Design of Fixed-Wing Micro Air Vehicles for Indoor and Outdoor Missions

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The paper outlines the design procedure of the University of Arizona MAV team in developing micro air vehicle (MAV) systems for competing in both the indoor and outdoor sessions of the 2007 MAV Competition. The aircraft for outdoor mission is an enhanced version of a previously successful design, Dragonfly. Through iterations, the gull-shape dihedral was implemented in the Zimmerman wing, providing better roll stability. Selection of the propulsion system, power sources, video camera and integration of the autopilot into aircraft are presented in detail. For the indoor session, a tail-sitter MAV, Mini-Vertigo with vertical take-off, landing, and hovering capabilities (VTOL) was designed using a counter-rotating propulsion system. It consists of two out-runner brushless motors that align co-axially. This system eliminates negative propeller torque effects of other propulsions. Gyros provide in-flight stabilization of the aircraft. Step-by-step construction of airframes is described including rapid prototyping of molds for the wing and fuselage, lamination of sandwich structures, and packaging of all devices. Finally, flight tests were conducted and telemetry data were utilized in adjustments of PID control laws.

I. Introduction

Micro Air Vehicles were initially brought into the fore of technological innovation by the Defense Advanced Research Projects Agency (DARPA) in 1996. This brought about a plethora of interest from all parties, business and academics alike, in hopes that these small flying vehicles would be able to satisfy both civilian and military needs. In 1996, the International Micro Air Vehicle Competition was organized, where different parties would be able to showcase their progress and development in the field of MAVs.

The University of Arizona Micro Air Vehicle program is at the forefront in the development of fixed and flapping wing MAVs. Today MAV development has been mainly geared towards the development of autonomous systems. This year's 3rd US-European MAV Competition has brought about the introduction of an indoor competition in addition to its traditional outdoor competition. The indoor competition was introduced to spur research into VTOL (Vertical Take-Off and Landing) based MAVs in the hope that these types of MAVs would have the versatility of performing in both the indoor and outdoor arenas in the future. The following section discusses the design procedure of the University of Arizona MAV team in accomplishing its goal in competing in both the indoor and outdoor sessions of the MAV Competition.

II. Design Procedure

Outdoor Session

In this section, the design procedure for the outdoor session will be examined. In order to successfully compete in the outdoor session, the aircraft design is based on the requirements of the mission. The mission requirements for the outdoor session include:

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- identifying two targets at known GPS coordinates
- locating an unknown target in a given search zone
- dropping a sensor in a known drop zone
- flying under two arches
- perching on a platform for bonus points
- landing safely in a given radius

These tasks may be performed in any order. The goal is to design an Outdoor MAV (Raptor) that is no larger than 30cm (12 inches), has a flight endurance of 20mins, and accomplishes the mission.

A. Airframe

i. Previous Designs

Raptor's configuration is a reflexed wing together with a vertical stabilizer as shown in Fig. 1. The control surfaces used on Raptor are a rudder and elevator. The rudder provides control in the lateral direction and the elevator provides control in the longitudinal direction.

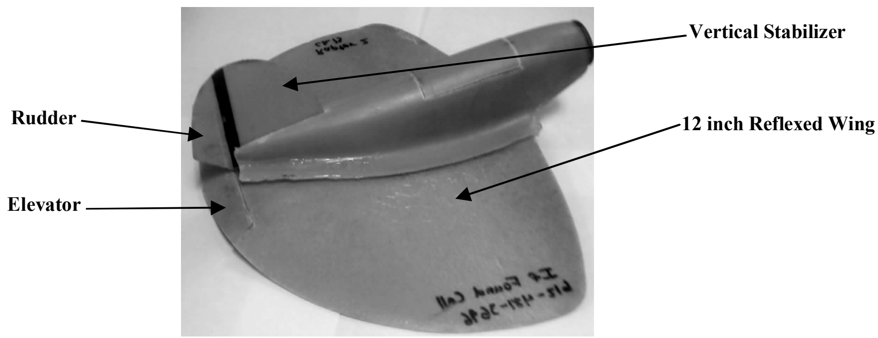


Figure 1. Outdoor MAV wing, fuselage and vertical stabilizer

The wing planform used in Raptor is derived from a history of past designs[1]. Early wings originated with the trapezoidal planform (Fig. 2) and transitioned into the Zimmerman planform (Fig. 3). The trapezoidal wing was designed due to its ease of construction, although it provided an uneven load distribution. With some research[2] it was found that the Zimmerman planform improved the uneven loading.

