Development of a 100-gram Micro-Cyclocopter Capable of Autonomous Hover

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ABSTRACT

This paper describes the design, development and hover testing of a cycloidal-rotor aircraft (cyclocopter) at Micro Air Vehicle (MAV) scale (∼100 grams). Cycloidal rotor (cyclorotor) is a revolutionary vertical take-off and landing (VTOL) concept, which has a horizontal axis of rotation with the blade span parallel to axis and cyclically pitching as it goes around the azimuth to produce a net thrust. The present cyclocopter has a hybrid configuration with two cyclorotors rotating in the same direction and a horizontal tail rotor, which is used to counteract the pitch-up moment produced by the cyclorotors. The independent rotational speed control of the three rotors along with the thrust vectoring capability of cyclorotors make the twin-rotor cyclocopter a highly maneuverable and versatile MAV. An innovative light-weight and high strength-to-weight ratio blade design along with a simplified passive blade pitching mechanism enabled the development of an extremely light-weight cyclorotor, which is the key to the success of the present vehicle. An effective control strategy was developed using a combination of rpm control and thrust vectoring to successfully decouple pitch, roll, and yaw controls. Due to the fast vehicle dynamics, a closed-loop feedback controls system implemented through a 1.5 gram onboard processor-sensor board was essential for the stable flight of the vehicle. The present 110 gram twin cyclocopter is smallest cyclocopter in the history to perform a stable autonomous hover.

1. INTRODUCTION

Growing interest in highly portable versatile flying platforms and recent advancements in microelectronics have led to the development of a scaled-down class of Unmanned Aerial Vehicles known as Micro Air Vehicles (MAVs). MAVs were formally defined as aircraft with maximum dimension of 15 cm and maximum weight of 100 grams by the Defense Advanced Research Projects Agency (DARPA) in 1997 [1]. DARPA intended to develop MAVs into military surveillance platforms that would increase situational awareness and reduce unit exposure times. Since then, applications of MAVs have ranged from reconnaissance, terrain mapping, and search and rescue in both military and civilian settings. For these type of missions, high endurance, maneuverability, and the ability to tolerate and overcome environmental disturbances such as wind gusts are critical requirements for MAVs. Within the past decade, numerous successful MAVs have been developed that fulfill many of these requirements. The existing vehicles can be classified into three major categories: fixed-wing, rotary-wing, and flapping-wing MAVs.

Fixed-wing MAVs are the most prevalent due to their high endurance-to-weight ratio and mechanical simplicity. One particular example is Aeroenvironment's Black Widow that weighs 80 grams and has an endurance of 30 minutes [2]. Although highly efficient, fixed-wing MAVs are incapable to hover and hence cannot be used in confined spaces such as indoor environments. In such scenarios, rotary-wing MAVs

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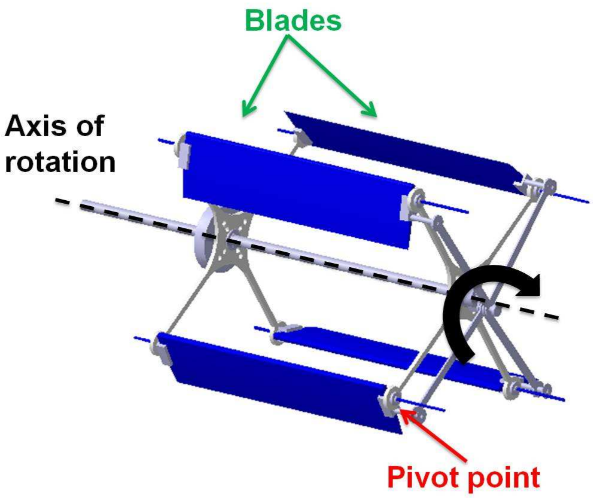


Figure 1: **Cycloidal rotor.**

tend to have higher mission performance due to their hover/low-speed flight capability. Conventional configurations for rotary-wing MAVs include single main rotor/tail rotor, co-axial rotor or quad-rotor designs [3–5]. However, these configurations have very low endurance (< 10 minutes) because hovering and low-speed flight modes are states of high power consumption, and the situation is further exacerbated by the degraded performance of conventional airfoils at the low Reynolds number range (10,000 – 50,000) at which these vehicles operate. In fact, the maximum achievable figure of merit for rotary-wing MAVs is currently 0.65, compared to the 0.85 achieved by their full-scaled counterparts [3, 6].

Flapping-wing MAVs, on the other hand offer highly maneuverable and gust-tolerant platforms, however, with efficiencies lower than rotary-wings. Because they emulate avian and insect-based flight, flapping-wing MAVs are typically mechanically complex and are easily decrepit due to their high frequency flapping motions. Much of the research into understanding the unsteady aerodynamics/aeroelasticity of flapping wings are still in the incipient stages and thus only a few flapping-wing MAVs have been successfully developed.

Unconventional vehicle designs such as cycloidal rotor-based configuration could be an alternate solution to developing a hover-capable, maneuverable and highly efficient MAV. The cycloidal rotor (cyclorotor) is a horizontal axis propulsion system where the blades span is parallel to the axis of rotation and perpendicular to direction of flight (Fig. 1). The unique arrangement of the cyclorotor blades with a blade pitching mechanism enables a passive cyclic blade pitching around the rotor azimuth. The pitching mechanism is designed such that the blades have a positive geometric angle of attack at both the top and bottom halves of the circular trajectory (Fig. 2) producing a net resultant thrust. Both the magnitude and direction of the thrust vector can be adjusted by varying the blade pitch amplitude and phasing, respectively.

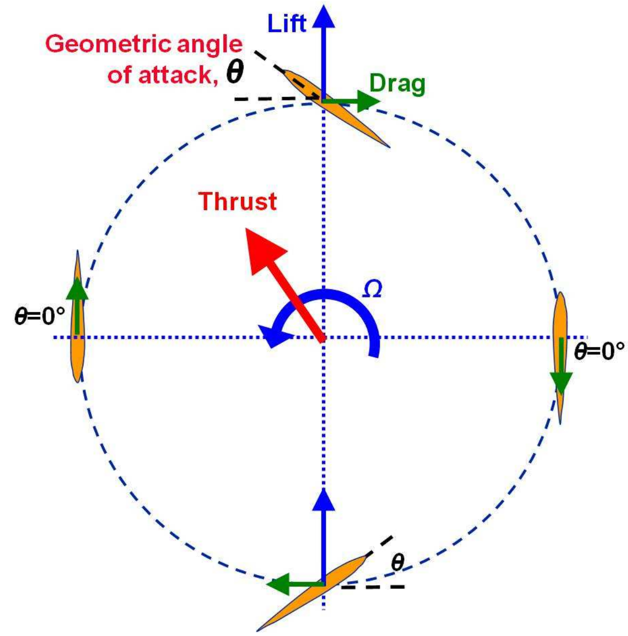


Figure 2: **Blade pitching kinematics.**

The fact that all the spanwise sections of a cyclorotor blade operate at similar aerodynamic conditions (flow velocity, angle of incidence, Reynolds number, etc.), makes it easier to optimize the rotor for maximum power loading (thrust/power). Recent studies [7] have shown that an optimized cyclorotor has the potential for higher power loading compared to a conventional rotor at similar disk loadings (Fig. 3). Another advantage of the cyclorotor is its instantaneous thrust vectoring capability (by changing the phase of cyclic pitching), which has the potential for improving the maneuverability and gust tolerance of the vehicle. Recent studies have also shown that an aircraft using cyclorotors could reach very high forward speeds without using any lift augmenting devices/surfaces [8, 9].

