to present a new architecture of a flapping-hovering machine, focusing on the thrust mechanism, it needed to be relatively stable to demonstrate its hovering abilities. From a control perspective, the machine's architecture is similar to that of a quad rotor and could theoretically be controlled in much the same manner if outfitted with accelerometers, gyros, a microcontroller and speed controllers. (To gain yaw control similar to a quad rotor, adjacent pairs of wings would need to be slightly rotated about their central axis, alternating between facing toward and away from each other.) Rather than implementing such an active control system, however, we opted to explore passive stability. The physical

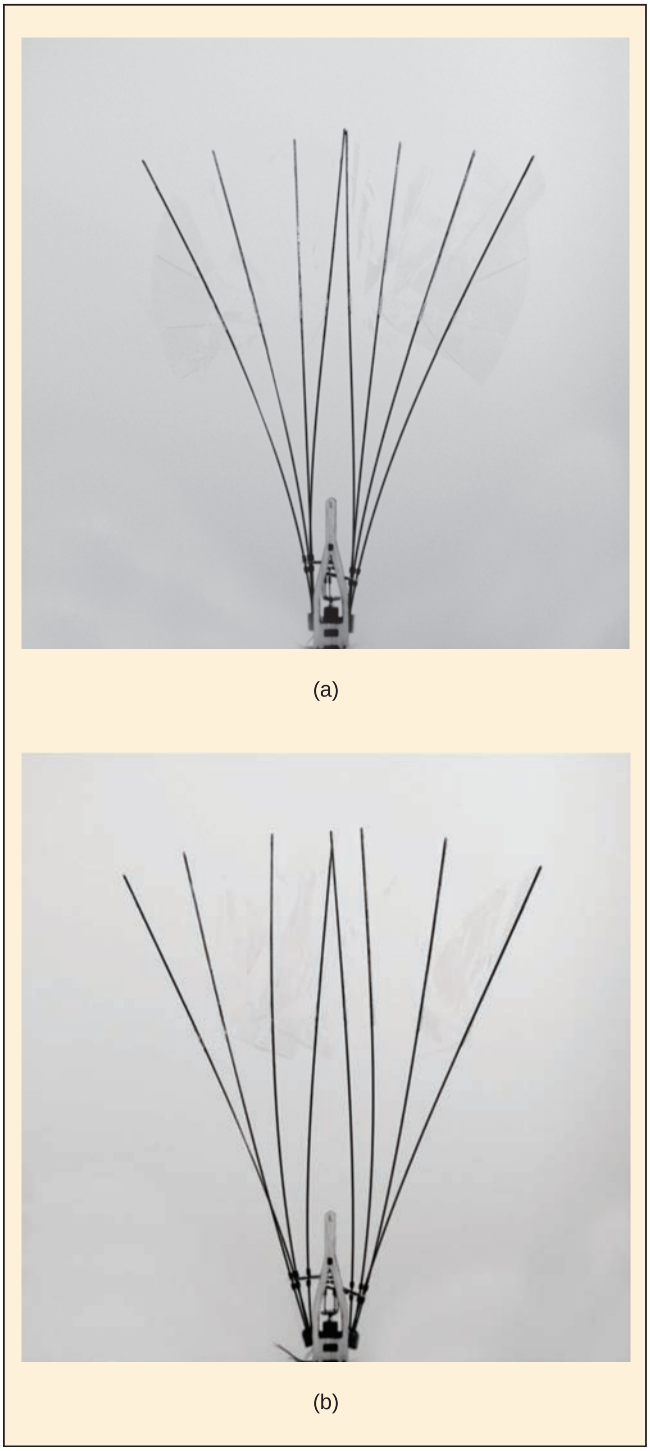

Figure 4. Elastic energy storage through passive wing shaft bending. Strobe images of the wings' (a) clap phase and (b) fling phase show the passive wing bending at 18 Hz.