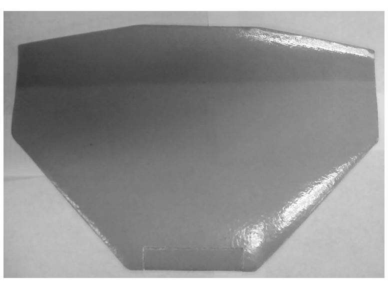


Figure 2. Trapezoidal Wing Planform

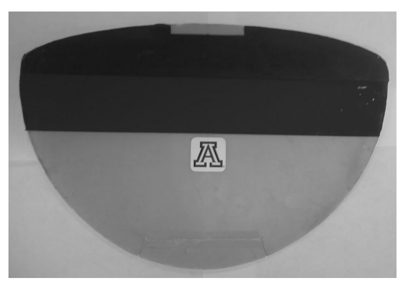


Figure 3. Zimmerman Wing Planform

The Zimmerman planform had three different phases of design. The flat Zimmerman (Fig. 4(a)) was the first to be flown and tested. It was very unstable in roll, thus the addition of 5°dihedral (Fig. 4(b)) enhanced roll stability. With further testing it was observed that more roll stability was required. The latest design consists of implementing the gull configuration (Fig. 4(c)) where the center section is dropped down 10mm and maintaining the 5° dihedral. This combination increases the pendulum affect and gives the stability necessary for completing the mission requirements.

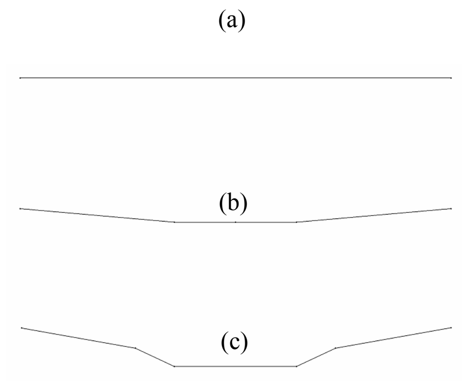


Figure 4. a) Flat wing b) 5° Dihedral Wing c) Gull Wing

ii. Construction process (airframe)

The outdoor MAV is designed to have a composite sandwich structure with Kevlar and a foam core (Fig. 5). SolidWorks™ is used to design the wing mold as shown on Fig. 6.

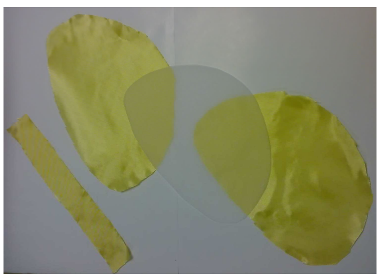


Figure 5. Kevlar and foam

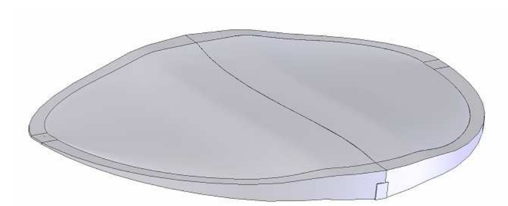


Figure 6. SolidWorks™ design of wing mold

By using rapid prototyping (CNC milling) the wing mold is created. The composite sandwich is then placed on the mold to be laminated. The mold and composite structure are then placed into a vacuum bag for twenty four hours. After this time duration the wing is taken out (Fig. 7) and cut into its final shape (Fig. 8).

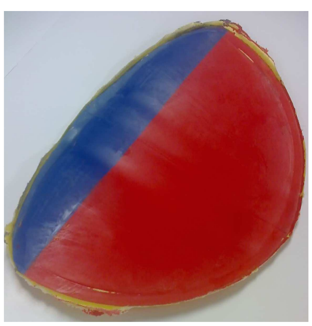


Figure 7. Un-cut Wing

Figure 8. Final Wing

When designing the fuselage the team decided to reshape the previous rectangular design. A smoother, rounder mold was created in order to improve the aerodynamics of the fuselage and to decrease the unused volume. Keeping the nose down thrust angle of 10° to allow for straight and level flight was an unchanged factor. The rectangular design of the fuselage is shown on Fig. 9 and the rounded design is shown on Fig. 10.