While many breakthroughs in cyclorotor research have occurred in recent years, attempts to develop a cycloidal rotor-based aircraft date back to early 20th century [10, 11]. Numerous full-scaled models intended to seat one pilot were developed, but none of the attempts were successful in achieving flight. In recent years, many UAV-scale versions of the cyclocopter were developed at the Seoul National University [12]. However, none of these vehicles could achieve stable flight. An 800 gram quad-cyclocopter configured with four symmetrically positioned cyclorotors was recently developed by

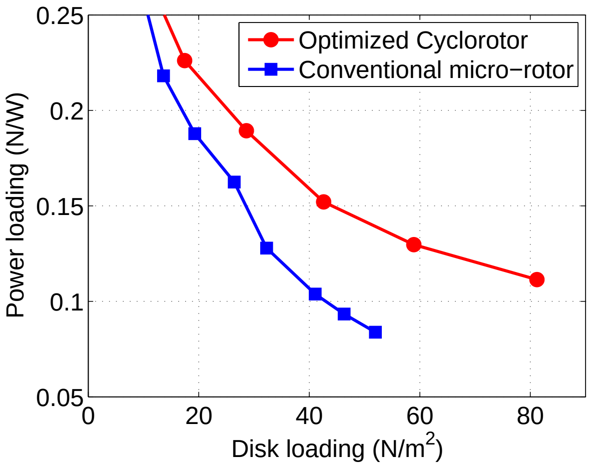


Figure 3: **Power loading (thrust/power) vs. disk loading (conventional micro-rotors vs. optimized cyclorotor) [7].**

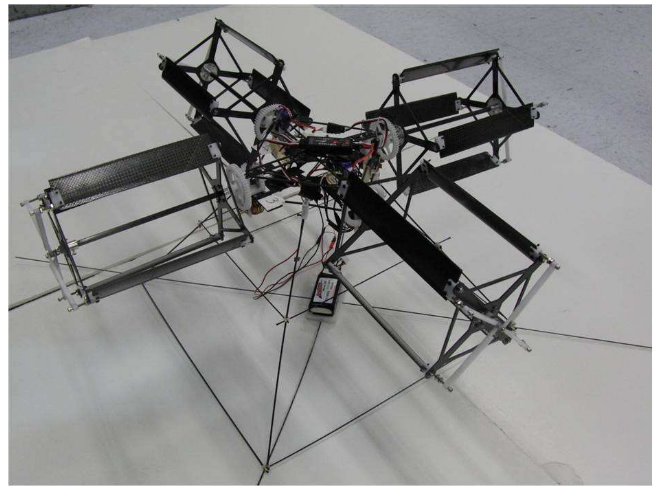


Figure 4: **800 grams quad-cyclocopter developed by the University of Maryland [13].**

the University of Maryland (Fig. 4). The cyclocopter MAV employed a feedback control system that enabled the vehicle to achieve stable tethered hover [13]. Complications during untethered flight testing were attributed to complex vehicle dynamics caused by excessive couplings in the pitch and roll dynamics. However, recently a hybrid cyclocopter configuration which utilized two cyclorotors (twin-cyclocopter) and a horizontal tail rotor for pitch control has been developed and successfully flight tested in hover [14]. The twin-cyclocopter weighs only 210 grams and is capable of autonomous untethered hover using an onboard feedback control system. However, this vehicle is still far from satisfying the 100 grams weight target set by DARPA, which forms the motivation of the present work.

The present research focuses on developing a twin-cyclocopter that weighs close to 100 grams with a goal for stable autonomous hover. Significant improvements to the structural design will reduce overall vehicle weight while preserving the structural integrity. Through autonomous stabilization implemented by an onboard closed-loop feedback control system, the twin-cyclocopter will attempt to demonstrate superior flight stability. The pitch, roll and yaw control was achieved through a combination of rotor rotational speed modulation and thrust vectoring of the two cyclorotors. The addition of a horizontal tail rotor system also decouples the pitch, roll, and yaw moments, greatly improving the control authority of the vehicle. Whereas previous research focused primarily on achieving stable hover, the current work intends to optimize the structural design of the rotor system and vehicle and also greatly reduce the overall vehicle dimensions and weight.

2. TWIN-ROTOR CYCLOCOPTER VEHICLE DESIGN

A 110 gram twin-rotor cyclocopter was developed with a lateral dimension of 28 centimeters (11 inches), longitudinal dimension of 21 centimeters (8.25 inches) , and a height of 18 centimeters (7 inches) (Fig. 5). From the component weight distribution provided in Table 1, it is evident that the cycloidal propulsion system account for approximately 33.3% of total vehicle weight. The two cyclorotors provide thrust vectoring capabilities, which is utilized for yaw control, while the tail rotor counterbalances the inherent pitching moment produced by the two cyclorotors rotating in the same direction and also controls the pitch dynamics of the vehicle. The unique hybrid configuration also enables independent rpm control of each rotor along with thrust vectoring of the cyclorotors which could dramatically improve the maneuverability of the aircraft.

The three rotors are powered using a 2-cell 7.4 volt 250 mAh Li-Po battery weighing 15 grams and three 2900 KV, 20 watts outrunner motors weighing 4 grams each. The operating rotational speed of the cyclorotors is about 2000 rpm. A 6:1 single-stage gear reduction is used between the cyclorotors and their respective motors, whereas the tail rotor uses a direct drive. A separate 1-cell 3.7 volt 125 mAh Li-Po battery (weighing 4 grams) powers the two Blue Bird BMS 303 servos used for thrust vectoring and the onboard 1.5 gram processor-sensor board used to implement a closed-loop feedback system, which enables autonomous vehicle stabilization.

