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Abstract—Ornithopters, micro air vehicles that fly by flapping their wings, are applicable to a wide range of fields including law enforcement, reconnaissance, and agriculture. Currently, the research and technology required to build such machines are in the early stages of development. The purpose of this research project is to design, develop, and construct an ornithopter with maneuvering and hovering capabilities. The model used in this project draws inspiration from previous ornithopter models as well as several species of insects. Digital prototypes were modeled in CAD software, and physical prototypes were 3D printed for testing purposes. Results from the experiments proved the device's success with maneuvering as well as stabilizing while hovering.

I. INTRODUCTION

Ornithopters have existed for several centuries. The first successful attempt at flying an ornithopter was in 1060 when a Benedictine monk leaped from a tower and used stationary wings to glide to the ground. Currently, modern ornithopter technology is being developed for practical applications in several fields [1].

Also known as micro aerial vehicles (MAVs), ornithopters use flapping mechanical wings that are responsible for creating the lift and thrust for the device [4]. By using biomimicry to model flying animals and insects and simulate natural flying, ornithopters are able to achieve greater mobility than typical fixed-wing aircraft or drones [2][3].

Ornithopters possess a number of features that make them ideal for use in various fields. Given their resemblance to insects and birds, ornithopters blend into the environment better than drones and other fixed wing aircraft. They are also much quieter and less disruptive than drones, allowing for greater usage in areas such as reconnaissance. Ornithopters are used by the military and law enforcement agencies, as well as for aerial photography for either recreational or scientific purposes [5]. They can be deployed to inspect power lines and fields, or to look for victims and assess damage after natural disasters or acts of terrorism [6][7]. Another application of ornithopters is in pollination. There have been significant losses in bee colonies around the world, especially in the United States and Europe. These losses are primarily caused by human factors like improper herbicide and pesticide use, loss of biodiversity, and habitat fragmentation [8][9]. Since bees are essential to agriculture, the decline of the honeybee population in recent years could potentially harm the food supply if their numbers decreased dramatically. In such a situation, ornithopters could be viable substitutes for pollinators. A device designed for such an application needs to be able maneuver in three-dimensional space, hover, and pick up pollen and distribute it elsewhere during its flight.

In order to stay airborne, the wings must create lift equal to the weight of the device [10]. Thus, the design and construction of the other components of the device pose several challenges. Electronic ornithopters require batteries and motors to fly as well as other sensors and hardware to navigate or control altitude in more complex ornithopters. Using all these components adds weight to the machine, making it difficult to generate enough lift to stay airborne.

The goal of this project is to build a lightweight ornithopter prototype, create a manual RF-based navigation system, and devise a manual maneuvering and autonomous angle correcting system. This paper will discuss the relative success of the
ornithopter after conducting trials as well as the technology’s future application and development.

II. PREVIOUS SUCCESSES

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>PAST ORNITHOPTER MODELS</th>
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</thead>
<tbody>
<tr>
<td>Design</td>
<td>Year</td>
</tr>
<tr>
<td>Battery-Powered Microflote [12]</td>
<td>2000</td>
</tr>
<tr>
<td>Delfly II [14]</td>
<td>2006</td>
</tr>
<tr>
<td>Chronis [16]</td>
<td>2007</td>
</tr>
<tr>
<td>NAV [17]</td>
<td>2009</td>
</tr>
<tr>
<td>Rutgers Cornell Ornithopter [18]</td>
<td>2010</td>
</tr>
<tr>
<td>Bionicopter [19]</td>
<td>2011</td>
</tr>
<tr>
<td>Nano Hummingbird [21]</td>
<td>2012</td>
</tr>
<tr>
<td>R2 Bird [22]</td>
<td>2013</td>
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<tr>
<td>Biosciotper [23]</td>
<td>2014</td>
</tr>
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The research process began with looking at successful ornithopters from the past to understand the important characteristics that would allow for controlled flight. Most of the models had masses below 25 grams (except for the Bionicopter and van Breugel ornithopter) as seen in Table I [15][23]. Additionally, most designs had either two or four wings. Most of the two-winged designs, such as the Delfly or the Baek ornithopter, have a forward flight bias while the four or eight wing designs, such as the Bionicopter and van Breugel ornithopter, are better suited for hovering [14][19].