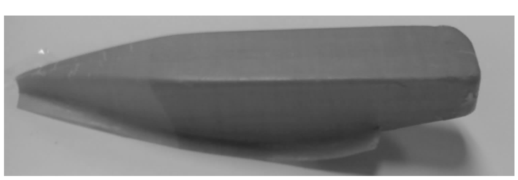


Figure 9. Rectangular Fuselage

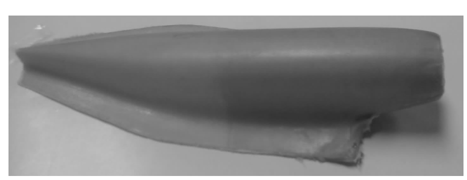


Figure 10. Rounded Fuselage

The design of the vertical stabilizer also makes use of the same composite sandwich structure used for the fuselage and wing. In addition, since the vehicle is not equipped with landing gears, additional carbon fiber strips are added to provide sufficient rigidity to the vertical stabilizer during landings.

B. Propulsion System

Based on past experience of different propulsion system combinations for previous 12 inch MAV designs, the team selected the power system set-up as shown in Table 1 and Fig. 11.

Table 1. Power System Description

Power System	Description	Mass (g)
Motor	Billet Bullet "Hot Wind" Single Stator brushless motor	23
Propeller	4.75 x 4.75 APC Speed 400 Electric Propeller	3.2
Speed Controller	Phoenix-10	7.7
3-Cell Lithium-Polymer Battery	ETEC 700 mAh	56.6
Total		90.5

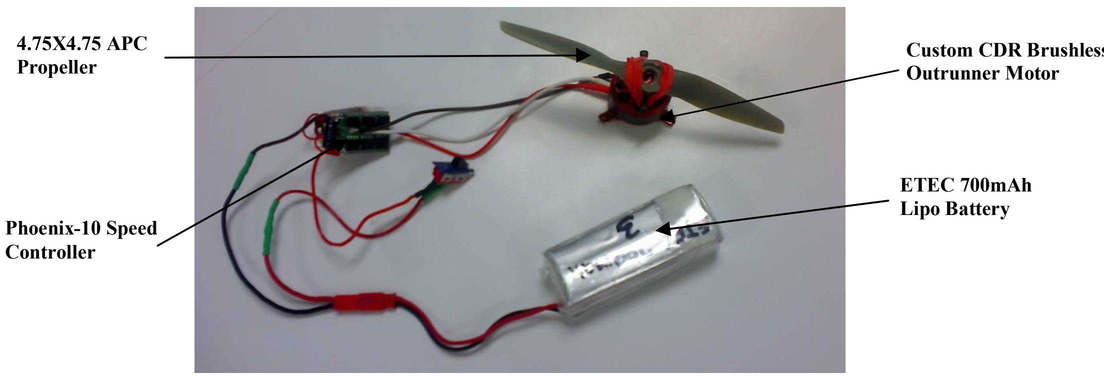


Figure 11. Power System Set-up

The Billet Bullet "Hot Wind" Single Stator brushless motor is made by CustomCDR. This out-runner motor is able to run off a maximum current of 10A and provides a pitch speed of 50-70mph. This allows Raptor to be equipped with a 10 amp Phoenix-10 speed controller. The Phoenix-10, made by Castle Creations is desirable in that it provides the user with the ability of programming a multitude of parameters to be tailor-made for a specific propulsion system. Examples of such parameters include the ability to program the cut-off voltage and controlling rotational direction of motor. Initially Raptor was designed to fly with a 400mAh 3 cell Lithium Polymer battery. However, due to additional weight and maximization of competitive flight time (20 minutes), 700 mAh Lithium Polymer Batteries are used. The ETEC battery brand is chosen mainly for its slender shape allowing it to fit inside Raptor's fuselage.

C. Components

Through the MAV06 Competition in Florida, the team realized that the camera used was not sufficient for identifying targets when the MAV was flying at high altitudes. This severely reduced the teams' chances to obtain satisfactory target identification during the competition. This year, the team has chosen the KX141 Color CCD camera which has higher resolution and a smaller optical angle. Although this camera is larger, it provides a clearer picture from the same altitudes. In order to send the video to the ground station a 200mW video transmitter is installed into Raptor. This was chosen due to its ability to transmit clear video signals at the maximum range of the competition site of 1500m. Two 2.5g Blue Arrow servos are used for the rudder and elevator of Raptor. The servos were chosen because of their light weight and sufficient torque.