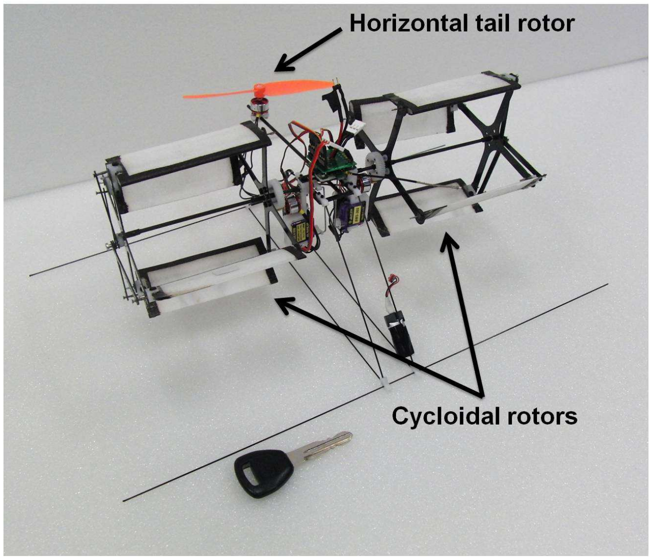


Figure 5: **110 gram twin-cyclocopter.**

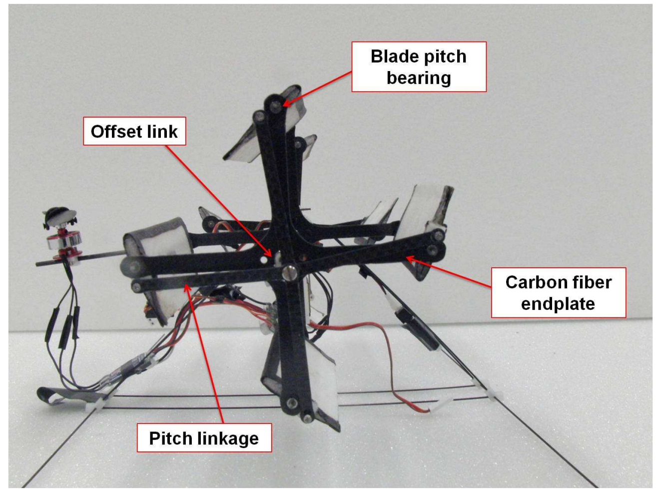


Figure 6: **Four-bladed cyclorotor.**

Table 1: **Weight distribution of the 110 grams twin-cyclocopter**

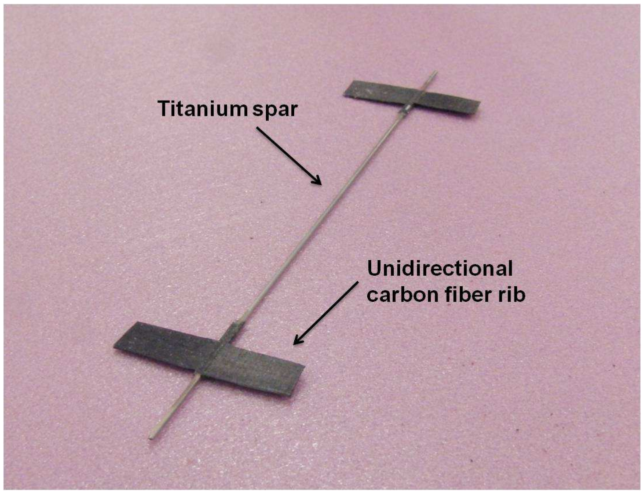
System	Weight (g)	% Total
Cycloidal Rotors	36	33.3
Electronics	19	17.3
Tail Rotor	18	16.3
Battery	15	13.5
Structure	10	9.0
Motors	8	7.0
Avionics	4	3.6
Total	**110**	**100%**

2.1 Cyclorotor Design

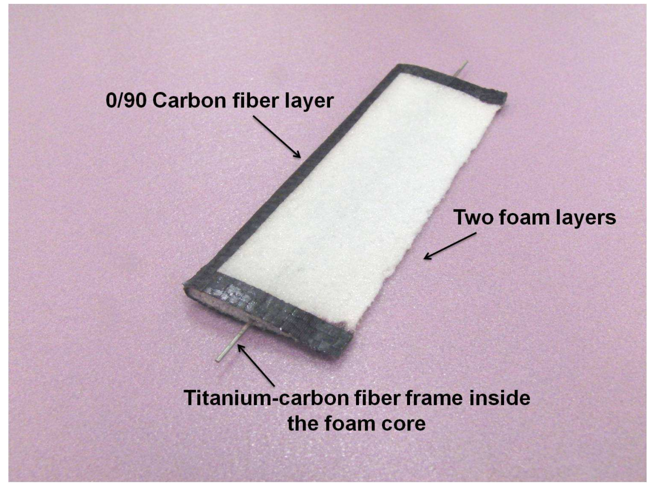
Systematic experimental parametric studies were performed in the past to optimize the performance of MAV-scale cyclorotors [8–9,14–16]. Several blade kinematics and rotor geometric parameters (blade pitching amplitude, location of pitch axis, rotor radius, blade airfoil, chord, planform, etc.) were varied in order to improve overall rotor performance in hover. Utilizing the understanding obtained from these studies, the present cyclorotor is designed for maximum thrust-to-power ratio (power loading). Each rotor consists of four blades with a NACA 0015 airfoil, 10.1 centimeters (4 inches) blade span, 3.3 centimeters (1.3 inches) blade chord, and a 5.1 centimeters (2 inches) rotor radius (Fig. 6). In addition, each blade pitches at a symmetric pitching amplitude of 45°. While optimizing the rotor parameters for maximum aerodynamic performance, emphasis was also placed on the blade and rotor structural design to reduce the overall rotor weight.

Aside from the four blades, as shown in Fig. 6, the cyclorotor consists of two carbon fiber end-plates and a blade pitching mechanism. One of the key design feature of the present cyclorotor is the non-rotating carbon shaft. Both the end-plates are allowed to rotate about the non-rotating hollow carbon fiber shaft on radial ball bearings. The blade pitching axis is located at the blade chordwise center of gravity location (45% from leading edge) in order to avoid the large pitching moment due to centrifugal force. The blades pitch about two radial bearings on the root and tip end-plates. As previously mentioned, the rotor configuration enables a passive blade pitching mechanism that will be described in the subsequent sections.

One of the biggest disadvantages of a cyclocopter is that rotor weight forms a significant fraction of the empty weight of the vehicle. Therefore, one of the main emphasis of the present work was to reduce the rotor weight without compromising on the total thrust and also maintaining structural integrity of the rotor. The rotor weight is directly related to the blade weight because it governs the centrifugal force, which is the predominant structural load on a cyclorotor. Designing light-weight blades for the cyclorotor is not easy because the centrifugal force acts in the transverse direction producing large blade deformations and even structural failure of the blades. Previous studies have shown that large bending and torsional deformations degrade the thrust producing capability and efficiency of the cyclorotor. Therefore, the emphasis of the present work was to design and fabricate extremely light-weight blades with large stiffness-to-weight ratio. The present blades uses an innovative carbon composite foam construction.



(a) Titanium-carbon fiber frame.



(b) Final finished blade (2 grams).

