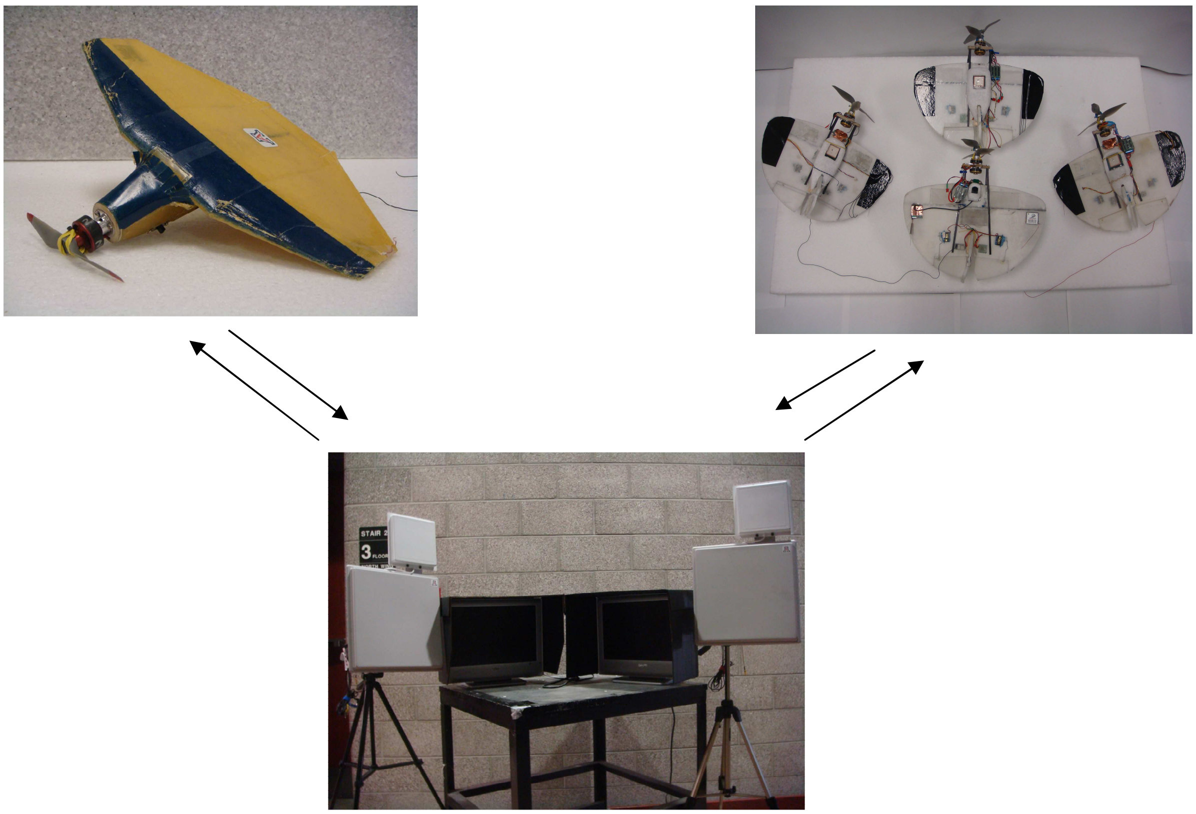
INTEGRATED MICRO AIR VEHICLE SYSTEMS



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I. Introduction

Removing the human element from the frontlines of battle has become an increasingly important strategy of military operations. Although in war the loss of human life was inevitable, recent advances in technology have made it possible to reduce that risk. One such advance has been the use of Micro Air Vehicle (MAV) technology. MAVs are extremely useful for gathering intelligence in areas too hostile for humans. The advantages of using MAVs in high-risk operations have become abundantly clear, and their development has seen tremendous growth in recent years.

The University of Arizona MAV program is at the forefront if the development of fixed and flapping wing MAVs. Presently MAV development was geared towards the development of autonomous systems. The University of Arizona MAV program has developed several vehicles capable of flying autonomously as well as communicating data and video in real time. These vehicles include a conventional fixed-wing MAV, a flapping wing MAV and most recently a tail sitter, Vertical Take-Off, and Landing (VTOL) MAV. The VTOL MAV has the ability to hover, making it possible to integrate technologies such as chemical signature detection and audio acoustic sensing. The capabilities have been demonstrated at previous MAV competitions; however, the team's objective at MAV08 was to determine how autonomous MAVs can be integrated into a large system to accomplish dynamic and multivariable missions.

The mission prescribed by the MAV08 competition was a true test of the current state of MAV technology. The rules required each team to use MAVs as a platform to successfully plan and execute a rescue mission. The mission creates a scenario where enemy forces have captured hostages in a bank and fortified their position with mines and guards in a patrol vehicle. The goal was to safely guide a team of commandos to an unknown room in the bank where the hostages were held without detonating a land mine or being detected by guards. To complete the mission, the MAVs performed a variety of tasks including locating the land mines, determining which room contains the hostages, and monitoring the guards to time the commandos approach to the bank. The complexity of the conditions was unprecedented in any previous MAV competition. It required developing MAVs capable of transmitting large amounts of data while simultaneously performing multiple operations. The following sections discuss the design of the MAV system that used to accomplish the MAV08 mission.

II. Mission Statement

The MAV ’08 committee selected fifteen teams from around the world to compete. The mission required the rescue of hostages under the control of a radical terrorist group known as the Mavedonian Advocates for Violence (M.A.V). In March 2008, the only Mavedonian bank (***Figure 3.1***) was overtaken by the M.A.V. group, who held the banking staff hostage and made demands to the World Bank and the Mavedonian government.

The M.A.V group held the hostages in a single room at the ground floor of the bank. Two of the terrorists patrolled the bank in a heavily armored vehicle. The bank building was surrounded by an unknown number of anti-personnel mines. The mission was conducted during a forty minute window of opportunity while three of the terrorists left the hostages unsupervised to make a televised broadcast. The mission objective was to rescue the hostages in the bank using two allied commandos during that forty minute time frame. Other mission requirements and parameters are listed in ***Table 2.1***.

Table 2.1. Project/Mission Requirements and Parameters

Metric	**Required**	**Desired**	**Units**
General Rules			
(4.1.1) Maximum Dimension of Vehicle	30	30	cm
(4.1.2) Perimeter of Arena	1	1	km
(4.1.3) Location of Team from Bank	<1	<0.3	km
(4.1.4) Minimum Vehicle Altitude before being detected by guards	100	100	feet (AGL)
(4.1.5) Minimum Vehicle speed before being detected by guards	10	10	Knots
(4.1.6) Height of tallest building in arena (bank)	12	12	M
(4.1.7) Window of Opportunity	40	40	Minutes
(4.1.8) UGV Minimum Size	NA	NA	Unitless
Landmine Parameters			
(4.1.9) Diameter of Landmines	15	15	Cm
(4.1.10) Lethality(effect) Zone of land mines	20	20	M
Competition Day Parameters			
(4.1.11) Maximum Number of Team Members at Ground Station	3	6	People
(4.1.12) Maximum Wind Speed during Mission	37 (20)	37 (20)	kph (knots)
(4.1.13) Maximum Precipitation during Mission	1	1	mm hour
(4.1.14) Voltage for power outlets during competition	220	110	V
(4.1.15) Frequency of power outlets during competition	50	60	Hz

III. Mission Strategy

In order to complete the mission successfully, three primary tasks had to be completed:

1) Survey the perimeter of the bank
- A vehicle must constantly monitor the position of the armored vehicle and help determine the optimum ingress point for the commandos.
- A vehicle must serve as the "eyes" of the team, giving real-time updates to help the team guide the commandos.

2) Determine room location of the hostages
- Several vehicles were needed to determine the location of the hostages.
- Each vehicle was to circle the bank and peer into the windows with cameras until the hostages were found.

3) Detect and disarm anti-personnel mines
- A vehicle was needed to protect the commandos from detonating the mines.
- The vehicle had to send the location of any landmines encountered to the simulated UGV. The UGV would simulate disarmament of the mines.

IV. Preliminary Design

After tabularizing all the mission requirements, the team brainstormed on the different tasks:

- Reconnaissance
- Locating the Hostages
- Landmine Detection and Disarmament

1) Reconnaissance

In order to accurately determine where the armed vehicle was at all times, a dedicated reconnaissance vehicle was required. The team researched the different types of vehicles.

a. Ornithopter

Figure 4.1. Cybird P1 Ornithopther[1]

An Ornithopter is shown in ***Figure 4.1.*** This bird-like vehicle is fully autonomous and can blend into the environment, making it virtually undetectable. However, it was determined that the Ornithopter's maximum loiter was fifteen minutes, well below mission requirements. Furthermore, the Ornithopter had a wingspan of 60cm, almost two times the maximum dimension and would cause the team to be disqualified. Current technology limits the minimum size of the Ornithopter, due to the large number of electronic equipment the aircraft carries.

b. Fixed-Wing Micro Air Vehicle

The team chose a fixed-wing MAV for the final design. The team has extensive experience dealing with this type of vehicle. Prototypes of the fixed-wing micro air vehicle have a maximum dimension of 30 cm. The vehicle is fully autonomous with a loiter time of more than 30 minutes.

2) Locating the Hostage

The hostages had unique audio and visual signatures. Based on that information the team planned to use MAV's using the method of audio triangulation to locate the hostage room. A plethora of different designs were examined for this task:

a. Ornithopter

The Ornithopter was considered because it was covert, quiet, and able to land on the roof. Three Ornithopters would land at set positions, and using audio triangulation, locate the hostages. The idea was quickly abandoned due to size constraints.

b. Rocket-Propelled Gliders

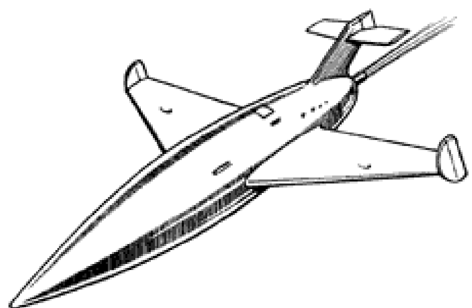


Figure 4.2. Rocket propelled glider[2]

This option proved to be very enticing. As shown in ***Figure 4.2***, a rocket propelled glider was a cheap option that could be be built easily. Unfortunately, variables such as positioning, reliability, safety of electronic equipment, and prior experiences prevented this option from being looked into more. Another problem was that in the event that the gliders were not correctly placed for audio triangulation, there would be no way for the gliders to reposition themselves.

c. Fixed Wing MAV (payloads dropping)

Another option was a fixed wing reconnaissance MAV able to drop a payload that contained the sensors and electronic equipment required for audio triangulation. Once again the idea was dismissed as the MAV was too heavy to fly with the weight of the payload and there was no backup plan in the event that the payload was dropped at the wrong location.

d. Tail Sitter Vertical Take-Off and Landing (VTOL) Micro Air Vehicle

Figure 4.3. Mini Vertigo(VTOL MAV)

The team settled on a tail-sitter VTOL MAV. The vehicle is tele-operated and capable of hovering for up 10 minutes. The advantage of using the VTOL MAV was the vehicles could be repositioned for audio triangulation. For example, if the signal was not clear in one position, the team could easily reposition the vehicles. Another advantage was the ability to "perch and stare", allowing the aircraft to perform both surveillance and hostage rescue. Once the location was triangulated, the location of the hostages would be confirmed.