For the competition, the Paparazzi autopilot system is used. The Paparazzi system includes the Tiny version autopilot board, GPS element, and an IR Sensor. To provide a wireless communication link with the ground station and pilot, an on-board modem and RC receiver are included in the autopilot system. The onboard modem used is the XBee™ ZigBee OEM RF Module that transmits signals at 2.4Ghz to the ground station.

Table 2. Raptor Components

Components	**Description**	**Mass (g)**
KX141 Uncased Color CCD camera	480 Line Resolution, 2 lux light sensitivity	13
3 Servos	Blue Arrow BA-TS2.5	9
RC Receiver	PENTA 5 MZK	2.8
Video Transmitter	200mW transmitter	7.6
Sensor Drop	Paintball	3.3
Autopilot	Paparazzi Tiny	24
IR Sensor	Infrared sensors board	5.2
Modem	XBee™ ZigBee OEM RF Module	3.8
Total		**68.7**

D. Autopilot

The autopilot software[3] performs navigation of the airplane and communication with external devices, such as infrared board and GPS. The autopilot has three modes – fully autonomous mode, augmented stability mode, and fully manual mode. These modes can be selected by an operator from the ground station.

When autopilot is in the stability augmentation mode, an operator of the ground station controls desired thrust and roll of the airplane. Actual commands for servos are computed by the autopilot control loop code. Pitch of the airplane is controlled automatically to ensure stable and controllable flight. Pitch and roll angles of the airplane are limited to the safe values of the calibrated airplane and are hard-coded into the current airframe configuration[4].

E. Flight Plan

When the airplane is in fully autonomous mode, a flight plan is used. The flight plan is based on waypoint notation. Currently autopilot does not track the trajectory, but guides the airplane from one waypoint to another according to the flight plan. The flight plan consists of one or several blocks, where each of the blocks specifies several commands for the autopilot. The blocks are executed in a sequential order. In case of emergency, an operator of the ground station may specify next block to execute.

Indoor Session

In this section, the design procedure for the indoor session will be examined. The goal of the indoor team is to design a MAV capable of maneuvering through a 3 meter square room avoiding any obstacles present and successfully identifying two targets while being controlled from a zone 10 meters away. This is a challenging goal due to a three month work period. However, the team managed to produce exceptional results. Important considerations in this project were suitable airframe, propulsion system, reliable components, and sufficient controllability.

A. Airframe
   i. Previous Designs

Based on the mission requirements of the indoor session, a Vertical Take-Off and Landing type Micro Air Vehicle was required. This MAV was to be capable of hovering in a fixed position stably. The initial airframe tested was an off-the-shelf Hobby Lobby's Telink Brand Convair XFY1 Pogo VTO Aircraft (Fig. 12).

Figure 12. Hobby Lobby's Telink Brand Convair XFY1 Pogo VTO Aircraft

Pogo consists of a large foam frame with fins extending above and below the fuselage. Control surfaces are hinged to the trailing edge of the wing and vertical fins. This design was used as an initial platform to provide a basic understanding when working with a VTOL MAVs. Since size is an important criterion to succeed in the competition, the team moved to a smaller airframe. A flat 30cm span wing of Zimmerman planform was used. This wing fits the maximum target dimension of 50cm. The Zimmerman planform had been successfully implemented on outdoor 12 inch MAVs (refer to Fig. 3). It is mainly used in the new VTOL MAV (Mini-Vertigo) to allow it the capability of transitioning to and from vertical and horizontal flight.

ii. Construction

The main wing of Mini-Vertigo is made of a foam material called Depron that is laminated with sheets of fiberglass as reinforcement. Attached to the wing is a vertical stabilizer, also made from the Depron laminate. This vertical stabilizer extends on both sides of the wing. Control surfaces are hinged to the wing by means of high strength Blenderm tape. Carbon rods are embedded through the wing along its longitudinal and lateral axis to increase rigidity of the airframe. Finally, Mini-Vertigo's landing gear is in the form of carbon rods attached to both sides of the wing and to the vertical fins. Fig. 13 and 14 show the constructed platform of Mini-Vertigo.