Figure 7: **Cyclorotor blade design.**

2.2 Blade Fabrication

As illustrated in Fig. 7(a), the first step of the 3-step blade fabrication process is to assemble a blade pitching frame composed of a titanium spar and two rectangular carbon fiber ribs. The 1.27 millimeter (0.05 inch) diameter titanium spar is positioned at 45% chord-wise location from the leading edge and acts as the blade pitching axis. The two carbon fiber prepreg ribs were cured to the titanium spar in an industrial grade oven at 350°F for 60 minutes. The carbon fiber ribs reinforce the tips on both sides of the blade and prevent the titanium spar from moving within the foam core. This carbon fiber-titanium frame provides large bending and torsional stiffness to the blades. The frame is then inserted between two 4 millimeter layers of foam core and cured inside a NACA 0015 airfoil blade mold at 350°F for 60 minutes. The cured NACA 0015 foam core is then wrapped with single layers of 0/90° orientation carbon fiber prepreg at the blade tips (to provide a hard point for blade attachment) and also around the leading edge in order to preserve the leading edge shape and also increase blade stiffness and crash-worthiness. The carbon fiber ribs are secured in position with heat-resistant tape and then wrapped in heat-resistant plastic to prevent the fiber from bonding to the blade mold during the heat treatment. The blade is then cooked at 350°F for 120 minutes in order to adhere the carbon fiber to the foam core. Finally, the blade is taken out of the mold and trimmed to the right dimensions. The final composite blade weighs only 2 grams, meeting the critical requirement of a stiff light-weight blade (Fig. 7(b)). All the previous blade designs were either highly durable (but heavy) or light weight (not durable) [14, 18]. However, the current blade design takes both weight reduction and blade durability into consideration.

2.3 Blade Pitching Mechanism

One of the key requirements for the success of a cyclocopter is a simplified light-weight blade pitching mechanism. Modeled after a four-bar linkage system, the present pitching mechanism enables passive blade pitching as the blades move about the circular trajectory. The schematic of the mechanism is depicted in Fig. 8 where the four bars of the linkage system are labeled L_1, L_2, L_3 and L_4. L_1, also referred to as rotor radius, is the distance between the blade pitching axis and the horizontal axis of rotation. The pitch links (of length L_3) are connected to the end of the offset link on one end and the other end is connected to point B which is at a distance L_4 behind the pitching axis. The connections at both ends of the pitch link are through pin joints to allow the rotational degree of freedom. With this arrangement, as the rotor rotates, the blades automatically pitches cyclically, where the pitching amplitude depends on the offset length, L_2, when the other linkage lengths remains fixed. The rotation of the offset link changes the phasing of the cyclic pithing and thereby changes the direction of the thrust vector.

The actual pitching mechanism implemented in the vehicle is shown in Fig. 6. For the present pitching mechanism to work, the offset link (L_2) needs to be installed at the tip of shaft in a non-rotating frame. That is reason why the present rotor was designed such that the shaft is not rotating with the rest of the rotor. In order to reduce mechanical complexities, the distance L_2 is kept constant, hence the blade pitching ampli-