3) Landmine Detection and Disarming

Landmines had to be detected and disarmed to open up a path for the commandos. Vehicles were specifically dedicated to locating the mines using chemical sensors. The vehicles researched were:

a. Ornithopter

The Ornithopter was a good option as it was slow, covert and quiet. However, as per the reasons described earlier, the idea was scrapped.

b. Rocket Propelled Glider

The idea of using multiple rocket propelled gliders was considered. Upon landing, the rockets would send information in regards to the concentration of explosives (TNT) in the air in its vicinity. Visualization of the approximate locations of the landmines would be obtained, after which EOD vehicles would disarm the mines. This would require an extensive number of gliders, which includes the same number of electronic equipment required for landmine detection. The team had limited experience in this area, and reliability was a concern, so the idea was abandonment.

c. Unmanned Ground Vehicles

The use of unmanned ground vehicles was another option explored. It could be used for long periods of time and was reliable. However the team had little experience in this field, the terrain of the mission area was unknown and may not have been conducive for ground vehicles. These factors led to the team to a different direction.

d. Tail Sitter Vertical Take-Off and Landing (VTOL) MAV

The team decided to use the VTOL MAV. The MAV was already used for audio triangulation, making the aircraft a multi-role platform. Also, the vehicle would be able to fly complex flight patterns that would enable the team to determine the position of the mines in a timely manner. Cost of building one vehicle would be diminished as at least 5 vehicles needed to be built and build time would decrease due to mass production. Different methods of mine detection will be discussed later in the paper.

Timing was an essential part of mission success. The vehicles have a limited battery life; the window of opportunity for the mission was approximately 40 minutes. As such, it was important that all phases of the mission were performed as efficiently as possible. A total of four team members, each with a specific task, would be on site to carry out the mission. There would be two ground stations located approximately 1km away from the bank. Each station would have an operator and a pilot to control multiple aircraft. ***Figure 4.4*** details the mission area.

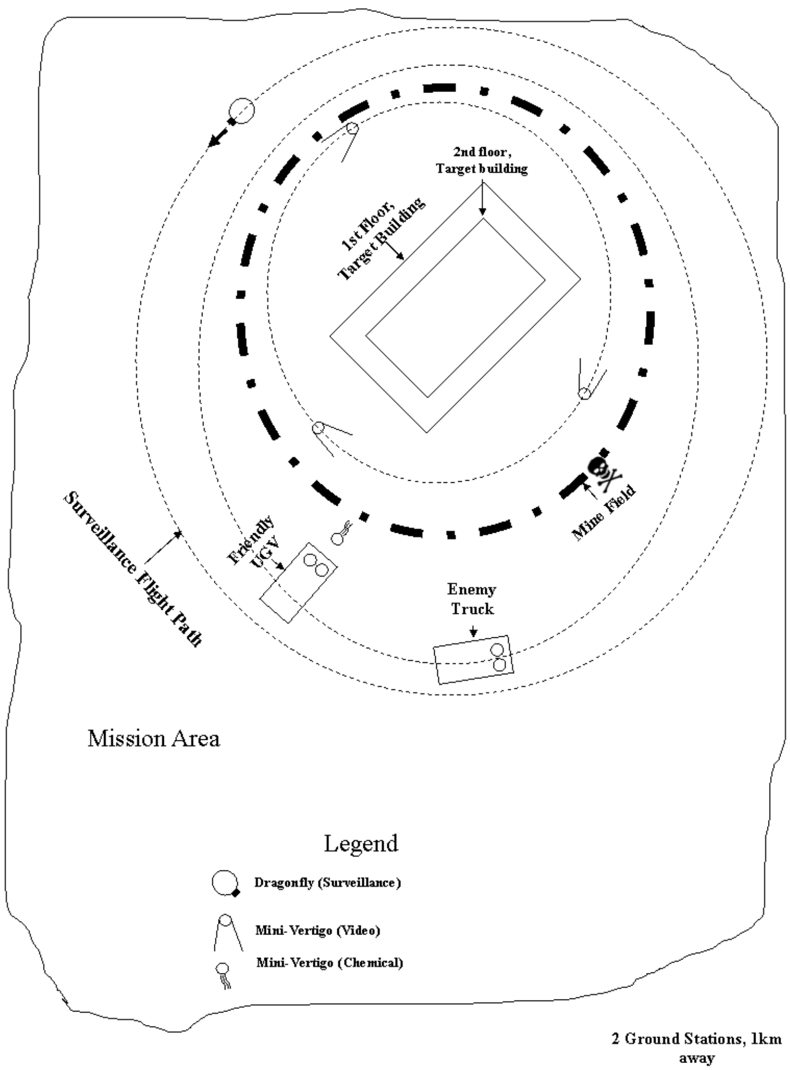


Figure 4.4. Diagram of mission execution

Three phases were required to complete the mission:

Phase I: Detect and disarm anti-personnel mines
- Chemical sensing and visual capabilities used to locate landmines on path from commando ingress point to bank perimeter
- Explosive Ordinance Disposal (EOD) vehicle disables landmines

Phase II: Survey the perimeter of the bank
- Dragonfly monitors the position of the armed vehicle
- Dragonfly helps the commandos determine the optimum ingress point by tracking the path of the armed vehicle
- Dragonfly serves as the “eyes” of the team, giving real-time updates to assist the team and commandos throughout the mission

Phase III: Determine location of hostages inside of the bank

- Mini-Vertigos locate the hostages visually
- Commandos directed through ingress path to hostage location

V. Design Procedure of Surveillance Vehicle (Dragonfly)

In this section, the design procedure for the surveillance vehicle is examined. The goal was to design a Surveillance MAV capable of loitering autonomously above a target area and relaying video of enemy vehicle movements back to a ground station. Dragonfly has a 30cm (12 inches) and a flight endurance of 25 minutes.

A. Airframe

i. Previous Designs

Dragonfly's configuration is a reflexed wing coupled with a vertical stabilizer, derived from a history of past designs, as shown in ***Figure 5.1***. A rudder and elevator are utilized as control surfaces on Dragonfly. Early wings originated from the trapezoidal wing planform in ***Figure 5.2*** and transitioned into the Zimmerman planform (***Figure 5.3***). The trapezoidal wing wasused in the past due to ease of construction, however, it provided an uneven load distribution. After extensive research, it was found that the Zimmerman planform improved the uneven loading characteristic of the trapezoidal planform.

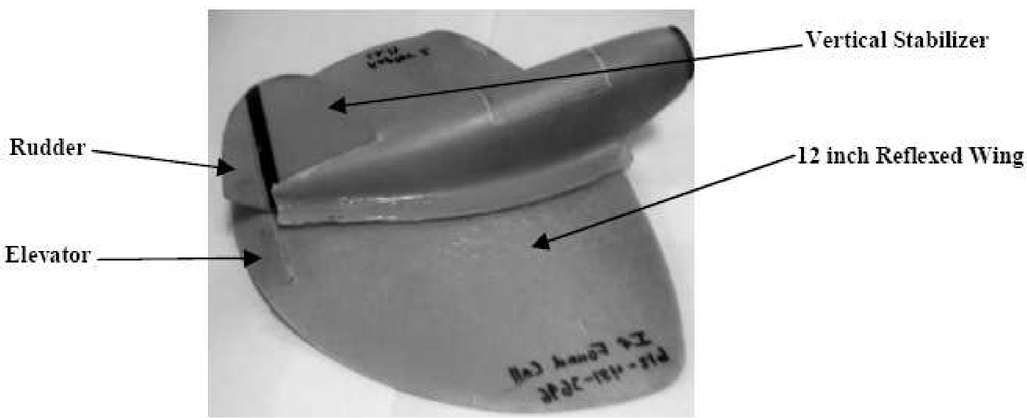


Figure 5.1. MAV wing, fuselage and vertical stabilizer

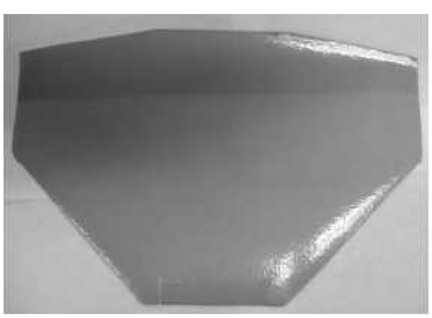


Figure 5.2. Trapezoidal Wing Planform

Figure 5.3. Zimmerman Wing Planform

ii. Current Design

With an increased need for more onboard electronic systems, a thick airfoil was developed to allow for space within the wing for additional components. As a result of this thickness, the wing's leading and trailing edges along with the integration of control surfaces were closely examined in a wind tunnel and optimized through an iterative process. The airfoil was a combination of two S5010-TOP24C-REF profiles overlapping each other, the upper surface has a 5% camber, while the lower surface only has a 3% camber. The distance between the two profiles was determined at the 0.24 chord line as $(t/c)_{max}$ and was found by acquiring the dimension of the largest component to be stored within the wing. Finally, a maximum thickness of $(t/c)_{max}$=8% was determined, which results in an absolute value of t_{max}=16.56mm at the root chord. The following picture illustrates the output of the excel spreadsheet developed to design the wing.

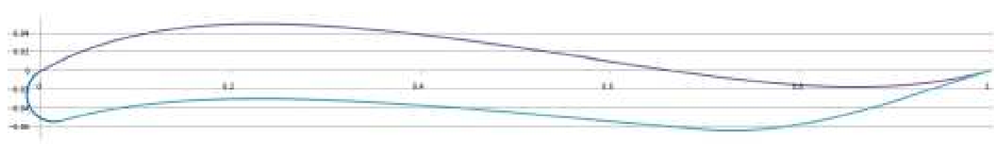


***Figure 5.4: Airfoil designed by geometrical approach*:**
$(t/c)_{max}$ = 8% at $(x/c)_{t,max}$ = .24 and $(t/c)_{max,inv}$ = 5.8% at $(t/c)_{t,max,inv}$ = .7

The maximum inversive thickness of the reflex $(t/c)_{max,inv}$=5.8% and its position in direction of the wing chord $(x/c)_{t,max,inv}$=.7 was a direct result of the postulation for the profile's thickness at the hinge point of the elevons, which may not be higher than 9 mm, and determined by the profiles used and boundary conditions chosen as described below. If the profile's thickness was chosen to be higher at this point (i.e. the point $(x/c)_{t,max,inv}$ moved closer to the trailing edge) the resulting turbulences at the lower side of the profile when deflecting the rudder to the upside would have demanded for coverage of the gap.

B. Construction Process

The Surveillance Vehicle (Dragonfly) was designed to have a composite sandwich structure consisting of Kevlar and a foam core (***Figure 5.5***). SolidWorks™ was used to design the wing mold as shown in ***Figure 5.6.***

Figure 5.5. Dragonfly foam and Kevlaron leading edge

Figure 5.6. Dragonfly mold

The wing was made out of three different sections cut out individually using a hot wire foam cutter (***Figures 5.7-5.8***). The top half of the **negative** foam was mounted and laminated with thick plastic to create half a mold. The **positive** foam was laminated with Kevlar and Epoxy and placed in the mold such that the 5° dihedral was sloping downward.