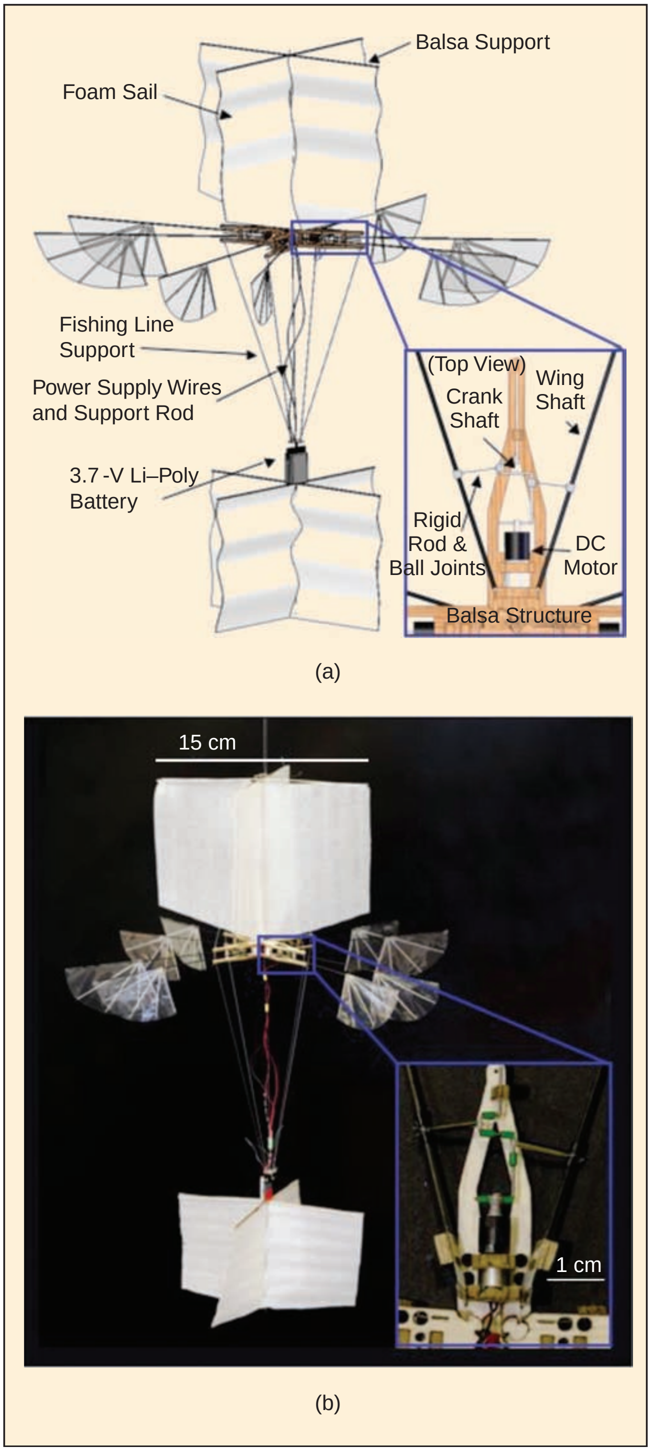

Figure 5. Design and material properties. (a) Solidworks designed computer-aided design (CAD) model. (b) Physical machine.

control concepts presented here could theoretically be directly converted to gains for a classical proportional-integral differential (PID) controller, replacing the sails with sensors and processing electronics. The passive mechanism we used is likely not applicable to situations where maneuverability is a high priority. However, for applications where stationary hovering and slow maneuvering flight is desired, such as for a stationary sensory monitor, such an approach may be of interest. Furthermore, in the emerging field of untethered flapping-hovering micro-air vehicles, where weight is of utmost concern, passive stability provides a simple and lightweight solution for tuning and testing the thrust portion of the design, which is the crux of the field at this point.

The stabilization dynamics are governed by two sails, which cause it to act like a damped pendulum. To intuitively understand the dynamics, think of the machine as a mass on a rod. If we were to place a pivot point below the mass, it would act as an inverted pendulum and thus be unstable. Placing the pivot point above the mass, however, causes it to act as a pendulum, which in the presence of damping will be stable. The pivot point is determined by the center of the drag forces caused by the sails. If this pivot point is above the center of mass, the system will be stable. To verify the stability of the model we used a first-order approximation of the free body diagram in Figure 3 (see "Verifying Stability Mathematically"). The stability of the device has been verified by its ability to recover from arbitrary launch orientations, including upside-down zero-velocity initial conditions that are typically very difficult for most aircraft to recover from (including helicopters).