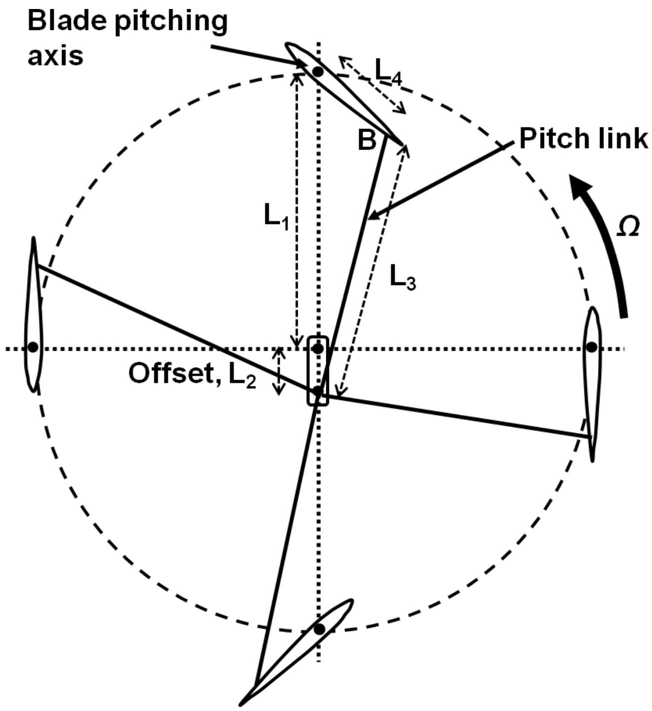


Figure 8: **Schematic of the blade pitching mechanisms.**

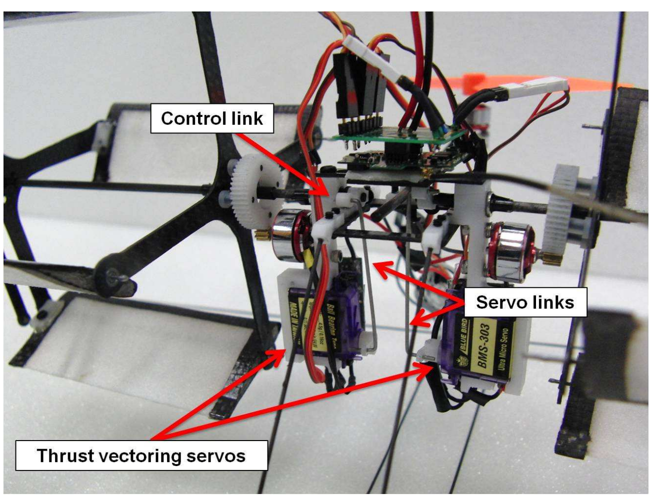


Figure 9: **Thrust vectoring mechanism.**

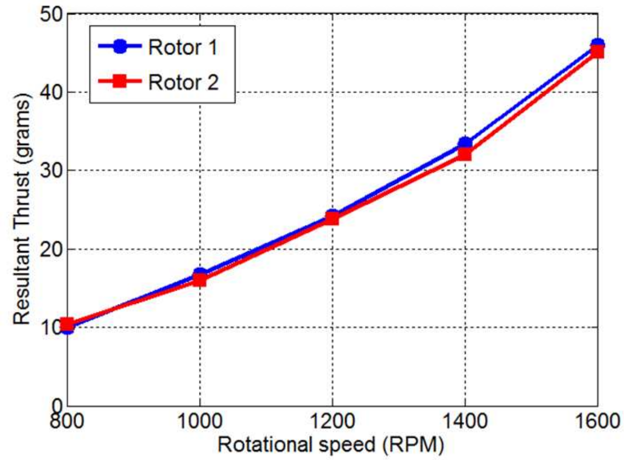


Figure 10: **Thrust vs. rotational speed of the two cyclorotors.**

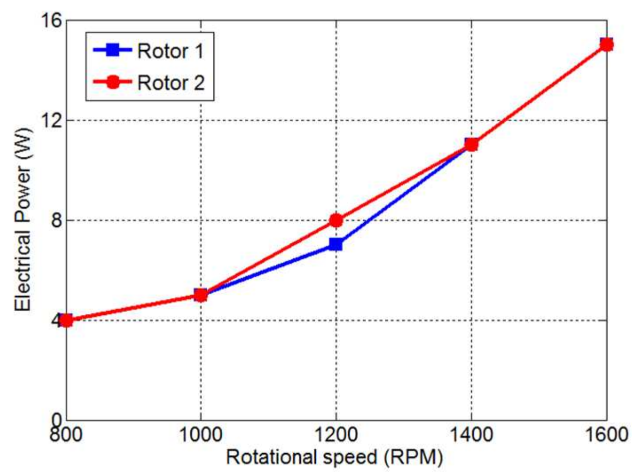


Figure 11: **Power required vs. rotational speed of the two cyclorotors.**

tude could not be actively varied in flight. Therefore, the only way to alter the magnitude of the thrust is to vary the rotational speed of the rotors. As mentioned, the direction of the thrust vector can be manipulated by rotating the offset link. The idea is implemented in the twin-cyclocopter by rotating the non-rotating carbon shaft by a 4 gram servo (capable of ±30° rotation) through a control linkage (Fig. 9). This could provide each cyclorotor with ±30° of thrust vectoring.

2.4 Rotor Performance

A systematic performance sweep was conducted from 600 to 1600 rpm until the cyclorotor produced enough thrust to support the vehicle weight. Each optimized

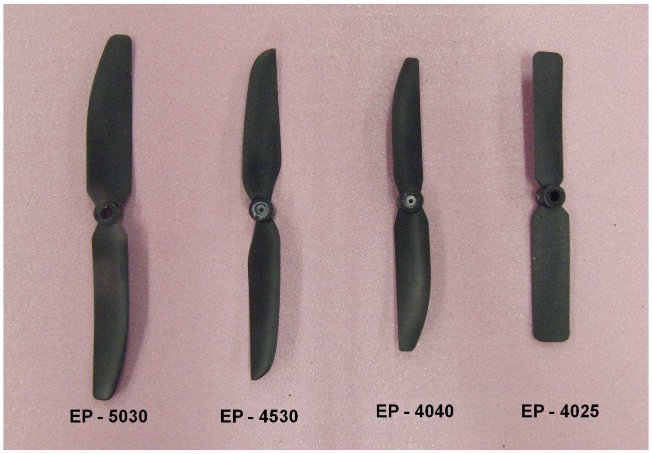


Figure 12: **Variation of tail rotor propellers tested.**

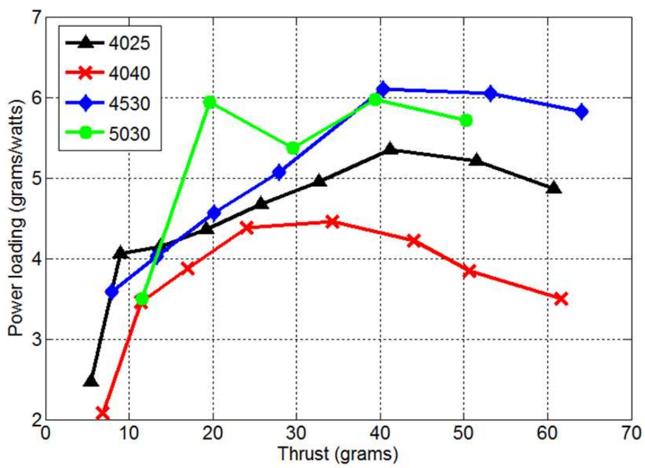


Figure 13: **Electrical power loading vs. rpm of various tail rotor propeller.**

cyclorotor produced 45 grams of thrust at 1600 rpm (Fig. 10). At the operating rpm, the rotor consumes 15 watts of electrical power (Fig. 11). Much of the power loss can be attributed to high friction from interactions between mechanical components (i.e gears, pitching mechanism, etc.). In order to reduce the frictional losses, major structural design changes were made until the rotor achieved minimum power consumption. Overall, the optimization of the cyclorotor was conducted using results from previous studies that varied blade kinematic and geometric parameters [8–9, 14–16]. Some differences in the performance of the two cyclorotors result from inconsistencies in the blade fabrication process and rotor assembly. However, both rotors are trimmed before flight testing to ensure that they are producing equal amounts of thrust.

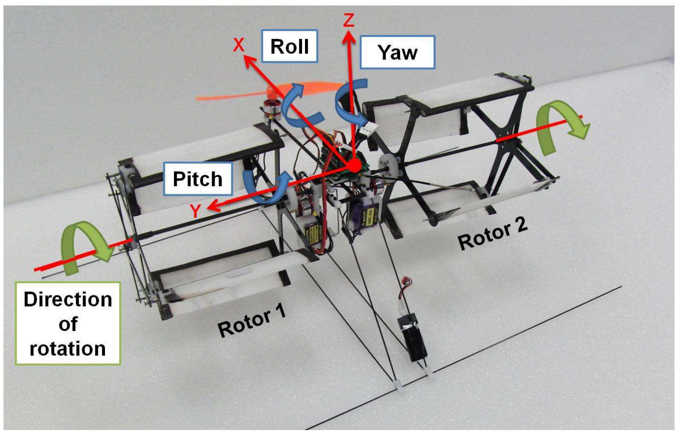
Various tail rotor propellers ranging from 4 to 5 inches diameter and 25 to 45° root pitch were systematically tested to maximize tail rotor efficiency (Fig. 12). From Figure 13, EP-4530 had the maximum efficiency and produced 50 grams of thrust at 9000 rpm. All the propellers were tested with a 2900KV 4 gram motor.

3. CONTROLS STRATEGY

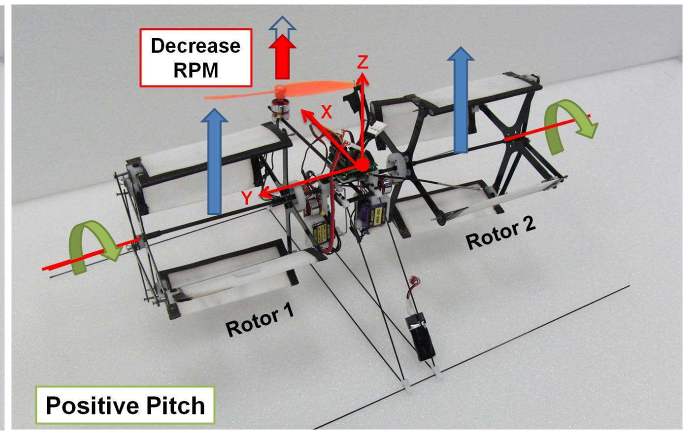
An attitude control strategy needed to be developed to enable the twin-cyclocopter to perform stable hover. Since the rotational speeds of both the cyclorotors and the tail rotor could be independently controlled, this capability was combined with thrust vectoring of the cyclorotors to develop an efficient and uncoupled control strategy.