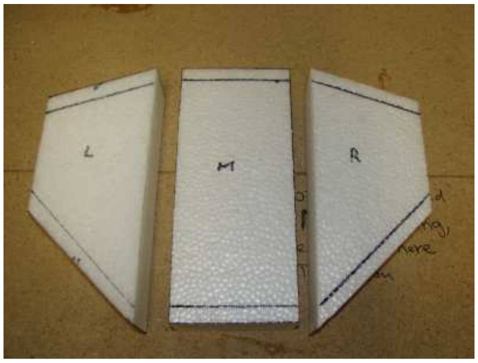


Figure 5.7. Foam pre-hot wire

Figure 5.8. Foam post-hot wire

The mold and composite structure were placed into a vacuum bag, directly under a heat lamp to allow for fast curing, for twenty-four hours. After this time, the wing was taken out (***Figure 5.9***) and cut to its final shape (***Figure 5.10***).

Figure 5.9. Un-cut wing

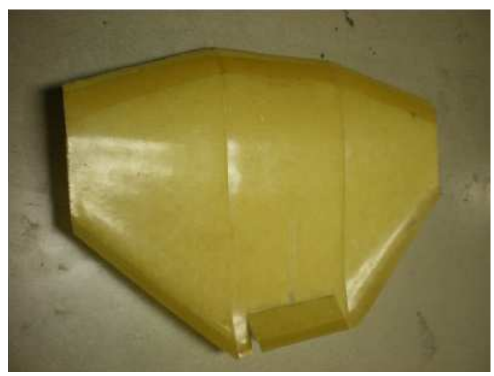


Figure 5.10. Final wing

When designing the fuselage the team decided to reshape the previously rectangular design (***Figure 5.11.***). A sleeker, annular mold (***Figure 5.12***) was created in order to improve the aerodynamics of the fuselage and to decrease the unused volume. Finally, a canopy was added to the fuselage on the upper surface of the leading edge to counter aerodynamic effects coming from the wake of the propeller (***Figure 5.13***). The nose down thrust angle of 10° was left unchanged to allow for straight and level flight.

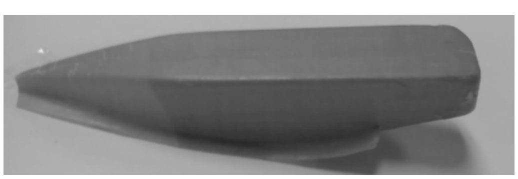


Figure 5.11. Rectangular Fuselage

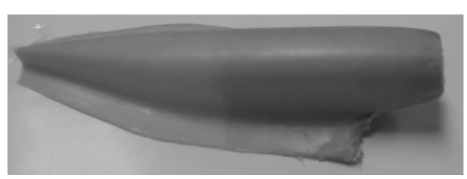


Figure 5.12. Rounded Fuselage

Figure 5.13. Rounded Fuselage mold with canopy

The design of the vertical stabilizer made use of the same composite sandwich structure used for the fuselage and wing. Since the vehicle was not equipped with landing gear, additional carbon fiber strips were added to provide sufficient rigidity to the vertical stabilizer during landings.

C. 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 5.1*** and ***Figure 5.14***.

Table 5.1. Power System Description

Propulsion System	**Description**	**Mass (g)**
Motor	Billet Bullet "Hot Wind" Single Stator brushless motor	23.0
Propeller	4.75 x 4.75 Speed 400 Electric	3.2
Speed Controller	Phoenix-10	7.7
3-Cell Lithium-Polymer Battery	Thunder Power 900 mAh	60.0
Total		**93.9**

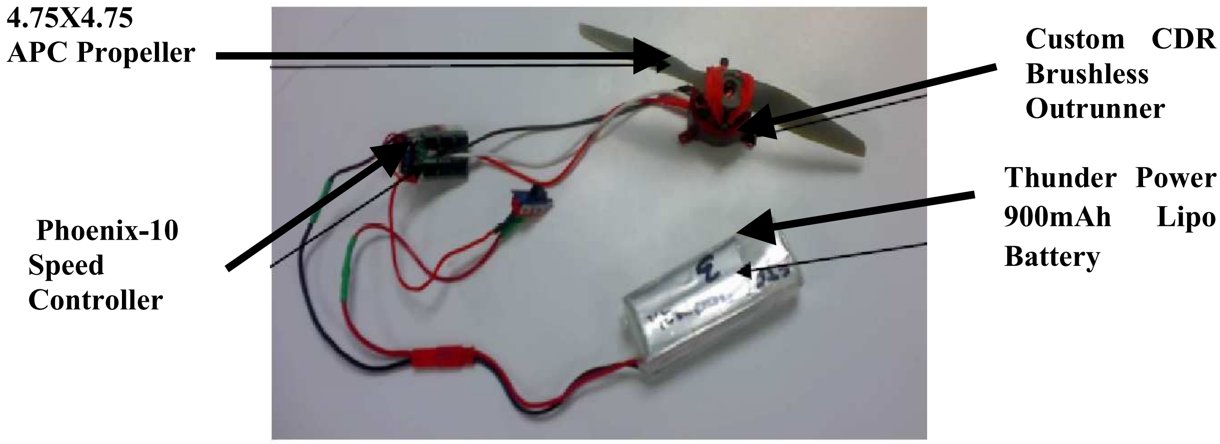


Figure 5.14. Propulsion System Setup

The Billet Bullet "Hot Wind" Single Stator brushless motor was made by CustomCDR, able to run off a maximum current of 10A and provides a pitch speed of 50-70mph. The motor allows Dragonfly to be equipped with a 10 amp Phoenix-10 speed controller. The Phoenix-10, made by Castle Creations, was desirable because it provides the user with the ability of programming a multitude of parameters tailor-made for a specific power system. Examples of such parameters include the ability to program the cut-off voltage and controlling rotational direction of motor. Initially, Dragonfly was designed to fly with a 400mAh 3 cell Lithium Polymer battery; however, a 700mAh lithium polymer battery allows for a decrease of weight and maximizes flight time (25 minutes). The ETEC battery brand was chosen mainly for its slender shape, allowing it to fit inside the Dragonfly's fuselage.

D. Components

During the MAV06 Competition in Florida, the team realized that the camera used was not sufficient for identifying targets while flying at high altitudes. This severely reduced the teams' chances to obtain satisfactory target identification capabilities during the MAV08 competition. The team chose the KX141 Color CCD camera which has higher resolution and a smaller optical angle. Although the camera was larger, it provided a clearer picture from high altitudes. To send the video to the ground station, a 200mW video transmitter was installed into Dragonfly. This was chosen due to its ability to transmit clear video signals at a maximum range of 1500m. Two 2.5g Blue Arrow servos were used for the rudder and elevator of Dragonfly. The servos were chosen because of their light weight and sufficient torque. For the competition, the Paparazzi autopilot system was used. The Paparazzi system includes the Tiny version autopilot board, GPS element, and an IR Sensor. The receiever 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 was the Aerocomm modem which sends signals at 900Mhz. A Solidworks drawing of the Dragonfly and all of its components is in ***Figure 5.15***; all the components are listed in ***Table 5.2***.

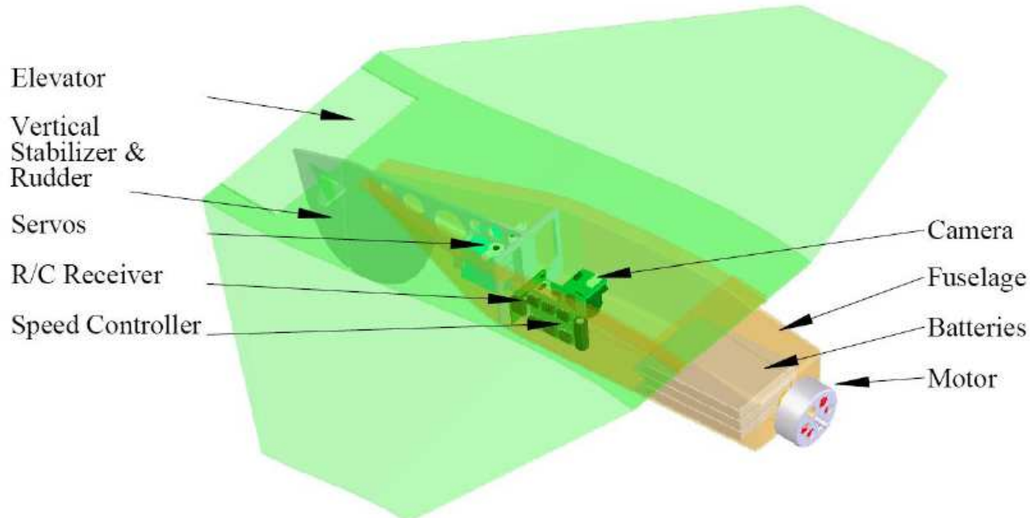


Figure 5.15. Dragonfly With Components

Table 5.2: Dragonfly Components

Components	**Description**	**Mass (g)**
KX141 Uncased Color CCD camera	480 Line Resolution, 2 lux light sensitivity	13
2 Servos	Blue Arrow BA-TS2.5	6
RC Receiver	PENTA 5 MZK	2.8
Video Transmitter	200mW transmitter	7.6
Autopilot	Paparazzi Tiny	24
IR Sensor	Infrared sensors board	5.2
Modem	Aerocomm 900Mhz Transiever	3.8
Total		**68.7**

E. Budget

Table 5.3 Cost of Dragonfly

Component Description	Quantity	Vendor	Cost
MPJet AC 22/4-60D OUTRUNNER Brushless Motor	2	Hobby Lobby	$95.80
Castle Creations Phoenix-25 Brushless ESC	1	Tower Hobbies	$67.99
Blue Arrow 2.5 gm Servo	3	BSD Micro RC	$57.00
Thunder Power TP910-3S Li-Poly Battery	1	RC Lipos	$46.95
Castle Creations Berg Microstamp 4L 4Ch Micro Rx FM	1	Tower Hobbies	$29.99
APC 7x5 Thin Electric Propeller	1	Tower Hobbies	$2.09
APC 7x5 Thin Electric Pusher Propeller	1	Tower Hobbies	$3.09
Infrared Sensor	1	FMA Direct	$69.95
2.4Ghz 200mW Transmitter and Receiver Set	1	Black Widow AV	$150.00
KX-141 High Resolution Color CCD Camera- NTSC	1	Black Widow AV	$199.00
Aerocomm 900Mhz Transiever	1	Aerocomm Inc.	$62.50
Cost per Vehicle (Not including Autopilot board)			$784.36
Cost of 2 Vehicles			$1568.72

VI. Design Procedure of Hostage and Mine Detection Vehicles (Mini-Vertigo)

In this section, the design procedure for the hostage and mine reconnaissance vehicles will be examined. The goal was to design an MAV capable of locating hostages or mines around the bank while hovering. Important considerations were given to designing suitable airframe, propulsion system, reliable components, and sufficient controllability.