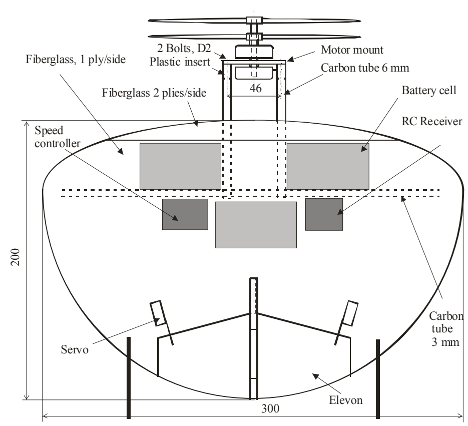


Figure 13. Mini-Vertigo Front View

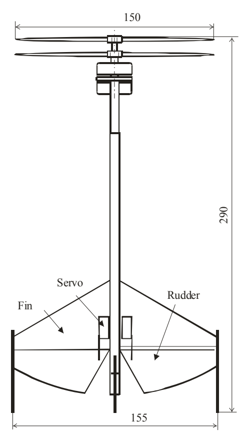


Figure 14. Mini-Vertigo Side View

B. Propulsion System

Initially, with Pogo a single motor and larger propeller was used. Flight testing with Pogo showed the team that hovering with such a propulsion system was detrimental. Unwanted torque effects caused Pogo to rotate uncontrollably. The team then decided on using a counter-rotating propulsion system. This system consists of two out-runner brushless motors that align co-axially. The choice of out-runner motors allows the motors to be set one behind the other, with a shaft through the stator of one motor, connecting the topmost propeller to the bottom motor. The second propeller is then attached to the top motor via a larger diameter adapter. The propulsive system setup is as shown in Fig. 15.

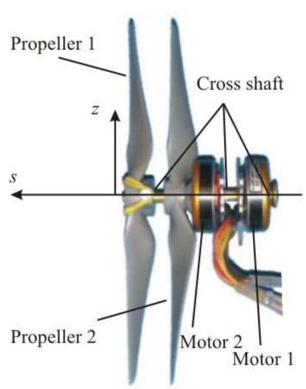


Figure 15. Contra-Rotating Motor system

This system proved very efficient in that it provided twice the thrust[5]. Torque issues were also ten times less than with a single motor and propeller.

C. Components

The criteria for choosing components for the mission are weight, reliability, and endurance. Choosing light weight components ensures a lighter platform with the ability to consume less power. Component reliability is based on its performance according to specifications provided. Component endurance relies on length of time before a failure occurs. The components used on Mini-Vertigo and their weights are listed below in Table 1.

Table 1. Mini-Vertigo Components

Component	**Description**	**Mass (g)**
Airframe	Carbon rods (3 mm)/Foam depron (6 mm)	26
Dual Motor/ Contra-rotating Propellers	MP Jet AC 22/4-60 D/ APC 7x5	50
3-cell Lithium-Polymer Battery	Poly RC 700mah	60
3 Micro Servos	Blue Arrow BA-TS-2.5	9
ESC	Castle Creations Phoenix-25	10
Receiver	Castle Creations Microstamp 4L	5
2 Video Transmitters	100mW Video transmitter	3.8g
Black and White Video Camera	Pinhole CCD Camera	3.6g
Color Video Camera	Pinhole CCD Camera	3.6g
5 Gyros	GWS Gyro	21g
On/off switch, wires	Misc.	6
Total		**192**

D. Stabilizing System

Gyros are the main stabilizing system on Mini-Vertigo. Gyros are devices that measure sudden changes in angular acceleration and send signals to the servos to counteract the motion. Initially, three gyros were used in order to make the plane controllable in flight. Two gyros connected to the elevator servos stabilize the plane on its pitch axis and the third gyro connects to the rudder to stabilize the plane in yaw. With this configuration, roll stability was manually controlled by the pilot.

After flight testing and analysis, 2 more gyros were integrated. The orientation of these additional gyros affected only the roll axis of the plane. As a result the plane became more controllable for the pilot. The set-up for the 5 gyros on Mini-Vertigo to manage its control surfaces is as shown on Fig. 16.