Figure 14(a) shows the pitch, roll, and yaw axes definition for the twin-cyclocopter. As previously mentioned, a horizontal tail rotor was added to counteract the vehicle's inherent pitch-up moment that is generated when both the cyclorotors rotate in the same clockwise direction. Although rotating the cyclorotors in opposite directions would eliminate the net pitch-up moment, it would also couple pitch and roll control and would also cause undesired rolling moment in forward flight. With the present controls strategy, pitch, roll, and yaw moments are completely decoupled other than through gyroscopic effects. The tail rotor is used to control the pitch by varying its rotational speed. For instance, a positive pitching moment can be obtained by decreasing the tail rotor rpm, and vice versa for negative pitch (Fig. 14(b)). Roll is directly controlled by differential rotational speed variation of the cyclorotors. Positive roll is executed when the rotational speed of the left cyclorotor is greater than the right (Fig. 14(c)). Finally, yaw is controlled by differentially rotating the two thrust vectors of the cyclorotors. A positive yawing moment is produced by tilting the thrust vector of rotor 1 forward and rotor 2 backward.

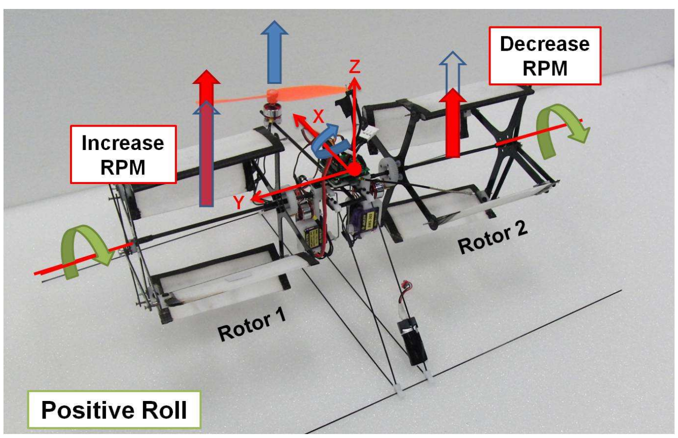
Ideally, all the thrust vectors should be perfectly vertical such that the twin-cyclocopter instantly lifts-off vertically when given a throttle. If the thrust vectors are not vertical, pitch, roll, and yaw moments may be coupled. For instance, varying the rotor rpm to induce a positive roll may also produce a positive yawing moment if the thrust vectors are tilted. This is discussed more elaborately in the flight testing section. Further complications arise from the effect of rotational speed on the direction of thrust vector. The thrust vectoring servos were adjusted such that, at the operating rpm, the thrust vectors of both the cyclorotors are perfectly vertical, minimizing couplings.



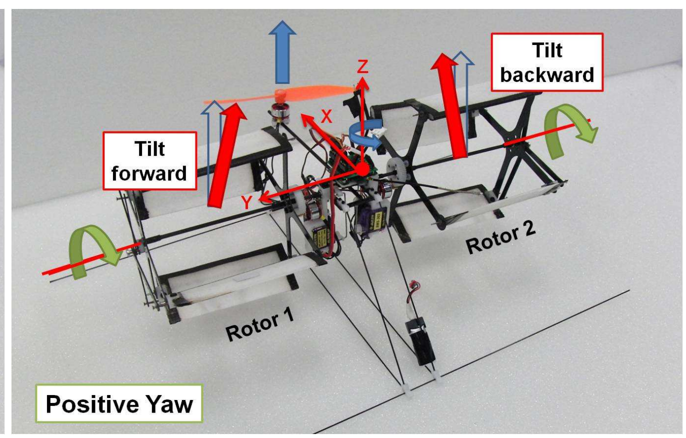
(a) Definition of pitch, roll, and yaw degrees of freedom.



(b) Pitch control.



(c) Roll control.



(d) Yaw control.

Figure 14: **Control strategy for twin-cyclocopter.**

3.1 Avionics and Telemetry

Because of the fast vehicle dynamics (due to very small vehicle inertia), the cyclocopter could not be stabilized without implementing an onboard closed-loop feedback control system. The avionic system on the vehicle includes a 1.5 gram processor-sensor board called GINA MOTE, which was originally developed by the University of California, Berkeley (Fig. 15). The principal components of this board are a TI MSP430 microprocessor for onboard computation tasks, ITG3200 tri-axial gyros, KXSD9 tri-axial accelerometer, and an ATMEL radio and antenna for wireless communication tasks. The wireless communication has a latency less than 20-30 milli seconds. The time critical inner loop feedback occurs at an update rate of 3 milli seconds. The user communicates with the vehicle using a LabVIEW interface.

The gyros measure the pitch (q), roll (p) and yaw (r) attitude rates while the accelerometers record the tilt of the gravity vector. The vehicle attitude can be extracted by integrating the gyro measurements with time. However, it is known that this leads to drift in attitude measurements [19]. Accelerometers on the other hand offer stable bias, but are sensitive to vibrations and in general offer poor high frequency information [20]. Therefore a complementary filter was incorporated to extract the pitch and roll Euler angles using a high pass filter for the gyros (4 Hz cut-off) and a low pass filter for accelerometers (6 Hz cut-off). The rotor vibrations were filtered out since it was sufficiently higher than the body dynamics.

On-board inner loop feedback was implemented using a proportional-derivative (PD) controller as shown in Fig. 16. The feedback states were the pitch and roll Euler angles (θ, ϕ) and the attitude rates (p, q and r). An outer loop feedback capability was provided for translational positioning by a human pilot or a position tracking system such as VICON. The final control inputs to the vehicle actuators are the individual rpms for the two cyclorotors and tail rotor and the two servo inputs as shown in Fig. 16.