A. Airframe

i. Previous Designs

Based on mission requirements, a Vertical Take-Off and Landing type Micro Air Vehicle was desired. The MAV had to be capable of hovering in a fixed, stable position . The initial airframe tested was an off-the-shelf 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 were hinged to the trailing edge of the wing and vertical fins. This design was used as an initial platform to provide a basic understanding of VTOL MAVs. Since size was an important criterion in the competition, the team moved to a smaller airframe. A flat 30cm span wing of Zimmerman planform was used. The Zimmerman planform had been successfully implemented on Dragonfly, the 12 inch MAV (***Figure 5.3***). It was mainly used in the new VTOL MAV (Mini-Vertigo) to enable transition between vertical and horizontal flight.

ii. Current Design

Mini Vertigo's configuration is a Zimmerman planform together with a vertical stabilizer as shown in (***Figures 6.1 and 6.2***). Mini Vertigo utilizes two control surfaces while still having a rudder, elevator and ailerons. The rudder is located on the tail, while the elevator and ailerons make use of the same surface and are controlled using transmitter mixing.

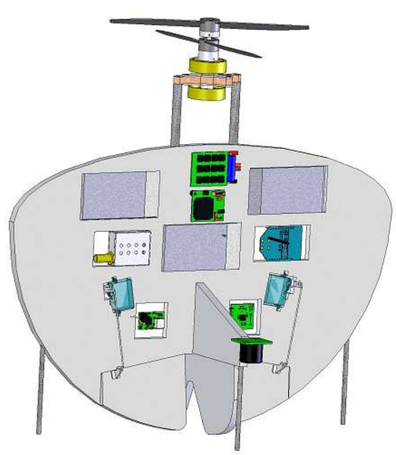


Figure 6.1. Mini-Vertigo (Front View)

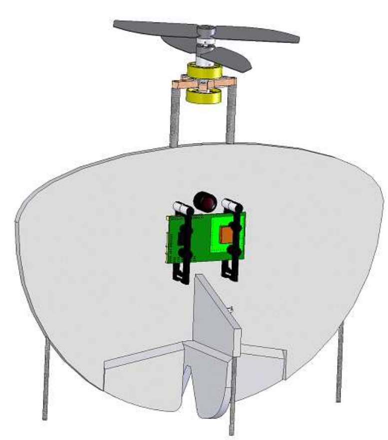


Figure 6.2. Mini-Vertigo (Back View)

The wing planform on Mini Vertigo was derived from a history of past designs that have been used by our surveillance vehicle[1]. Early wings originated with the trapezoidal planform (***Figure 6.2***) and evolved into the Zimmerman planform (***Figure 6.3***). The trapezoidal wing was initially used 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.

B. Construction

The main wing of Mini-Vertigo is made of a foam material, Depron, and is reinforced with laminated sheets of fiberglass. Attached to the wing is the vertical stabilizer, also made from the Depron-fiberglass 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. (***Figure 6.1 and 6.2***) show the constructed platform of Mini-Vertigo.

C. Propulsion System

Initially, a single motor and larger propeller was used. Flight testing with Pogo proved that hovering with such a propulsion system was detrimental. Unwanted torque effects caused Pogo to rotate uncontrollably. The team decided on using a counter-rotating propulsion system to provide stability. The 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. This configuration has a shaft running through the stator of one motor, connecting the topmost propeller to the bottom motor, and the second propeller is attached to the top motor via a larger diameter adapter. The propulsive system setup is shown in (***Figure 6.3***).

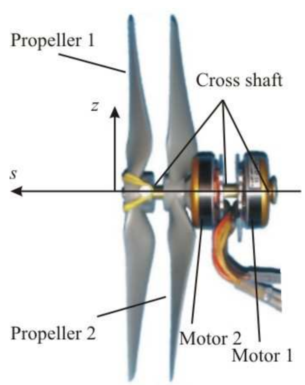


Figure 6.3. Contra-Rotating Motor system

The system proved very efficient in that it provided twice the thrust[5] and torque issues were significantly less than with a single motor and propeller.

D. 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 the specifications provided, while its endurance relies on length of time before a failure occurs. The components used on Mini-Vertigo and their weights are listed below in (***Table 6.2***).

Table 6.2. Mini-Vertigo Components

Component	**Description**	**Mass (g)**
Airframe	Carbon rods & flats (3 mm)/Foam depron (6 mm)	52.5
Dual Motor/ Contra-rotating Propellers	MP Jet AC 22/4-60 D/ APC 7x5/7X5P	61.3
3-cell Lithium-Polymer Battery	Thunder Power TP910-3S Li-Poly Battery	60
3 Micro Servos	Blue Arrow BA-TS-2.5	9
ESC	Castle Creations Phoenix-25	10
RC Receiver	PENTA 5 MZK	2.8
Video Transmitter	200mW transmitter	7.6
2 Digital Gyros	Gyro Breakout Board - Dual Axis IDG300	5.6
Modem	Aerocomm 900Mhz Transiever	3.8
Autopilot Board	Paparazzi Tiny	24.2
IR Sensor	FMA Direct Co-Pilot	5.2
CMOS Camera		4.6
On/off switch, wires	Misc.	6
Total		**252.6**

E. Budget

Table 6.3 Cost of Mini-Vertigo

Component Description	**Quantity**	**Vendor**	**Cost**
MPJet AC 22/4-60D OUTRUNNER Brushless Motor	2	Hobby Lobby	$95.80
Castle Creations Phoenix-25 Brushless ESC	1	Tower Hobbies	$67.99
Blue Arrow 2.5 gm Servo	3	BSD Micro RC	$57.00
Gyro Breakout Board - Dual Axis IDG300	2	SparkFun Electronics	$149.90
IMU 5 Degrees of Freedom	1	SparkFun Electronics	$109.95
Ultrasonic Range Finder - Maxbotix LV-EZ4	1	SparkFun Electronics	$24.95
Thunder Power TP910-3S Li-Poly Battery	1	RC Lipos	$46.95
Castle Creations Berg Microstamp 4L 4Ch Micro Rx FM	1	Tower Hobbies	$29.99
APC 7x5 Thin Electric Propeller	1	Tower Hobbies	$2.09
APC 7x5 Thin Electric Pusher Propeller	1	Tower Hobbies	$3.09
2.4Ghz 200mW Transmitter and Receiver Set	1	Black Widow AV	$150.00
KX-141 High Resolution Color CCD Camera- NTSC	1	Black Widow AV	$199.00
Aerocomm 900Mhz Transiever	1	Aerocomm Inc.	$62.50
Cost per Vehicle (Not including Autopilot board)			$999.21

VII. Systems Integration

A. Flight Plan

The aircraft has a flight plan for fully autonomous mode. The flight plan was based on waypoint navigation. Currently autopilot does not track the trajectory, but guides the airplane from one waypoint to another according to the flight plan. The flight plan consisted of one or several blocks, where each of the blocks specified several commands for the autopilot. The blocks were executed in a sequential order. In case of emergency, an operator of the ground station would specify next block to execute.

B. Autopilot

i. Dragonfly

All MAV's used by the University of Arizona MAV Team are equipped with the Paparazzi Autopilot System. The Paparazzi autopilot system is an open source autopilot system that was initially developed and used by ENAC in France. All planes were equipped with the Paparazzi Tiny 0.99 board. The autopilot has three modes – fully autonomous mode, augmented stability mode, and fully manual mode. The modes can be selected by an operator from the ground station. When autopilot was in the stability augmentation mode, an operator of the ground station controls desired thrust, roll and pitch of the airplane. Actual commands for servos are computed by the autopilot control closed loop code. Pitch and roll gains are adjusted in this mode and are tailor made for each aircraft. Pitch and roll angles of the airplane are limited to safe values of the calibrated airplane and are hard-coded into the current airframe configuration[5].

For the Dragonfly fixed wing MAV, the autopilot system was fully autonomous and relies on FMA Direct Co-Pilot IR Sensors for attitude stabilization and the U-blox GPS unit located on the Tiny board for 3-Dimensional localization. The autopilot transmits telemetry data and receives specific commands to and from the ground station with the use of a 900Mhz Aerocomm transeiver.

The IR Sensor was key to the stability of the Dragonfly MAV, as it provides the autopilot system with information concerning the attitude of the vehicle. This allows the autopilot system to navigate the aircraft accordingly.

The Aerocomm transiever allows the team to be able to monitor real-time information from the aircraft such as battery life and adjust aircraft parameters such as gains and navigation controls. It also allows the team to be able to modify flight plan waypoints without needing to reprogram the vehicle. Initially the modem used was an X-BEE Pro 2.4GHz Model. Due to the fact that the team uses a 2.4GHz video system, this caused major interference issues with the modem. Extensive tests were carried out and they showed that although the modem and video system were placed at different channels, the interference caused by the video system could not be removed. The team therefore decided to try using a modem that was in the 900MHz frequency range. What makes this transceiver unique is that it utilizes AeroComm's "masterless" protocol, enabling communication with any other in-range transceiver for true peer-to-peer operation. This 1 x 1inch transeiver has a range up to 1 mile while still maintaining the weight and space constraints of the aircraft.

ii. Mini-Vertigo

Mini Vertigo uses the same paparazzi system that the Dragonfly uses. However, due to the fact that Mini-Vertigo is a VTOL MAV that would be flying at a high angle of attack, the use of digital gyros are implemented. The gyros serve the purpose of stabilizing the aircraft. What this does is that it measures the angular velocity changes with respect to its axes. This data is provided to the autopilot, which translates to a stabilizing reactionary movement by the control surfaces of the aircraft. This together with the IR Sensor helps the autopilot system have full attitude control of the aircraft. This augmented stability system is used for Auto 1, where the pilot will be tele-operating Mini-Vertigo during certain parts of the mission. For the autonomous phase of the mission, Mini-Vertigo will make use of the GPS unit for navigation

C. Sensors

i. Video Detection

The goal of the audio/video system was to successfully locate the hostages inside the bank structure. A video signal transmits the MAVs video camera (***Figure 7.1***), allowing active visual scanning. Due to limited knowledge of hostage location, it was imperative to have enough time to search for them, which was why three MAVs had to be used for this part of the mission.

After extensive testing, the team chose a Black Widow 200mW 2.4 GHz transmitter due to its built in microphone, and core voltage of 5V, allowing for efficient power consumption. At 12.5g, the device was light enough to be used on Mini-Vertigo (***Figure 7.2***).

Having three separate cameras and microphones available on the aircraft made the mission easier to accomplish. Since each transmitter was equipped with a microphone, the ground station had to have speakers. Being able to hear any crucial sounds was helpful in locating the hostages.

Figure 7.1. Camera

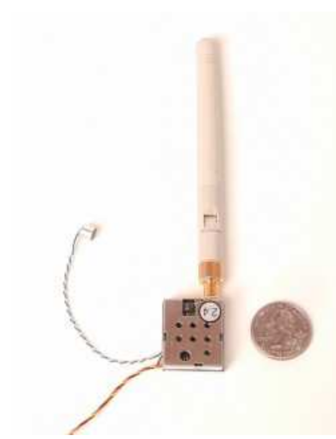


Figure 7.2. Video Transmitter (w/ microphone)

After testing the video system on Mini-Vertigo, the results were satisfactory. At a height of 5m and 2.25km away, the video and audio signals were notably clear from the ground station. For the television setup, the user at the ground station was able to clearly hear voices from a distance ranging 5-15 meters away from the microphone.