III. TECHNICAL BACKGROUND

A. Aerodynamics

The design used for the ornithopter wings, as shown in Figure 2 was tailored to maximize the wing’s aspect ratio (AR)—the ratio between the wingspan and the chord line (distance from the leading edge to the back edge of the wing)—and maintain the device’s structure without becoming too large and heavy or too thin and flimsy.

Because wings with a higher AR produce a larger amount of lift, high aspect ratios (ARs) are key characteristics exhibited by all of the wing models designed for this research project [26][27]. As the AR increases, the lift-drag ratio increases and the battery usage becomes more efficient. High AR devices show significant decreases in the amount of induced drag produced by the devices movement through the air. This is due to the lesser area at the wingtips, leading to a smaller induced vortex and reducing the amount of drag on the device [26]. Induced drag has the most significant impact on flight at low speeds it makes a high AR wing shape ideal for ornithopters.

While high ARs have certain advantages, they can also pose some difficulties: as the AR increases, the wings weight increases, structural strength decreases, and aeroelastic flexibility becomes unsustainable [28]. The wing would then require additional internal structural support. Given the weight challenges of an ornithopter, the added mass must provide for enough lift to outweigh its cost.

IV. PROCEDURE

A. Overview

This project consisted of designing an ornithopter that can maneuver and hover. The ornithopter is comprised of customized 3D printed parts, including four wings and a body, two motors, two servos, a compound gear system, and a crankshaft. The ornithopter was programmed in two modes:
one where the ornithopter hovered in place, and a second in which the ornithopter was manually controlled. Each mode was tested by suspending the ornithopter using a pulley system to simulate flight and evaluate the device’s performance.

B. Designing the Wings

Three wings were printed and tested to finalize general shapes and materials. The models were printed with photopolymer resin in a FormLabs Form 2 3D Stereolithography printer (SLA) to reduce the weight of the device and increase flexibility and precision. However, the photopolymer resin used made the wing perimeters too thin, which led to breakage.

The prototyping process provided valuable information to use for future models regarding both material and design drawbacks that required improvement. The flexible resin material was pliable and it made the wings deform in response to air resistance during flight; therefore, it failed to provide sufficient lift to sustain flight.

To improve the wing design, the length of the center shaft and the wing frames were increased to improve the wings’ structural integrity. The wingspan was also extended to increase the aspect ratio and create more lift. New wing designs were modeled based on the bee, mosquito, green lacewing, and dragonfly species’ wing shapes. All the wingspans are approximately 20 centimeters long, while the width of each wing loop was based on the particular wing shape. The width of the shaft and the wing frames for each design are 3 millimeters. This small width was designed to help minimize wing weight, allowing the machine to achieve more lift without sacrificing the wings’ strength or resistance to deformation in flight. The perimeters of the wings are completely closed to maintain the structure of the wing and reduce deformation when exposed to air resistance. Additionally, the flexible models are reinforced with wire and new models are printed in durable resin rather than flexible. The individual wings are mirrored across a longer center shaft with a 2.5-millimeter diameter hole in the center of the shaft to attach the wing to the flapping mechanism.

C. Designing the Body and Frame

The body must be lightweight and compact. The original design featured a hollow cylinder with accommodations for various components. Although at first a completely solid surface, the perimeter of the body was then reduced to a crosshatch pattern as seen in Figure 4 to maintain structural integrity and reduce weight. As shown, the Arduino microcontroller would have slid into the slot alongside the accelerometer and servo motors — this stacking design would keep a center of gravity at the middle of the ornithopter, maintaining ornithopter balance. Except for the servos, these components were placed and glued into the ornithopter — one servo motor attached to a bar running across the bottom (as seen at the top of A in Figure 4) and the other attached to the first servo.

The other components — the motors, wings, gears, and axles — were attached to the top of the body. The wings attached to the frame through an axle in the center. The motors were placed in the four larger holes around the center, and the gears were connected to the frame via axles positioned near the perimeter of the body. This symmetrical first body design was advantageous in its center of mass, its ability to hold all of the components, and its capacity for four motors.