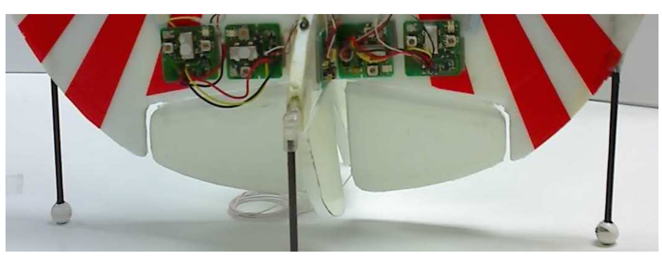


Figure 16. Gyros and Control Surfaces of Mini-Vertigo

III. Flight Testing

Outdoor

Due to Raptors maximum dimension of only 12 inches stability was a key issue when flying. Specifically, pitch stability was a major issue on Raptor. Having the correct position of center of gravity is essential to successful flight. Raptor's CG is 2.9mm behind the leading edge. Keeping a nose down orientation at this CG was found to increase the restoring moment while flying. Also, roll stability was found difficult to control. Due to Raptor's roll sensitivity, having only an elevator and rudder are adequate. Since Raptor is missing the conventional ailerons the airplane needs to take larger turns when maneuvering.

Orientation was also a problem when flying Raptor manually. Since the aircraft is an elliptical shape it is challenging to see which direction the nose is pointing when flying at great distances. To help alleviate this problem contrasting the top and bottom wing was essential. This was done by painting the top surface of the wing bright red and blue as shown on Fig. 8. This allowed the pilot to distinguish if the airplane was upside down/right side up or flying towards/away from him.

During the design stage of integration of the autopilot, the airplane control system was tuned to perform safely even under rough flight and weather conditions. The autopilot control gains in roll and pitch, as well as navigation gains were adjusted in favor of safety of the airplane flight as compared to fast response.

Flight tests in fully autonomous mode showed that even in strong wings of about 10 m/s, the autopilot kept the airplane flying at safe levels of roll. However, this reduced the airplane's ability to keep following its designated trajectory as shown in Fig. 1. The airplane followed the path for the flight into the wind, but deviated from the trajectory while flying with the wind, which is more obvious from Fig. 1a. Distance between points of the trajectory plots shows the change of the airplane's ground speed during each of the flight. The airplane ground speed measured by the GPS was about 5 m/s for the flight into the wind and about 25 m/s for the flight with the wind. Roughly, the airspeed was about 15 m/s and wind speed was about 10 m/s.

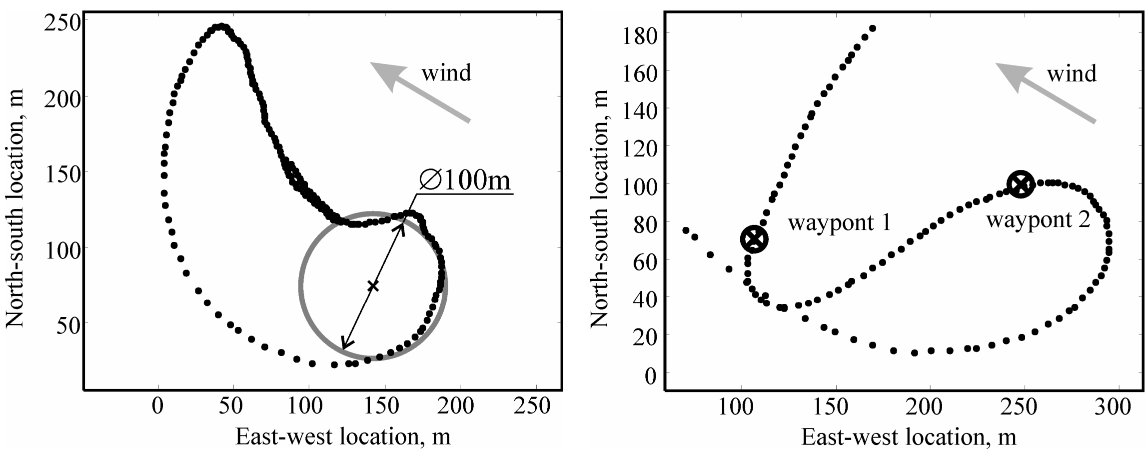


Fig. 1. Navigation at relatively strong winds: (a) trajectory navigation and (b) waypoint navigation.