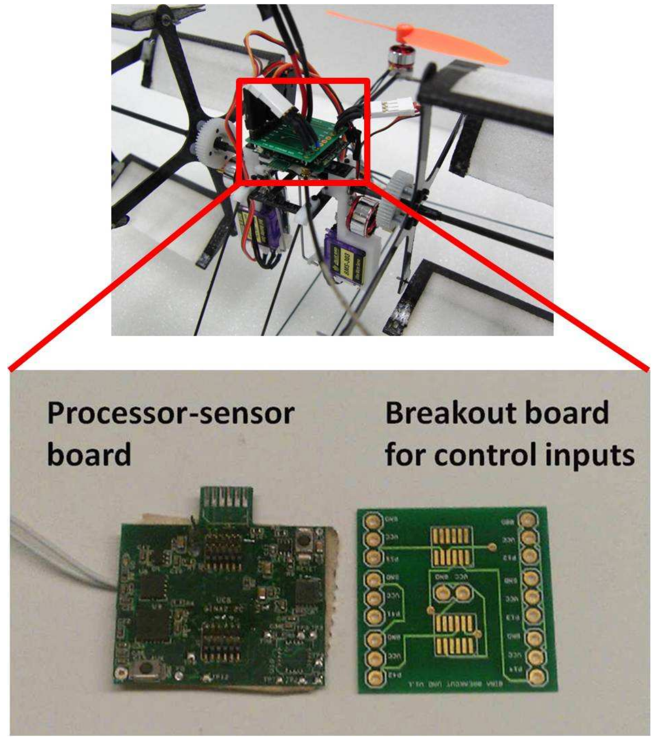


Figure 15: **GINA MOTE.**

4. FLIGHT TESTING

Prior to free-flight testing, the first step was to test the vehicle on separate single degree-of-freedom test stands to individually examine the vehicle response in pitch, roll, and yaw degrees of freedom with and without the feedback control system. The next step was to test on a gimbal stand (all three degrees-of-freedoms) to investigate cross-couplings and also to evaluate the effectiveness of the closed-loop feedback system in stabilizing the vehicle and rejecting external disturbances. These tests clearly showed that the vehicle dynamics was too fast that a human pilot would not be able to stabilize the vehicle even on a stand without the feedback control system. During the tests, the proportional and derivative gains were tuned using the Ziegler Nichols approach. The gains offered acceptable stiffness and damping to reject external disturbance with minimal oscillations were chosen. Once repeatability in vehicle stability was established on the gimbal stand with a given set of trim and gain values, free flight tests were conducted. It must be noted that achieving stable attitude in the gimbal setup was an important necessary condition to ensure stable free flight. It enabled quick troubleshooting with minimal damage to the vehicle.

As described before, the control strategy is such that the pitch, roll and yaw inputs lead to a decoupled pitch, roll and yaw response respectively. However, this is only possible if the thrust vectors for each of the cyclorotors are in the vertical direction. Consider for instance that the thrust vectors are inclined with respect to vertical and a roll input is given by differentially varying the rpms of the cyclorotors. This implies that there is a horizontal component of thrust which is not balanced out. This results in a yawing moment causing an undesirable roll-yaw coupling. Also, if the thrust vectors are not perfectly vertical, when a yaw input is provided, which results in opposite rotation of the thrust vectors while maintaining the rpms, the vertical com-

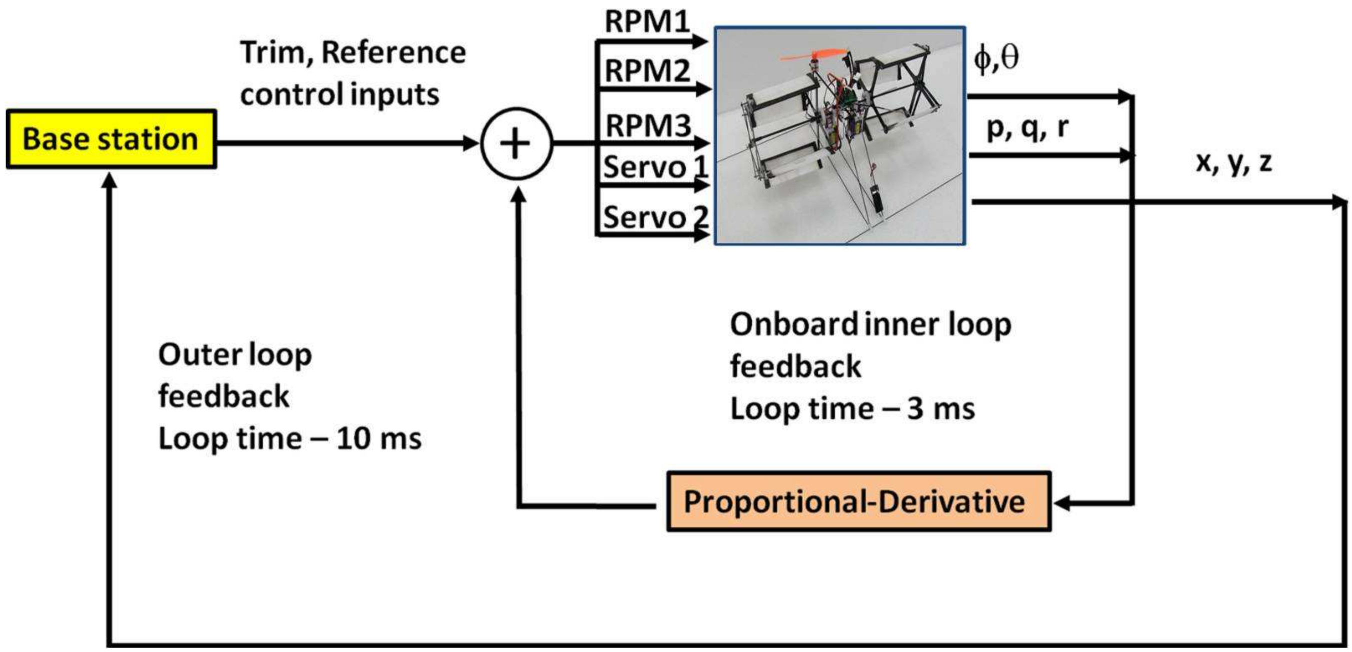


Figure 16: **Schematic showing the inner-loop feedback control system implemented.**

ponent of the thrust of one cyclorotor would increase and the other one would decrease causing the vehicle to roll (yaw-roll coupling). Therefore, the vehicle has to be carefully trimmed to ensure that there is no coupling between roll and yaw.