After 3D printing the design, several problems became evident. The body interfered with the movement of the wings because the diameter of the body was larger than the length of the wing shaft. Second, despite efforts to use less material and
make the body lighter, it was still too bulky compared to the wings thus further hindering flight. Finally, since each wing was controlled by a separate set of gears, there was no way to control the position of the wings relative to each other.

Due to the issues with the first model, the body was completely redesigned into a more compact and simpler frame as shown in Figure 5. The Arduino was housed off of the body of the ornithopter and connected to the device with long wires to decrease weight and size. The new design is lightweight, and no longer interferes with the movement of the wings. However, the new model only held two motors, and therefore sacrificed some of the power of the four motors from the previous design.

D. Designing the Maneuvering Sails

The sail seen in Figure 6 is a simple cross pattern that stabilizes the ornithopter and allows for directional changes in the horizontal plane. Inspired by the Cornell ornithopter, the sail directs the downward airflow by the wings to rotate the ornithopter and change the angle. When the sail is directly below the ornithopter, no torque is exerted on the sail. However, when the sail is at an angle, the air forced downwards by the wings exerts torque on the slanted sail causing the ornithopter to change direction.

Additionally, when a breeze comes from the side of the ornithopter, the bottom of the tail angles away from the air flow. In doing so, it decreases the sail surface area facing the air flow and mitigates the effects of the breeze by decreasing the amount of air resistance on the ornithopter. By projecting the sail at a complementary angle to the acceleration when the ornithopter is hovering at an angle, the ornithopter will return to its target acceleration, as shown in Figure 6. In manual mode, the ornithopter can move and change direction by angling the sail and flying at a slant. This system allows the ornithopter to control its flight in both hovering and manual mode.

There were several different iterations of the sail design. All included the same cross pattern but varied in width, length, and weight. When the sail was larger and heavier, the center of gravity shifted and when at an angle, would exert a torque opposite to the desired direction. The final sail measured two rectangles of cardboard (6.4cm x 10.4cm) arranged with the wide side parallel to the ground; this was then connected directly to the servo motors. This final design was small to provide some of the stabilizing characteristics and avoid impacting the center of gravity.

E. Construction of the Ornithopter

As shown in Figure 7, the device is made up of a gear set (A), two wings (B), the body (C), two servos (D), a crankshaft (E), the sail (F), two shaft connectors (G), steel wire, and two motors. Each wing is connected to the crankshaft via the shaft connectors and positioned twenty-five millimeters away from the center. One of the servos is attached to the ornithopter through the pegs which protrude from the bottom of the body. The other servo is then attached to the connected servo via the servo horn.

The motors operate at a maximum of around 49,000 RPM. However, this value is too high for stable flight, so to reduce this speed a 14.933:1 gear system is used, which has the added benefit of increasing the motors torque. The system is designed to keep the motors in the middle of the body, closer to the center of gravity. As shown in Figure 8, it consists of a forty toothed gear (H) which is attached to a ten toothed gear (I). The forty-toothed gear meshes with two fifteen-tooth gears (J) connected to the motors. A slightly raised fifty-six toothed gear (K) sits on the outer part of the ornithopter and meshes
with the ten toothed gear. The wings and the forty toothed gear are secured in place with a straight piece of wire which slides through the three center holes in the body. Overall, this gear system is used to keep the motors at the middle (closer to the center of gravity) of the ornithopter, decrease the RPM, and increase the torque of the motors.

A crankshaft, similar to that on the Cornell Ornithopter, was used to flap the wings as seen in Figure 9. The straight ends of the crankshaft fit into the two opposing holes at the ends of the ornithopter. The fifty-six toothed gear slides onto the bottom part of the crankshaft before being secured. The two shaft connectors slide onto the protruding section of the crankshaft. The crankshaft is connected to the wings, and as it spins it rotates the wings approximately 70 degrees back and forth. As the gear rotates, the shaft connectors pull the wings back and forth as shown in Figure 10.

**F. Construction of Wiring**

The wiring of the ornithopter was split into two parts: the controller (transmitter) and the ornithopter (receiver). For testing, these two were combined to control the ornithopter and analyze results.