As shown in Fig. 2, the altitude hold mode performs well during the fully autonomous flight for the navigation along the circular path and for the navigation through the waypoints. The error in altitude as a difference between the commanded altitude and the altitude measured by the GPS was no greater than 2 m for both test flights. The roll, pitch, and throttle PID controllers were tuned to perform at safe values of the airplane attitude and throttle even taking into account absence of the direct measurement of the airspeed for the current configuration of the autopilot. Thus, current autonomous vehicle performs well, keeping a rather narrow band of the "safe" values of the commanded values for roll, pitch, and throttle.

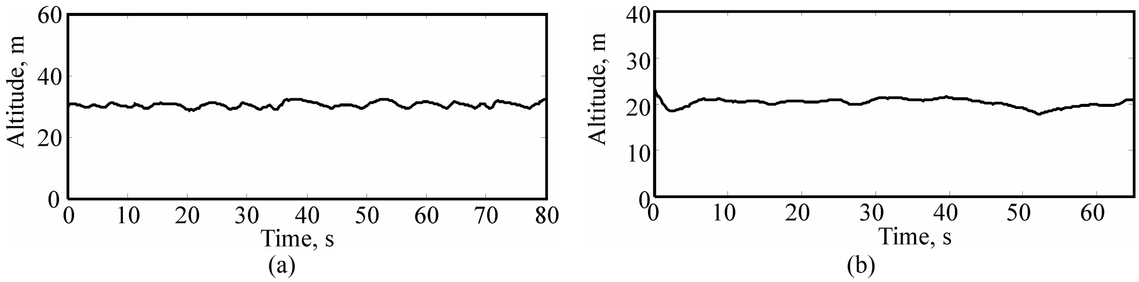
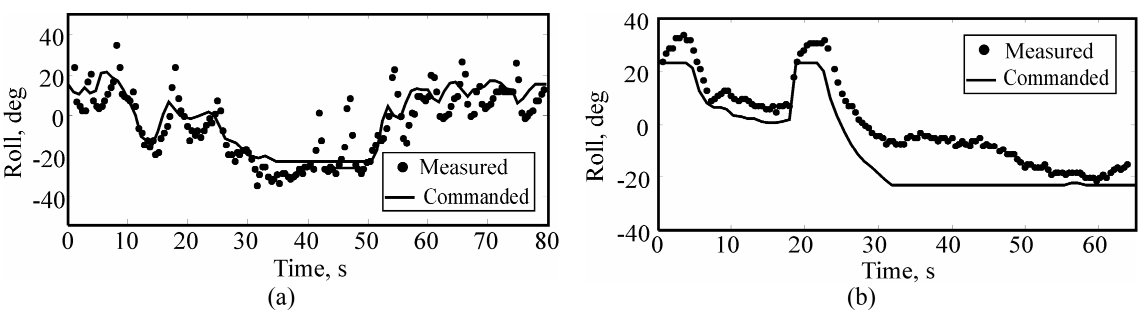


Fig. 2. Altitude hold mode during the flight (a) along the circular trajectory and (b) through the waypoints.

The commanded values were limited in the autopilot computer code to ± 25 deg for roll, 0—15 deg for pitch, and throttle was limited to 20—42% during autonomous flight. Autopilot control loop is activated at 60 Hz, which is enough to react to most of the in-flight conditions in a timely manner. The roll limitation is activated during both flights, as shown in Fig.3ab, as a constant horizontal part of the commanded roll plot. The actual commanded value would be greater in magnitude, but that would bring the airplane to the "unsafe" flight condition, when airplane flight stability condition would be more dynamic than static one, and will greatly depend on the airspeed which is assessed very approximately.



The airplane autonomous control system is adjusted to operate at the "safe" levels of attitude, keeping the reliability of stable flight as a primary goal. In addition, the autopilot will be tuned to allow greater accuracy for the completion of the flight objectives, while keeping reliability at the current level.

Indoor

Initially, Mini-Vertigo was tested without the aid of stabilizing gyros. However, hovering Mini-Vertigo proved to be uncontrollable for the pilot. After the first three gyros were integrated to counteract sudden changes in pitch and yaw, the plane attained stable hovering capabilities. Despite the improved stability by the integration of these gyros, slight effects of torque were experienced with changing throttle. The plane would roll about its axis while hovering and this introduced some difficulty in flying the plane. To fix this problem, two more gyros were wired in series to the gyros responsible for controlling pitch thereby, adding stability to the roll axis. This greatly improved the plane's overall stability and flight performance.