Through the use of three separate microphones, the concept of audio triangulation could be implemented. Acoustic localization is the science of using sound to determine the distance and direction of an object. The objective was to utilize three Mini-Vertigos to detect a primary audio source. The use of computer software and programming was necessary to obtain three audio signals simultaneously and detect the primary location. Due to time constraints and the complexity of the technology involved, audio triangulation was a task that was not finalized for this mission.

ii. Landmine Detection

Locating and neutralizing the land mines was an integral part of the success of the mission. If the mines are overlooked, the commandos run would have to navigate through the minefield blindly. The mission would end catastrophically if the commandos were to enter the effective fatal zone of one of the landmines. Much of the research and design consideration was devoted to integrating explosive detection technology onto the MAVs.

Mini-Vertigo provided the platform to demonstrate new technology for locating landmines. Many ideas were proposed to accomplish the mission. Infrared cameras are highly reliable and enable the observer to see the land mines because the steel casing has a different infrared signature than grass or soil. The major drawback of the camera was that it was prohibitively expensive and excessively bulky. Metal detectors were researched because they were proven to work in this application. However, the size, weight, and sensitivity to heights greater than a few inches off the ground excluded the use of metal detectors on MAVs. Low frequency acoustic reflection was another possibility because the sound waves can penetrate soil very easily but reflect off of metal. The drawback was that low frequency acoustic reflection was sensitive to other local electronic signals and the interference with other electronic components on the vehicle would to be too great of a risk. Using an aerosol spray to react with the explosive compounds to get visual confirmation was another solution. After the reaction, a visual cue would signal another MAV to search using a video camera. This method was abandoned because of restrictions in the competition requirements. After much research, the best technology for the mission was chemical sensing. Chemical sensing is a highly advanced technology that takes the chemical vapors in the air and analyzes the chemical signatures. When the sensor recognizes a chemical signature similar to a preset group of known explosives, it outputs a signal telling the observer the source of chemical explosive vapor nearby

iii. Chemical Sensor

After extensive investigation the team purchased a chemical sensor from Alpha Mos, a French Company (***Figure 7.3***). The Enose model was selected due to its chemosensory board containing a 4 grid array sensor. Important specifications include a sampling rate of approximately 30Hz (with 8 averages) for each of the 4 sensory channels. The total weight of the sensor was 36.2g, but without the sensor stands the weight was reduced to 13.5g.

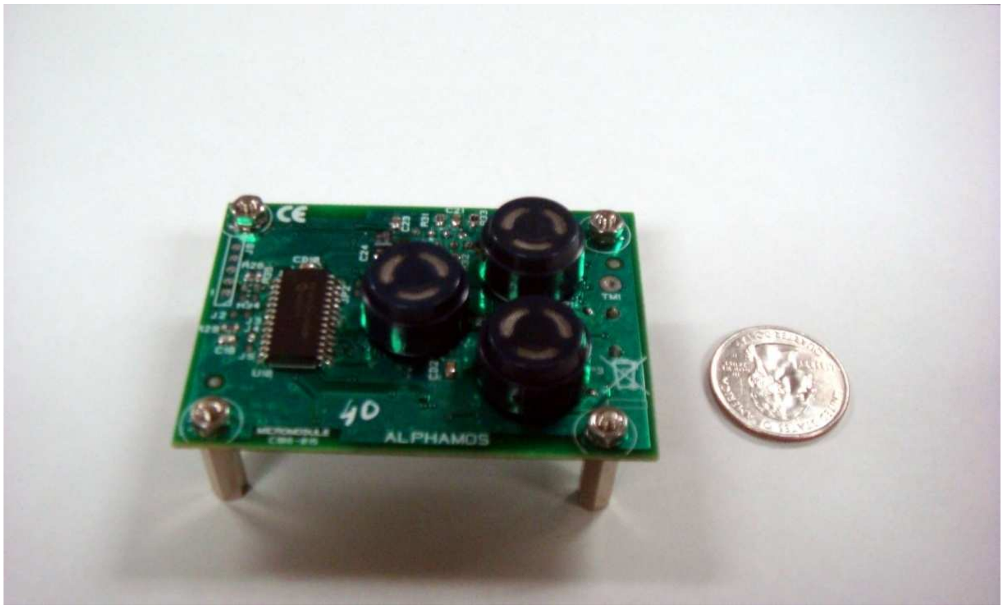


Figure 7.3. Chemical Sensor

The physical principle of the device was to ensure proper detection of an odorous compound. It was vital to have the right materials and electronics to accomplish the mission. The chemical sensor consists of a thin film metal oxide and provides a wide range of different sensitivities. The reason for this was to detect volatile organic compounds. The sensitivity can be controlled by a few particles per million (ppm) and changes the tuning for identifying compounds. The interaction between the semiconductor material of the sensor and odor molecules was important for the device to function properly.

Trinitrotoluene (TNT) is a chemical compound with the formula $C_6H_2(NO_2)_3CH_3$. This yellow-colored solid is a reagent (reactant) in chemistry, but is best known as a useful explosive material with convenient handling properties. The chemical sensor must be trained to identify this compound. The sensitivity is a property of the sensor and the chemical characteristics of TNT cause the sensor to be adjusted down to a few parts per billion (ppb) to properly recognize the correct scent.

In order for the sensor to read data and identify a compound, its resistance is converted into voltage and through the device, it is digitized. The FCG or fractional change in conductance was used in conjunction with the chemical concentration, as it is proportional to it. The chemical concentration is what distinguishes TNT from other compounds. Correctly tuning the chemical sensor's sensitivity was vital to locating and identifying the desired odor or compound. This was done to be able to make the nose of the sensor have the capability to successfully sniff and detect TNT.

The integration of the chemical sensor with the Mini-Vertigo aircraft was crucial. Since the vehicles are small and lightweight, any big disturbance, such as a force may alter performance. Mini-Vertigo had a total weight of 244.5g, so the chemical sensor was an ideal fit structurally. The device was small in relation to the MAV, as shown by the dimension above. ***Figure 7.4*** shows a picture of the chemical sensor next to a mini vertigo.

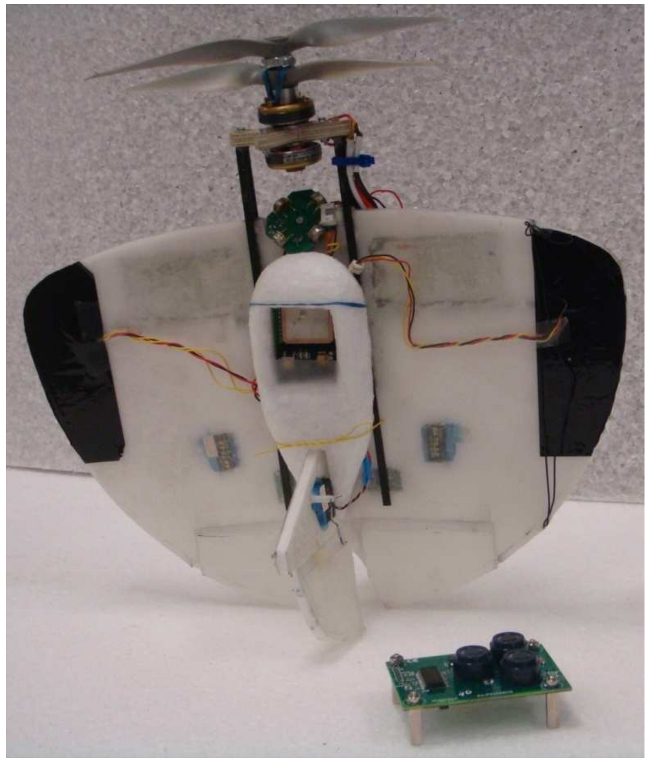


Figure 7.4. Chemical Sensor beside Mini-Vertigo

The other important part of sensor integration was to find a way to adapt it to the current setup of the vehicle. The sensor was hard wired to the autopilot board, which is the mainframe of all of the electronics on board the MAV. Power is supplied by the autopilot, which is directly connected to the batteries on Mini-Vertigo. The autopilot transmits the data down to the ground station via a modem and a corresponding laptop.

To test the sensor, XScent, a product of GMA Industries, Inc, was used. XScent is an inert pseudo scent used to mimic the chemical signature of TNT. Using XScent was a safe way to test the sensor while simulating the behavior of a real chemical reaction. Testing enabled the development of software analysis to equate the sensor outputs with relative amounts of explosive chemical vapors contained in the air. The chemical sensor and its corresponding software interpolate the data due to the response strength of the odors. This is based on distance, as the signal strength becomes stronger upon approaching the target odor. In order to program the sensor for the right odor of TNT, the sensitivity had to match the compound.

A good strategy was needed to efficiently scan the minefield. The theory was that while mini-vertigo flies in a pass perpendicular to the direction of the wind, it would encounter plumes of XScent. The sensor would register the strength of the signal due to the amount of the explosive chemical vapor. The Mini-Vertigo would turn upwind for a short period, afterwards turning perpendicular to the wind to double back on its path. This was how the Mini-Vertigo would scan the field for mines. As explained earlier, the signal wass less when the source was farther away and grew in strength as Mini-Vertigo flew closer to each mine. ***Figure 7.5*** shows an example of the how the mine sweeping would be accomplished.

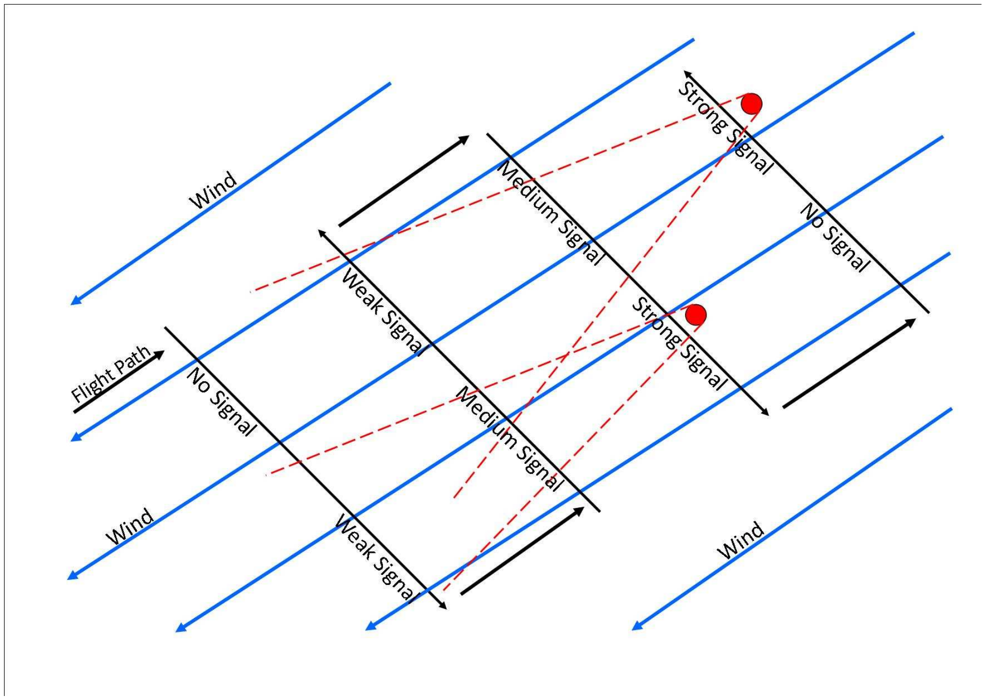


Figure 7.5. Anticipated Flight Pattern of MAV for landmine detection

D. Ground Station

A proper setup was crucial to mission success. The following components were utilized to get everything functioning properly:

- Antennas
- Audio/Video Receiver
- Filter
- Amplifier
- Small fan
- Audio/Video Cables
- Power Supply
- Tripod
- Modem

Since the list consists of many objects, there had to be a way to set up the ground station very quickly (***Figure 7.6***). This was crucial as mission time constraints required utmost efficiency. It was convenient to manually connect each component every time; however, a better method was developed.