The controller (Figure 11) was constructed with an Arduino UNO R3 Microcontroller, a joystick and a 433Mhz RF transmitter, and all components are combined on a breadboard. This controller demonstrated manual control of the ornithopter.

The wiring on the ornithopter (Figure 12) consisted of an Arduino Pro Mini, an accelerometer, a diode, a 10k Ohm resistor, a metal-oxide-semiconductor field-effect transistor (MOSFET), two DC motors, and two servo motors. These components are soldered to each other according to Figure 12. This wiring, combined with the controller, demonstrated the ornithopters ability to switch between autonomous and manual control.

The tester wiring included a joystick, potentiometer, accelerometer, two servos, and an Arduino Mega Microcontroller as shown in Figure 13. This allowed the ornithopter to switch from manual to hovering, and for accelerometer data to be collected during testing.

**G. Code Development**

The code was written in C/C++ for an Arduino Microcontroller and consists of the main file and multiple header files, which are linked to the main code source. The ornithopter operates in two different modes. Hovering mode allows the ornithopter to suspend in three-dimensional space, and manual mode allows for the motion control of the ornithopter.

Manual mode allows the user to move the ornithopter using a remote controller. The remote controller consists of a joystick for moving the device in the X- and Y-directions, a potentiometer to regulate movement in the Z-direction, and a button to switch the ornithopter between the hover and maneuvering modes. Data gathered from user inputs to the remote controller are sent to the ornithopter via an RF trans-
mitter. Upon receiving the data, an Arduino Mega connected to the ornithopter adjusts the motors to control flight. After powering on the device and before liftoff, the ornithopter records the current accelerometer value and sets it as the target value. Then, the ornithopter is flown to the desired location using normal joystick controls. After that, pressing the joystick button on the controller makes the ornithopter enter hovering mode.

Once in hovering mode, the ornithopter records acceleration in the X, Y, and Z axes every ten milliseconds. The ornithopter then compares the target acceleration values—where the ornithopter would not be accelerating in any direction—to current acceleration values. Using a proportional-integral-derivative (PID) controller and taking into account the difference between the target value and current value, the ornithopter can correct its position in the Z direction by varying the amount of power going to the motor. As the ornithopter changes position in the X-Y plane, it adjusts its servos to decrease the difference between the target and current value.

H. Conducting Trial Flights

In all the trials testing X and Y plane hovering mechanisms, the servos and sail assembly were removed and placed onto a testing assembly. The testing assembly consisted of a motor, which replaced the ornithopter prototype in terms of weight, and a wooden cross, which attached the assembly to the pulley
system. The testing assembly was counterweighted using a pulley system. The ends of the wooden cross were attached to a fishing line which was connected to a small sack that held the weights. The weights were strung over a horizontal PVC pipe as seen in Figure 14. Additionally, there was a small amount of lubricant on the PVC to decrease the friction between the fishing line and pipe. The counterweights weighed 181.4g (while high, this also has to counter the friction of the pulley and the weight of the wires hanging down the testing assembly during testing). These weights were used to reduce the amount of downwards force on the testing assembly. The testing primarily analyzed the X-/Y-plane hovering capabilities of the navigation system by creating a cross breeze on the testing mechanism. Once the hovering mode was turned on, and the assembly was steady, the fan was turned on and accelerometer data was fed to the computer via the Arduino Microcontroller (similar to first test). After approximately 20-25 seconds, the fan was turned off and data stopped being taken. To be successful, the sail must rotate towards the opposite direction of the wind, both to be more aerodynamic and to be able to correct itself back to its original angle using the air which would be directed onto the sail from the beating wings of the ornithopter.