The team also experimented with different propeller sizes to see which would give the best performance. It was found that a 7/4 propeller size worked best for the application. The team noticed that with increasing propeller diameter hovering stability increased. However, Mini-Vertigo was limited to the 7/4 propeller size in order to achieve a minimal maximum dimension. The team also experimented with the location of the center of gravity of the plane. A lower center of gravity produced a more stable hovering plane. This was due to decreased sensitivity to control inputs from the pilot.

Weights were then introduced on the airframe to determine the maximum required payload. The effect of adding weight to the plane caused it to be more stable in flight. However, power consumption increased resulting in shorter flight times. The team managed to arrive at an optimal flying weight which allowed for five minute flights.

IV. Final Design

Once the flight testing phase was accomplished for both Raptor (Outdoor MAV) and Mini-Vertigo (Indoor MAV) both MAV Designs were finalized to fly the original mission. The final versions of Raptor and Mini-Vertigo are shown on Fig.17 and 18 below.

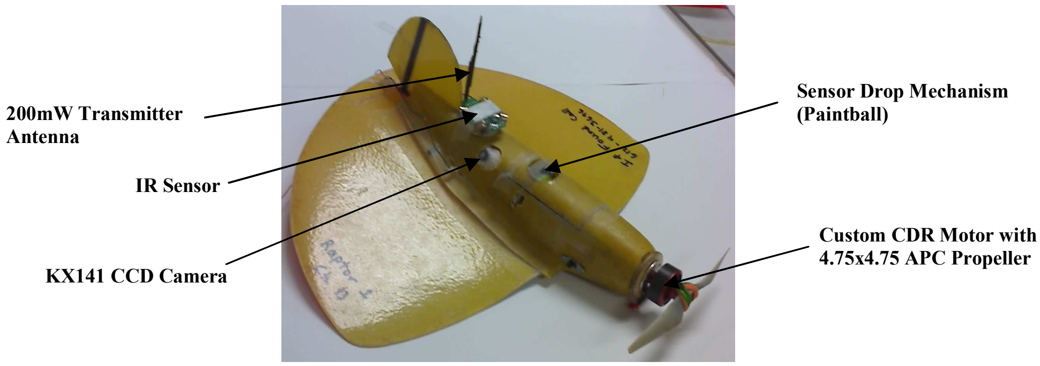


Figure 17. Raptor Final Design (Components not shown are in fuselage)

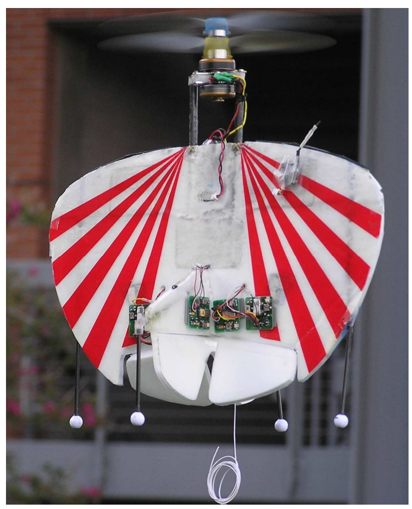


Figure 18. Mini-Vertigo Final Design

V. Conclusion

Both the Indoor MAV (Raptor) and Outdoor MAV (Mini-Vertigo) has been successfully designed to accomplish its specific mission requirement. As outlined in this paper, the designs of both MAVs were tailor-made to be able to effectively complete the mission requirements of the competition. The flight testing phase for both MAVs brought about interesting conclusions. Parameters such as PID gains in Raptor's autopilot system to placement of Mini-Vertigo's gyros were finalized. To date, the team has successfully tested Raptor's autopilot system for 80% of its mission requirements. In the following weeks, the flight plan of Raptor will be finalized to encompass the full mission scope of the competition. Concerning Mini-Vertigo, the team's pilot, David Addai-Gyansa has been successfully practicing flying the whole mission using only a color pinhole CCD camera placed on Mini-Vertigo. With more practice, the pilot would have the ability to complete the whole mission during the allotted time.

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