Figure 7.6. Ground Station

The components that were the most burdensome to connect were the amplifier, filter and receiver all to a power supply and a television. An aluminum box (6"x4"x4") served the purpose of internally connecting many of the problem components, such as the amplifier, audio/video receiver and filter. Carefully placing these items and adhering them to the box made setup much faster. The heat radiating from the components inside the box dictated the need for a small 12V fan to be added.

All of the power wires of these components were soldered together and to a male JST connector, connecting to the receiving female JST connector wired directly to a power adapter. All of the components operated at 12 volts except for the amplifier which has a voltage regulator, simplifying the power connection.

The box was able to reduce the connection process to two cables. The first was the power cable with the JST connector while the other was the audio/video cable that connects to a television. This simplified setup made the system ready to go as soon as the equipment was brought out.

The amplifier was connected to a 19dB gain antenna to allow for maximum signal strength. The antenna was placed on a tripod via the use of an elbow bracket. The bracket allows the ground station box to be mounted in close proximity to the antenna, eliminating the need for a long cable. Having all of these components set up on a tripod as one structure, enabled the ability to pivot the setup upward or downward and essentially put it in any orientation. An extra antenna and modem were added to the ground station so a laptop can be connected to the setup and transfer data to and from the aircraft.

The modem was attached to Velcro at the top of the metal box. Its corresponding antenna was much smaller than the one used for the video with only an 8dB gain capability. Because of its size, it was mounted above the larger antenna directly connected to it with nuts and bolts. The ground station was capable of providing successful signal at almost 2km away. This was more than adequate for the competition and prepared the team for any unknown obstructions during the mission.

E. Safety Procedures

Due to the complex nature of the mission, several safety procedures were developed to keep singular failures from having catastrophic effects. One procedure was collision avoidance between each vehicle by establishing operational altitudes specific to each phase of the mission. Dragonfly was to launch from the ground station and immediately climb to an altitude of 55m AGL. The aircraft could not fly below its minimum altitude of 45m in order to avoid collision with the Mini-Vertigos operating below that altitude. Dragonfly would not fly above 65m or team members at the ground station would lose sight of the target vehicle and the aircraft below.

Mini-Vertigos equipped with cameras launched from the ground station and climb to an altitude of 40m. To avoid detection from patrolling terrorists, a minimum altitude of 30m had to be maintained in horizontal flight. After ingress to the target area, the vehicles were to transition to vertical flight and descend to an altitude of 3m. They were to circle the bank, searching for any visual evidence of the hostages. After visual confirmation was achieved, the Mini-Vertigos were to land safely on the ground.

The Mini-Vertigo equipped with a chemical sensor was to launch from the ground station and climb to an altitude of 15m. It will cruise in horizontal flight at this altitude until it was 125m away from the bank. It will transition to vertical flight and descend to an altitude of 2m, where it will begin searching for land mines. Due to the sensitivity of the chemical sensors, the maximum allowable altitude was 3m. The minimum altitude was 1m, because recovery from failure below altitudes of 1m would be nearly impossible.

Another set of safety procedures were developed in the event of component failure. If one of the vehicles lost signal with the ground station for more than 5 sec or traveled out of the fly zone, the vehicle would switch to “home mode” or “reversion mode,” and would navigate to a pre-assigned location, the “home waypoint”, and circle at a constant predetermined altitude until an explicit command for normal flight was received. If the autopilot failed, a special indicator of downlink signal loss would appear on the screen of the ground station. A tele-operator would be on standby to manually operate the vehicle in case of failure. The autonomous mode of operation can be overridden, and manual control of the airplane could be imposed with the RC unit. If the GPS unit failed, the airplane would land immediately, keeping the same heading and a safe landing attitude. While landing, the aircraft does not accept heading deviations. In the case of battery failure, the airplane would reduce thrust to zero and glides to the ground. In the event of total signal lost the aircraft would cut power and make a controlled crash landing in the safest location available, and would exhibit behavior typical of total signal loss. As another safety procedure, Dragonfly and the Mini-Vertigos were to land immediately if the wind surpassed 11 m/s and 5 m/s, respectively.

VIII. Final Design

The final design was a culmination of all the processes and concepts described in earlier sections. Each system relied on the other to complete each mission phase efficiently. Chemical sensing sets the pace by clearing a path for the commandos and vehicles. Dragonfly would allow the rescue team to evade enemy forces attempting to inhibit their progress. The Mini-vertigos and their cameras act as the eyes of the team, keeping the commandos out of danger by circling around the bank to locate the hostages.

The ground station acts as the center of all communication (***Figure 8.1***). All vehicles were directly linked to the ground station, and allowing the operators to quickly analyze the situation and relay the info to the commandos. Aircraft performance benefitted from the ground station operators to adjust to the situation in real time. If dragonfly were to spot the enemy truck moving toward the mini-vertigos, the tele-operator could adjust accordingly and hide the vehicles from enemy view. Similarly, the commandos could be instructed to evade the enemy by hiding behind designated spots in the mission area.

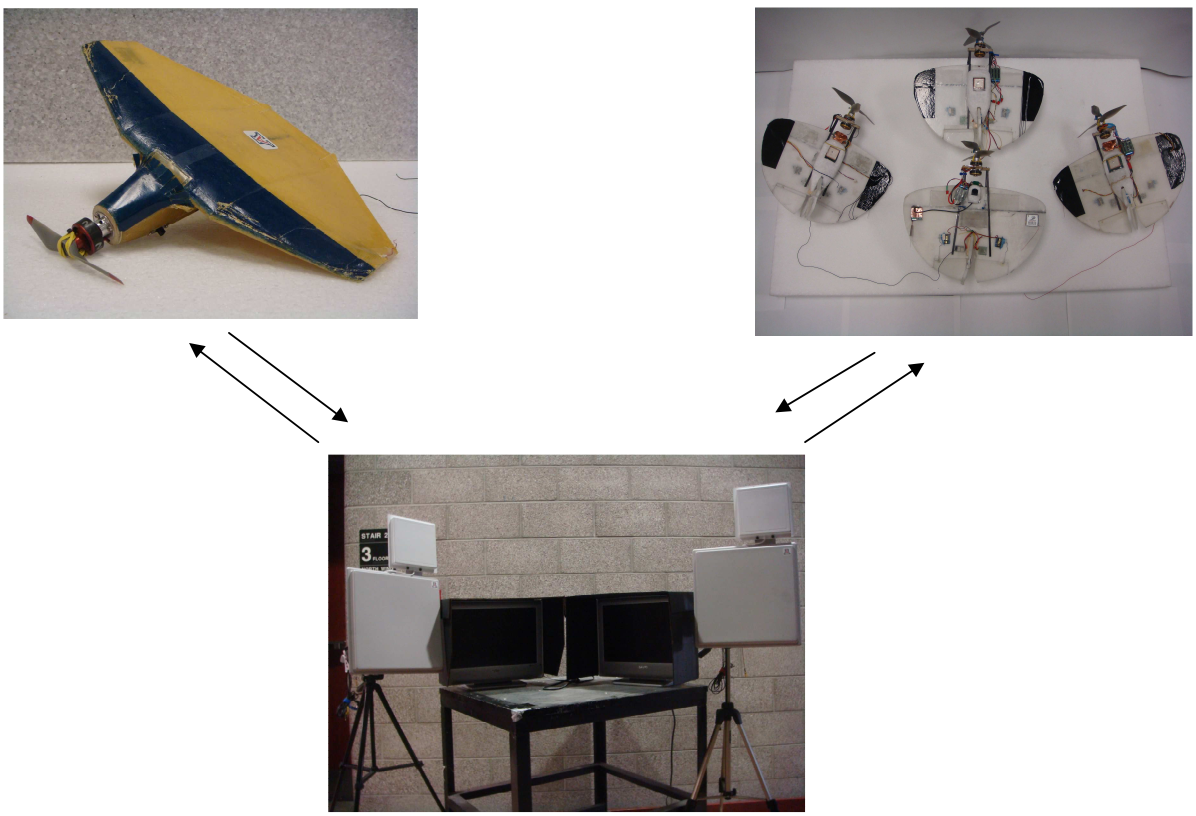


Figure 8.1. MAV System

IX. Flight Testing

i. Hovering Tests

The plane was flown in stabilization mode using gyroscopes. During flight, the plane was trimmed to hover predictably with little input from the pilot, otherwise known as flying "hands-off." Once the trimmed positions of the control surfaces are recorded, the radio transmitter trims were set to zero. The pushrods were bent to move the control surfaces to the correct trim position.

ii. Stabilization Mode

After the hovering tests, the plane flew in stabilization mode equipped with an infrared (IR) sensor to maintain the desired attitude. The pilot used the radio transmitter sticks to set the required bank angles while the plane maintained these angles in flight. The angle of attack of these flights was set to approximately 45 degrees. Tests were conducted in the field where the pilot operated the vehicle visually, flying circle and figure-8 patterns while the gyroscope gains were adjusted from the ground station.

iii. Fully Autonomous Mode

Once stabilization mode tests were complete, the fully autonomous phase began, using a GPS device and the ground station to locate waypoints within the field. A flight plan was generated and programmed into the autopilot with this data. The vehicle was launched first in stabilization mode. At a desired location in flight the pilot switched over to fully autonomous mode and the plane flew from one way-point to another according to the programmed flight plan. The procedure was repeated while navigation gains were adjusted from the ground station until the system worked reliably.

iv. Camera Mode

A video camera and transmitter were mounted onboard the vehicle. The camera was angled such that it made an angle of zero degrees with the horizontal while the vehicle was at a 45-degree angle of attack. The ground station was equipped with a video monitor and receiving antenna. The vehicle was first flown visually in stabilization mode within a 5m altitude while the camera was adjusted for optimum angle. Once the camera angle was set, the pilot flew the vehicle via display from the onboard camera. The process was until a suitable angle was attained.

X. Preliminary Overview

A Mini-Vertigo equipped with a chemical sensor and a forward facing camera would enter the mission area from the ground station. The chemical sensing aircraft would sweep the ingress path for a period of ten minutes, scanning for any mines that may compromise the safety of the rescue team and the success of the mission. The on-board camera would link to the ground station, displaying the terrain in real time to allow for the pilot to tele-operate the vehicle. The vehicle flies in stability augmentation mode, where the aircraft would be stabilized through the use of IR sensors and gyros. Once a mine was detected, operators at the ground station would record the GPS coordinates of the mine. After all mines had been located on the ingress path, the ground station operator sends the EOD vehicle to "disarm" the mines.

Flying autonomously at an altitude of 40m and a speed of 15m/s, Dragonfly would reach the bank and begin to survey the perimeter. Dragonfly reduces its speed to 10m/s and loiters for 20 minutes. Real time video would be transmitted back to ground station operators, allowing them to adjust the flight plan of the Mini-Vertigos and warn commandos of any incoming threats. With the use of the surveillance feed the hostage rescue could be timed and executed safely.