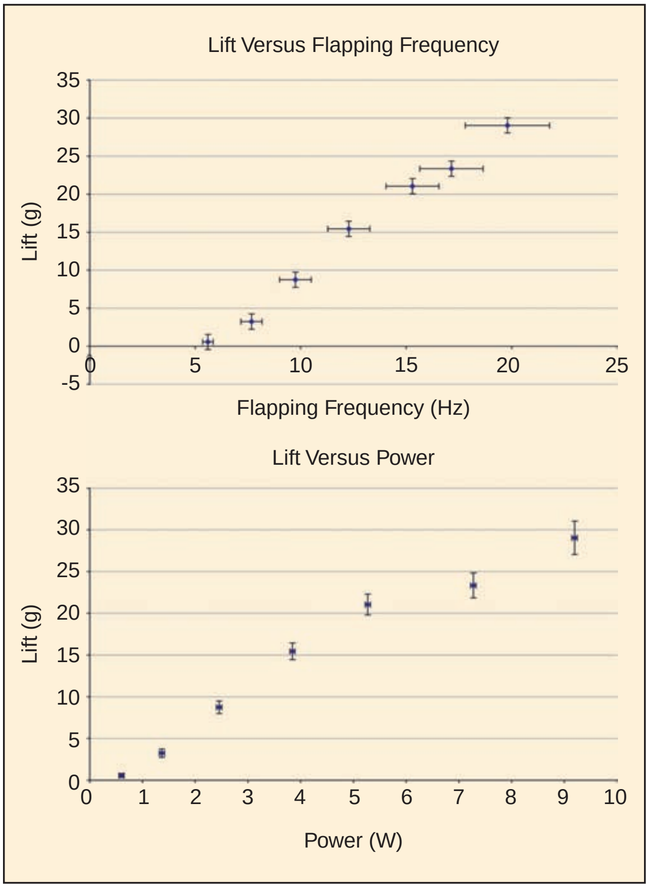

Figure 6. *Operating characteristics. Lift and frequency for various power arrangements.*

Results

The design can be operated under a variety of configurations, depending on the need for longer flight times or increased payload capacity for tools such as sensors and cameras. Power, lift, and flapping frequency were measured using a digital multimeter, a scale, and strobe light (Figure 6). The nonlinearity at approximately 7.5 W is likely due to a second oscillatory mode resembling a standing wave that appeared at this power. Furthermore, the motor efficiency becomes nonlinear as the power increases. We operated the machine just below this point, at 6.9 W. Under maximum lift conditions, the craft operates at a Reynolds number of roughly 8×10^3. Our

Verifying Stability Mathematically

To verify the stability of the machine mathematically and understand the details of the design, we modeled the system with a first-order approximation.

Using the free body diagram in Figure 3, we found the following governing equations:

$$\sum F = F_t j' - F_{DW} j' - Mgj - F_{D1} i' - F_{D2} i' = M\overrightarrow{a}$$
$$\sum M = -cM \sin\theta + aF_{D1} - bF_{D2} = I\ddot{\theta}$$

for the simplified system, $I = Mc^2$.

The rotation point of the system was defined to be at the balance of the drag forces on the sails, imposing the constraint:

$$aF_{D1} = bF_{D2}.$$

To analytically examine the system we approximated the drag force as being linearly proportional to the velocity. This approximation is reasonable for low translational velocities. Next, we used a small angle approximation.

Drag on the top sail: $F_{D1} = d_1(\dot{x}' - a\dot{\theta})$

Drag on on the bottom sail: $F_{D2} = d_2(\dot{x}' + b\dot{\theta})$

Drag on the flapping wings: $F_{DW} = d_w \dot{y}'$

$$d_i \text{ is of the form } \frac{1}{2}\rho C_d A,$$

where ρ is the fluid density, C_d is the drag coefficient, and A is the area.

The system was put into state space, and the eigenvalues were examined for stability. The response was examined for an initial 10° offset of the tilt angle. It can be concluded that for stability the center of rotation, defined by the two sails as above, needs to be above the center of mass.

Calculations

Calculations were done using the following values measured from our system:

$$d_1 = 0.03142$$
$$d_2 = 0.02244$$
$$d_w = 0.01$$
$$a = 0.091 \text{ m}$$
$$b = 0.268 \text{ m}$$
$$M = 0.025 \text{ kg}$$
$$g = 9.8 \text{ m2/s}$$
$$F_t = 1.05 \times \text{M} \times \text{g}$$
(thrust slightly higher than the hovering condition)
$$c = 0.00833 \text{ m.}$$