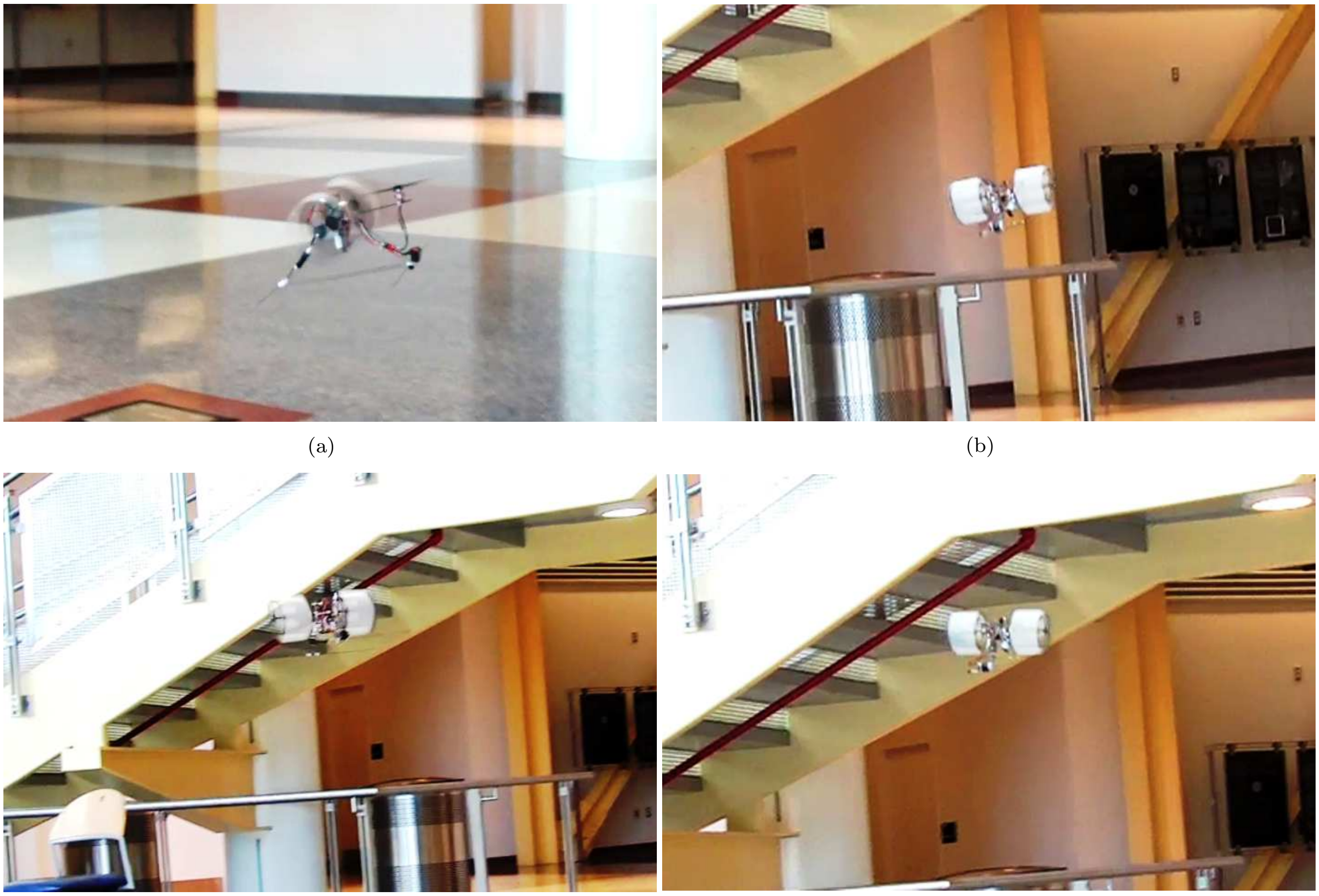
During free flight testing, the twin-rotor cyclocopter was powered by a 7.4 volt 250 mAH battery that weighed approximately 15 grams. Even though the trim values were obtained from the gimbal stand tests, these values would change in free flight because the position of the center of lift (of the entire vehicle based on the relative contribution from each rotors) is not known exactly a priori and therefore have to be determined through systematic flight testing. The vehicle was trimmed in roll by differentially adjusting the cyclorotor rotational speeds, whereas the pitch trim was achieved by varying tail rotor rpm. Differential tilting of the cyclorotors was used to trim yaw. The trimming forms the most important step in successfully flying the vehicle. Once the vehicle is perfectly trimmed, a pure throttle command simultaneously increases the rotational speeds of all the rotors such that all the moments are cancelled and the center of lift is at the center of gravity of the vehicle. Even though trimming is an important necessary step, it is the feedback controller that ensures the vehicle can reject any of the external disturbance and perform stable autonomous hover. Based on the flight tests, the feedback gains had to be tuned for stable hover. Figure. 17 shows the autonomous hover of the twin cyclocopter. The flight performance was determined by observing whether the vehicle assumed a stable hover attitude with minimal drift.

Successfully scaling down a vehicle to close to 100 grams and maintaining stable autonomous hover is an important achievement. For a cycloidal-rotor based vehicle, the free flight demonstration of the 110 grams MAV asserts the concept's potential to be a light-weight highly portable versatile vehicle.

5. CONCLUSION

The objective of this research was to design, build and perform autonomous hover testing of an efficient cyclocopter MAV at 100 gram scale. The cyclocopter developed in this study is a hybrid configuration with two optimized cyclorotors and a conventional horizontal tail rotor for pitch control. Independent rotational speed control of each of the three rotors combined with the thrust vectoring capability of the cyclorotors makes this vehicle configuration highly maneuverable. The attitude control strategy of the present vehicle is designed such that pitch, roll and yaw control are completely decoupled. A closed-loop feedback control system was implemented on an onboard processor-sensor board that enabled stable autonomous hover of the vehicle. Specific conclusions derived from this study are summarized below:

i. The twin cyclocopter used efficient cylorotors that were optimized based on detailed experimental parametric studies. Each rotor consists of four



(a) (b) (c) (d)

Figure 17: **Autonomous stable hover of the 110 gram twin-cyclocopter.**

blades with a NACA 0015 airfoil, with a blade span of 10.1 centimeters (4 inches), chord of 3.3 centimeters (1.3 inches), and rotor radius of 5.1 centimeters (2 inches). In addition, each blade pitches at a symmetric pitching amplitude of 45°. Choosing the right chord/radius ratio (0.65 in this case) and pitching amplitude was critical because these parameters significantly affect the hover efficiency of the cyclorotor.

ii. A simplified, light-weight and low friction pitching mechanism was implemented which helped reduce the cyclorotor weight. Modeled after a four-bar linkage system, the pitching mechanism enabled passive cyclic pitching of the blades. The pitching axis location was chosen to be 45% blade chord, which is the blade chordwise center of gravity location in order to eliminate the large pitching moment due to centrifugal force. This greatly reduced the torsional deformation of the blades and also decreased pitch-link loads and the torque on the thrust vectoring servos.

iii. An innovative blade design and fabrication process was used to construct light-weight composite blades with extremely high stiffness-to-weight ratio. Each weighed 2 gram and was composed of a two-layer foam core with an embedded titanium-carbon fiber skeleton structure and wrapped with carbon fiber strips at the leading edge and at the blade tips. Significant reduction in blade weight greatly reduced the magnitude of the centrifugal load acting on the rotor structure and blade pitch mechanism and enabled the design of an extremely light-weight cyclorotor. This played a key role in the success of the present cyclocopter.

iv. The novel control strategy utilized the thrust vectoring capability of the cyclorotors along with independent rpm control of each rotor. Since both of the cyclorotors were rotated in the same direction, a pitch-down moment was needed through the incorporation of a horizontal tail rotor. With the present controls strategy, pitch, roll, and yaw moments are decoupled. The tail rotor is used to control the pitch by varying its rotational speed, yaw is controlled by differential thrust vectoring of the two cyclorotors, and roll through differential variation of the rotational speeds of the cyclorotors.

v. Systematic trimming of the vehicle and careful tuning of the feedback gains on a gimbal stand and also during flight testing were essential for the successful flight of the vehicle. It was also observed that a slight tilt in the cyclorotor thrust vectors could cause significant coupling between roll and yaw control. Once properly trimmed, the feedback control system was able to autonomously stabilize the attitude of the vehicle in flight with only pure throttle command from the human pilot. The present 110 gram cyclocopter is till date the smallest cycloidal rotor-based aircraft to have ever flown successfully.

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