Operating under the watch of Dragonfly, three Mini-Vertigos would ingress autonomously to the bank perimeter from ground station at a speed of 8m/s and an altitude of 15m. Upon successful ingress to the perimeter, each aircraft would switch to semi-autonomous mode, whereby the tele-operator would begin to locate the hostages with the on-board cameras. After finding the hostages, the final ingress path would be determined, allowing the commandos to extract the hostages.

Avoiding detection was a critical part of mission success. Dragonfly would inform the ground station of enemy positions to prevent the Mini-Vertigos from being compromised. Once the location of the threat was identified, the Mini-Vertigos would be given the go ahead to enter the mission area. Dragonfly's endurance time of 25 minutes mandates a swift search and rescue of the hostages, after which, the ability to monitor enemy movement would be significantly hindered.

Both the Dragonfly and Mini-Vertigo were designed to accomplish their mission phase requirements. As outlined in this paper, the designs of the MAVs were tailor-made to complete mission requirements as specified by the competition committee. The flight testing phase for both MAVs brought new understanding of how MAV systems work. Parameters such as PID gains in Dragonfly's autopilot system, to solving interference issues associated Mini-Vertigo's autopilot system were finalized.

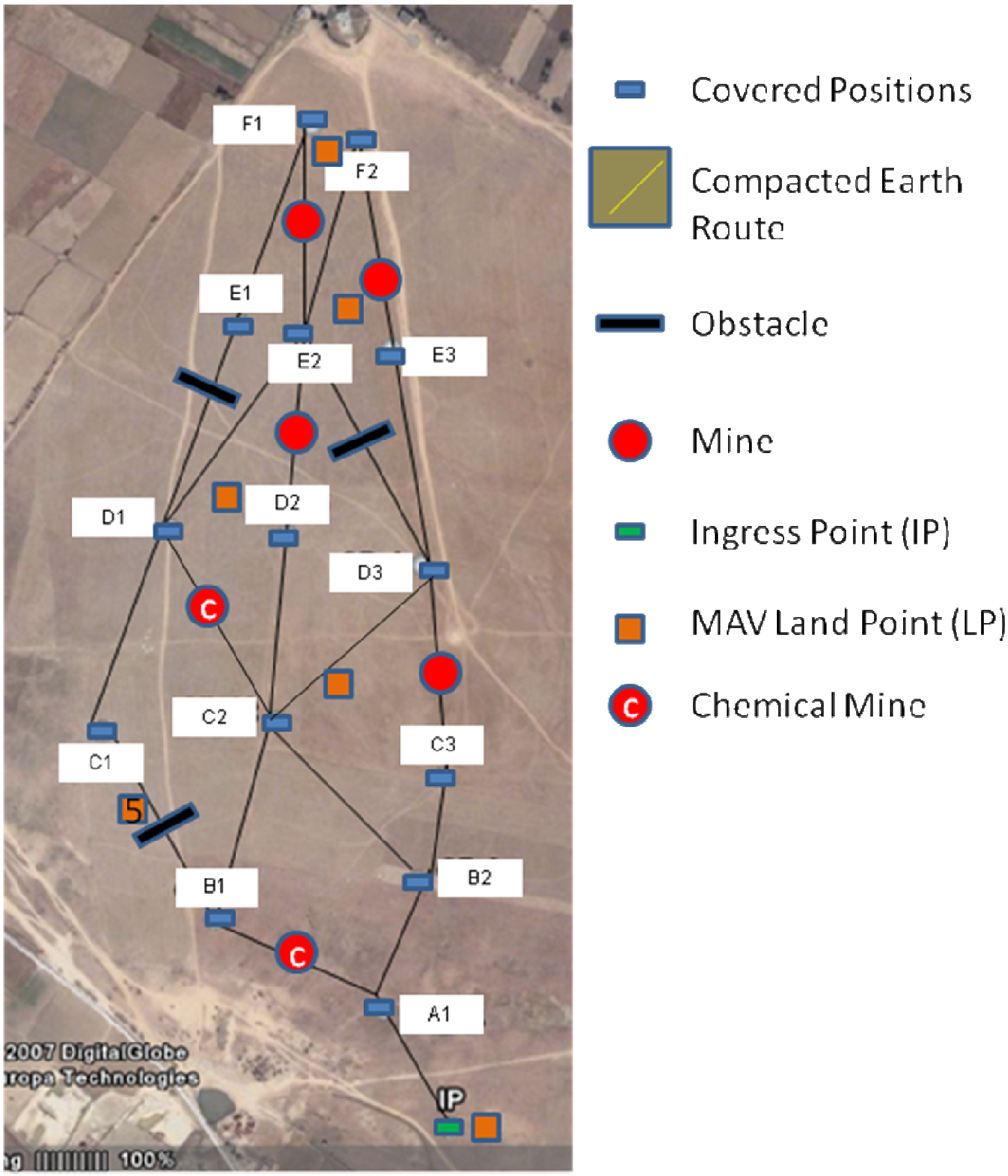
There are certain aspects of the mission that were explored, and with enough time could be completed. While the team obtained a chemical sensor that can easily fit on Mini-Vertigo, time has not permitted sufficient testing to effectively place it on Mini-Vertigo as of yet. Audio triangulation has also been explored, however, abandoned the research to devote more time to higher yield developments.

Overall, many breakthroughs were made for this competition. The stabilization system and altitude control systems on the autopilot board allow for more user friendly piloting. Integrating a 900MHz modem solved the interference issues and enabled a high quality audio/video system.

XI. Mission Plan and Execution

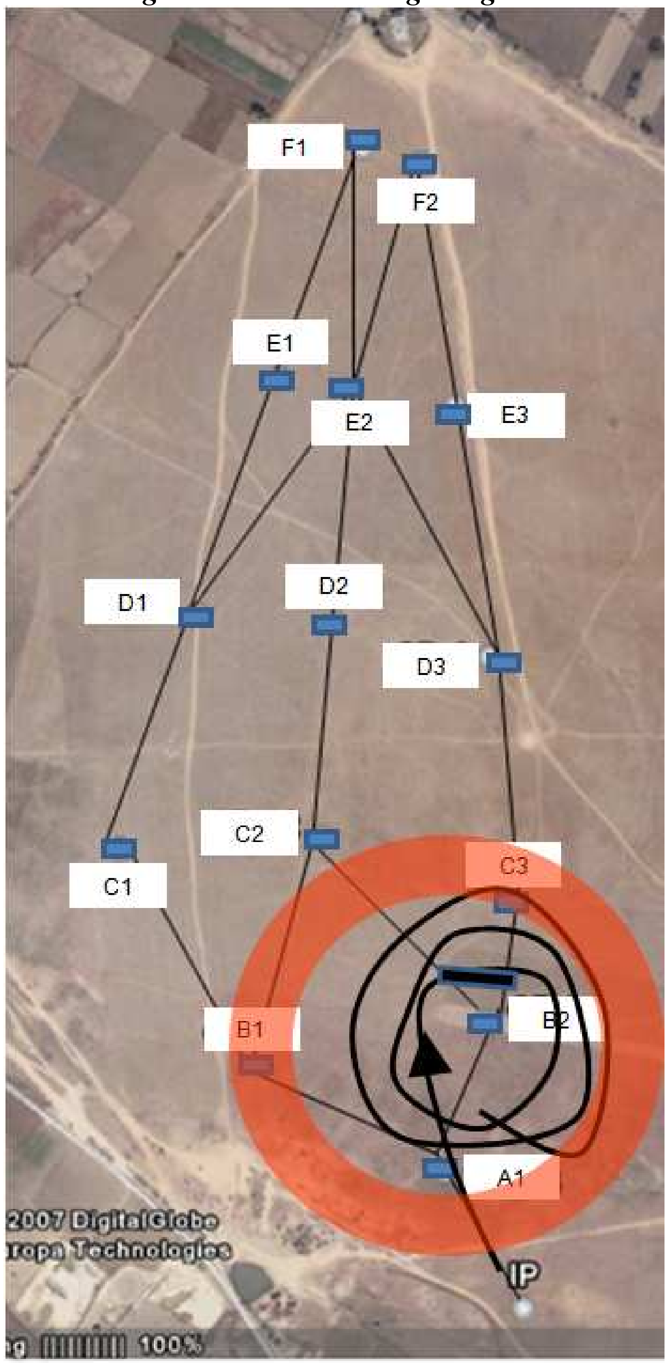
The time period preceding the competition involved a design freeze and finalization the mission plan. The team had to adapt to multiple changes to the mission requirements initiated by event organizers. Changes included the locations of the land mines and cover points as well as the inclusion of obstacles in the field as seen in ***Figure 11.1***. The mines were limited to locations in the center of the paths and only two of the six mines contained the chemical substance needed to be detected by chemical sensing. The cover points shown on the figure below represent areas where the commandos and UGV could hide from being seen by the guards. They also provided a way for the ground station team to communicate with the commandos and UGV by creating a location-based map for navigation. The obstacles were blue sheets placed on the ground which were located between cover points and represented areas on the paths where the commandos and the UGV were not allowed to traverse.

Figure 11.1. Revised Mission Area



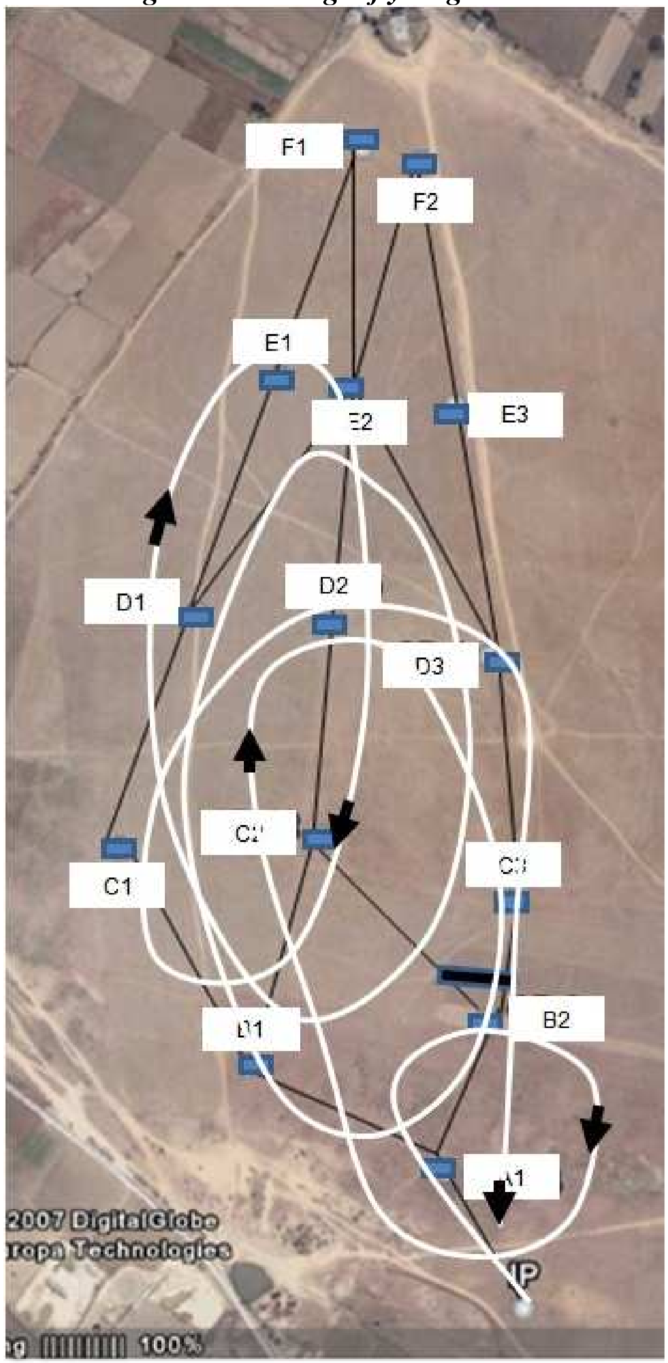
Based on the adjustments to the rules, the team revised the mission plan. Phase I of the original mission plan remained unchanged during the performance of the mission. A Mini-Vertigo was launched and flown in stability augmentation mode, with the plane flying at a high angle of attack. A camera on the Mini-Vertigo provided live feed to the ground station so the team could locate obstacles and cover point along the paths. The pilot flew Mini-Vertigo visually with the help of ground station operators. Due to the endurance limitations, Mini-Vertigo flew a flight path as shown on the ***Figure 11.2***. The ground station crew determined the area in the vicinity of B2 contained obstacles.