V. CONCLUSION
A. Summary of Results
For the X-axis, as shown in Figure 16 in the Appendix, the blue dotted line in the center of the graph represented the target acceleration value, where the testing assembly would be hovering. At \( t = 0 \), the testing assembly acceleration values for the X-axis read higher than that of the target acceleration values in the X direction as a result of the upwards tension from the tethering wires from which the testing assembly was suspended. At \( t = 0.4 \) the fan was turned on, simulating a gust of breeze. Accordingly, acceleration values dropped and continued until \( t = 1.1 \), whereupon the acceleration value began to increase back towards the target acceleration value. This indicates the success of the hovering mechanism in the X-axis because the servo angle adjustments began to affect the acceleration. The acceleration plateaued at a value less than the desired hovering values at \( t = 1.5 \) due to the lack of downwards air flow which would have come from the ornithopter. This downwards air flow would have pushed the ornithopter in the opposite direction of the wind due to the stream of air redirecting off of the sail. Therefore, the acceleration values would have continued to increase until they reached desired hovering values.

For the Y-axis, as shown in Figure 17, the blue dotted line represents the target acceleration, just as in the X-axis graph. The acceleration values for the Y-axis were less than that of the desired acceleration values in the Y direction due to the tension in the suspension wire. At \( t = 0.5 \), the fan was turned on, and the acceleration began to increase. In response, the sail began to angle away from the air flow in order to counter the acceleration. At \( t = 1.1 \), the accelerometer began to record a decrease in accelerometer values, which demonstrated a success in the hovering mechanism for the Y-axis because the change in the sails position was able to bring the acceleration values closer to desired acceleration values. Similar to the X-axis correction, the Y-axis acceleration did not return to the ideal acceleration due to the lack of downward air flow. Theoretically, the desired acceleration for hovering should have been zero meters per second square, which would indicate no movement in the X and Y planes, but imperfections in the accelerometer caused the ideal hovering values to be slightly offset. A larger portion of the offset cam from the accelerometer not being mounted to the testing assembly so that the accelerometer would be parallel to the ground. Due to the non-parallel mounting, a component of gravitational acceleration factored into the offset for the desired values.

B. Successes and Shortcomings
There were several different designs for the body of the ornithopter. The first design, as seen in Figure 4, had too large of a diameter for the printed wings and was too heavy despite efforts to reduce mass with a cross-hatching design. Additionally, the motor holes were slightly smaller than the motors themselves. After this, the body was completely redesigned (Figure 5) with a design closer to the frame of the Cornell Ornithopter (Figure 1). In the same batch of 3D printed parts, the gears were too small for the resolution of the Ultimaker 2 3D printer, leading to the creation of larger gears – this, however, required us to lower the gear ratio and therefore the torque of the motor.

In the first batch of 3D printed wings, a single wing frame was printed to test the viability of using the FormLabs 2 printer. The wing was too thin and cracked (Figure 15) leading to the creation of a thicker and sturdier wing in the next batch. In the second batch there was no hole for the crankshaft, and instead it was drilled. A hole was added to the Solidworks model for future batches.

A number of changes were made to the initial code. The original servo library was not responding correctly, so the software servo library was switched. Initially, the RF transmitter could not connect to the receiver unless they were held within an inch of each other, a range far too small for the needs of the ornithopter. The issue was resolved by soldering a wire to the RF transmitter to serve as an antenna, thus increasing the range. Additionally, Arduino’s built-in serial plotter was used to graph the data from the accelerometer. Even after removing noise, the graph was not advanced enough. MATLAB was then used to display the ornithopter data in a more understandable manner.

C. Future Advancements
Additional improvements to the ornithopter design revolve entirely around reducing its weight. The hardware for the navigation system should be housed on board the ornithopter in the future in order to make the ornithopter equipped for fully autonomous flight. However, the hardware is heavy, and makes it difficult for the ornithopter to create sufficient lift to sustain flight. To counteract the additional weight, the device could be
printed with lighter but equally strong materials. Additionally, the friction in the gears could be reduced in order to maximize the motors’ power and lift potential.

Adding more functionality to the ornithopter in order to better simulate pollination would require more parts, such as sensors and additional batteries, all of which add extra weight to the device. Until these components are made smaller and lighter, generating enough lift to get an ornithopter in the air will be even more difficult.

However, the research to make all of these components smaller and lighter is still in progress. Once electronic components are made lighter, the capabilities and uses of ornithopters will expand immensely.
APPENDIX

Fig. 16. Accelerometer and Servo Values in Response to the Fan in the X-Axis

Fig. 17. Accelerometer and Servo Values in Response to the Fan in the Y-Axis
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