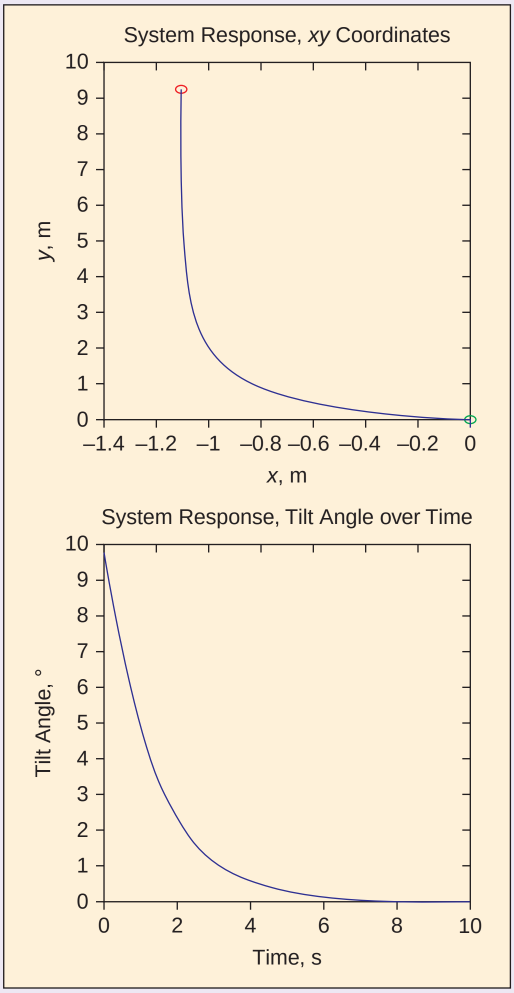

Figure A1. *Stable system response with the center of mass located below the pivot point. The system started at (0,0) with a tilt angle of 10° at time 0 (green circle) and proceeded to stabilize, ending at the red dot.*

Analyzing this system yields the eigenvalues: $\{0, -1589.1, -2.2, -0.7, 0, -0.4\}$.

The two zero-value eigenvalues are due to the rigid body modes. This can be verified by adding a spring in the *x* and *y* dimensions, causing all the eigenvalues to be negative.

The system's response to an initial 10° offset yields the curves shown in Figure A1.

Moving the center of mass to just above the pivot point yields the eigenvalues: $\{0, \{0, -1.1032 \times 10^9, -2.1751, 0.021627, 0, -0.4\}$.

The system's response to an initial 10° offset yields the curves shown in Figure A2.

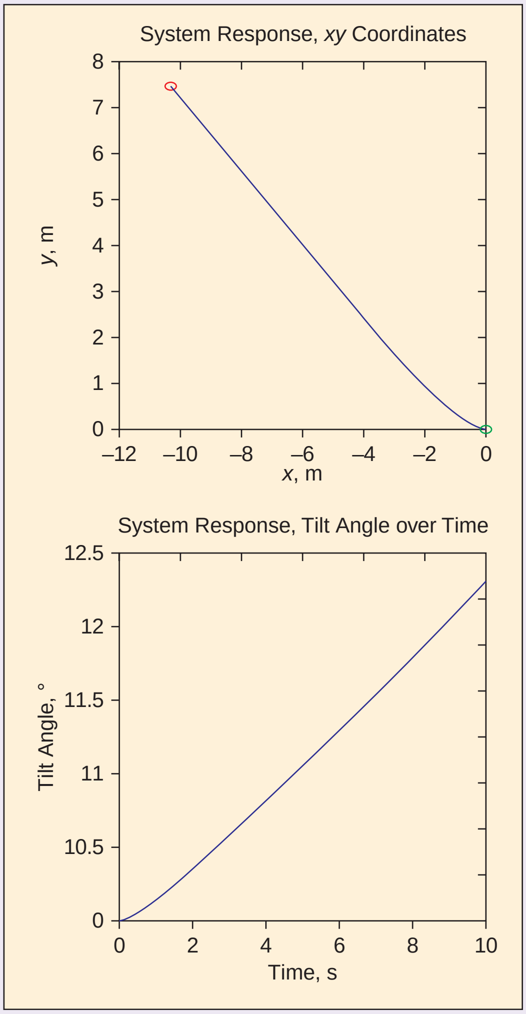

Figure A2. *Unstable system response with the center of mass located above the pivot point. The system started at (0,0) with a tilt angle of 10° at time 0 (green circle) and did not stabilize, ending at the red dot.*

Flapping flight employed by insects offers several advantages over ornithoptic flapping flight employed by larger birds.

current mode of operation uses two 3.7-V, 90-mAh Li-poly batteries in series to provide a nominal output voltage of 7.4 V. At these voltages, the flapping transitions into a second oscillatory mode: a standing wave with nearly zero lift production. To minimize this effect, we implemented a 0.8-Ω resistance to reduce the voltage. This also reduced the stress on the motors and lowered the maximum height achieved. Operating conditions were measured to 6.5 V at 1.07 A for a total lift of 25 g capable of 33-s flight.

Conclusions

Although our machine is not yet on scale of small insects, it operates within the same aerodynamic flow regime, and we expect that design principles will scale favorably to such a size using currently available technologies such as piezo-electric vibrating actuators and emerging low-weight batteries and composite structural materials [5]. We also emphasize the importance of using passive dynamics and stability for the simplification of the design of such machines. Currently, electronics technology is not at the point where a small and light enough active control package can be fabricated for a subgram machine. Ultimately, we hope flapping-hovering flight will open the door to new applications and provide further insight into the mechanisms underlying insect and hummingbird's remarkable flying abilities.

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Keywords

Micro-air vehicles, flapping flight, hovering flight, bioinspired robotics, passive stability.

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