Figure 11.2. Mini-Vertigo Fligth Path



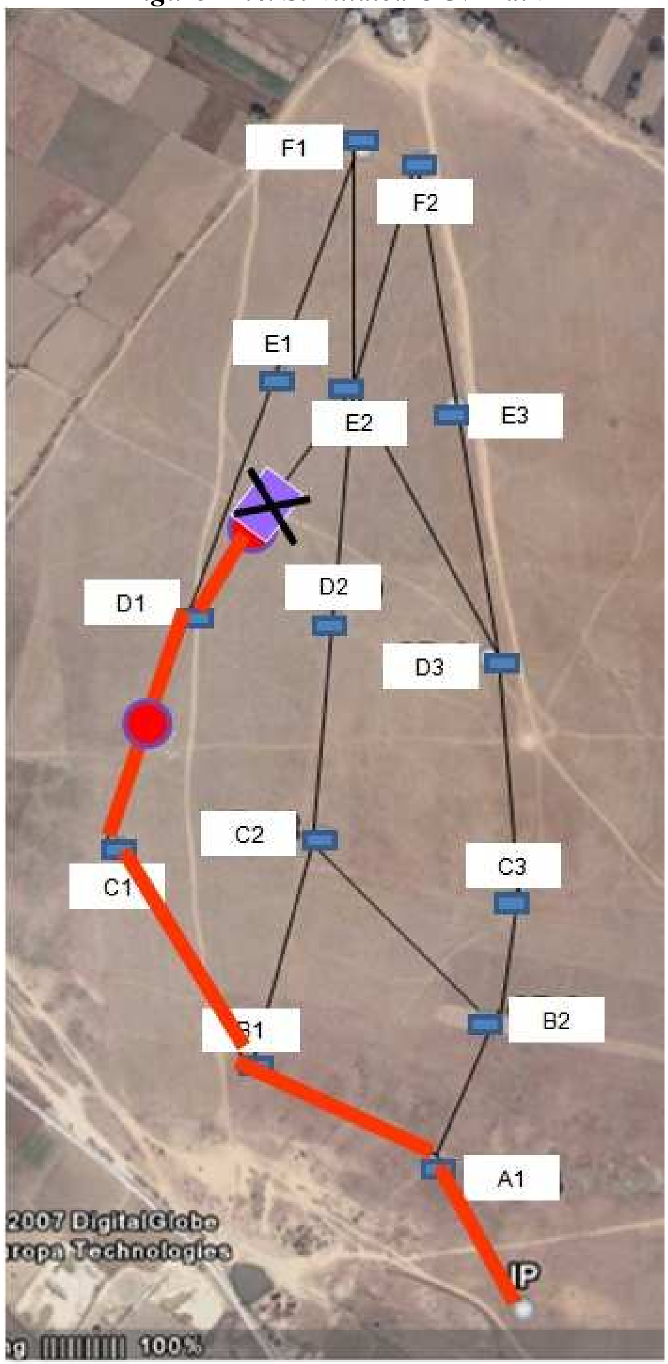
Mini-Vertigo flew for 12 minutes and landed close to cover point B2. Phase 2 of the mission began immediately afterward and Dragonfly was launched and switched to fully autonomous mode. Dragonfly followed the path outlined in the ***Figure 11.3*** below according to assigned waypoints. Dragonfly flew up to cover points E1-E3 and it was determined that path A1-B1-C1-D1-E2 was obstacle free

Figure 11.3. Dragonfly Flight Path



A few minutes after Dragonfly was launched, the commandos and Simulated UGV were commanded to go to cover point A1 and then to B1 because Mini-Vertigo determined the area around B2 contained obstacles. The timing of the ground vehicle and commandos were done with the help of Dragonfly. As shown on ***Figure 11.4***, the simulated UGV followed the path IP-A1-B1-C1-D1-E2. The UGV was equipped with two cameras, one forward facing and one left facing, and a chemical sensor. A landmine was detected between C1-D1 using a camera and then it was considered disarmed. However, on the path between D1-E2, the UGV was destroyed by an undetected mine. It was also seen by the terrorists 35 minutes into the mission.

Figure 11.4. Simulated UGV Path



Once the UGV was destroyed, the commandos were sent to the next cover point. The path the commandos took is shown on ***Figure 11.4***. The commandos reached cover point D1, but the mission time was nearly concluded. At that time, the team decided to send dragonfly back to the ingress point and attempt an autonomous landing. Dragonfly successfully landed and the mission was over.

XII. Conclusion

Overall, the project was a success. Based on the outlook of the teams performance, there are a number of lessons learned that will be applied in future projects. From the onset, electrical components have been the biggest problem. Interference issues and errant electronics and programming set the team back for months. It was not until a week before the competition did all the issues get resolved. Reliability of electronics equipment was an ongoing battle as none of the members of the team had much expertise in this area. This could be especially seen in the video system. Although the team managed to get the video system operational, the quality of the video was not up to par with what was needed to excel in the competition. This could be due to interference or any other unresolved issue.

Other things that need to be looked into is the chemical sensing technology. The team only received the sensor 2 weeks the competition, which was not enough time to calibrate the system properly and test it to ensure it worked reliably during the competition. Audio triangulation was looked into. However due to time restrictions the idea was quickly abandoned. Future projects should allot more time to research and develop this promising technology.

More time before the competition should be allowed for practicing full-scale mission scenario. This is one of the most important aspects of the competition as teams were supposed to make use of their systems to carry out a mission in a set amount of time. Timing is key in this phase, because the ground operator, video operator and pilot need to work together and synchronize their operating procedures to complete the mission. This can only be done if all systems are ready at least a month before the competition without any major changes to system itself.

XIII. Acknowledgments

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XIV. References

[1]Coopamah, D., Krashanitsa, R., Malladi, B., Silin, D., Shkarayev, S.V., "Design of Dragonfly Micro Air Vehicles at the University of Arizona," The 2[rd] US-European Competition and Workshop on Micro Air Vehicles, September 2006, Florida, USA.

[2]Grasmeyer, J.M., Keennon, M.T., "*Development of the Black Widow Micro Air Vehicle*", 39th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 2001.

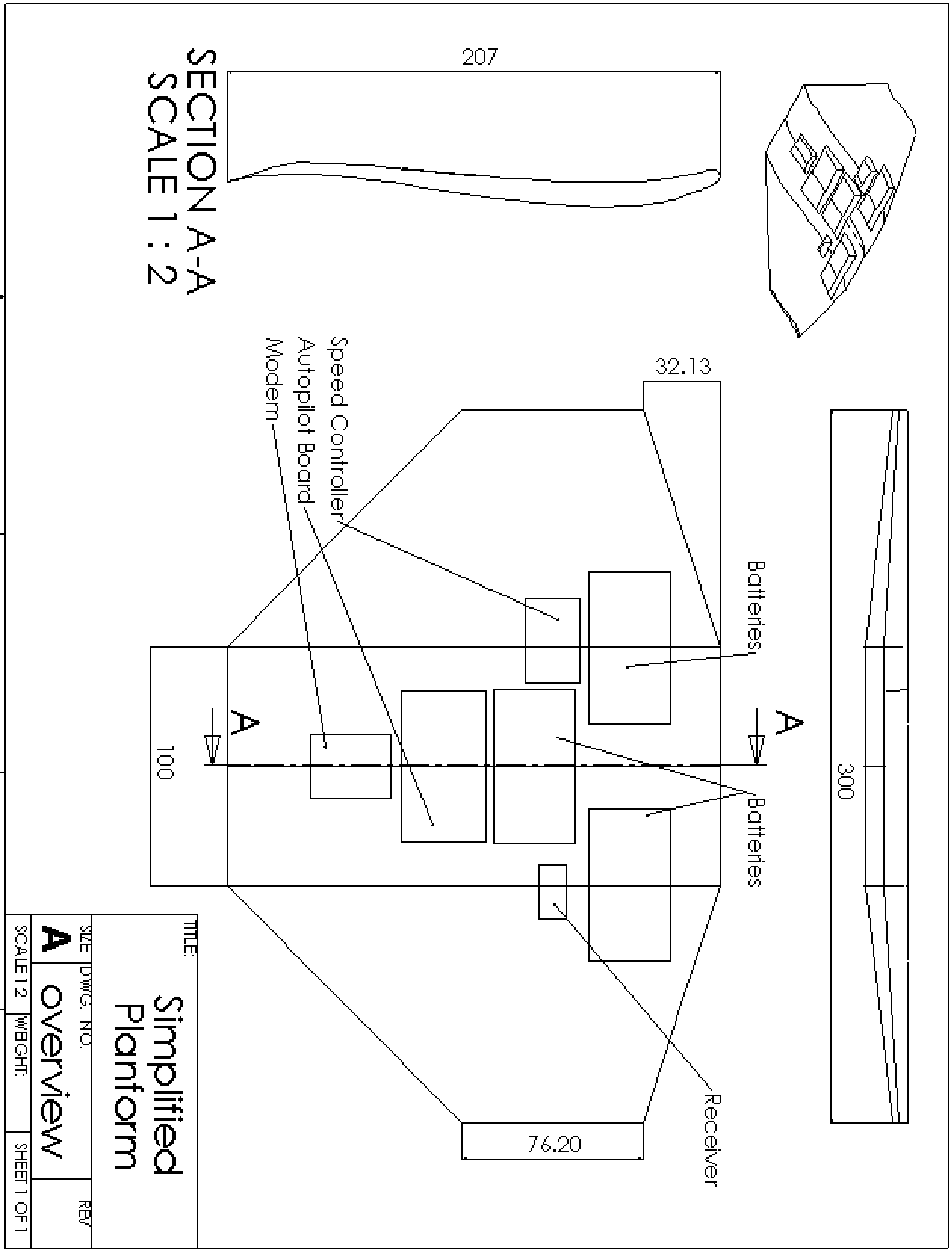
[3]Platanitis, G., and Shkarayev, S., "Integration of an Autopilot for a Micro Air Vehicle," Infotech@Aerospace, September 26-29, 2005, Arlington, VA, AIAA-2005-7066.

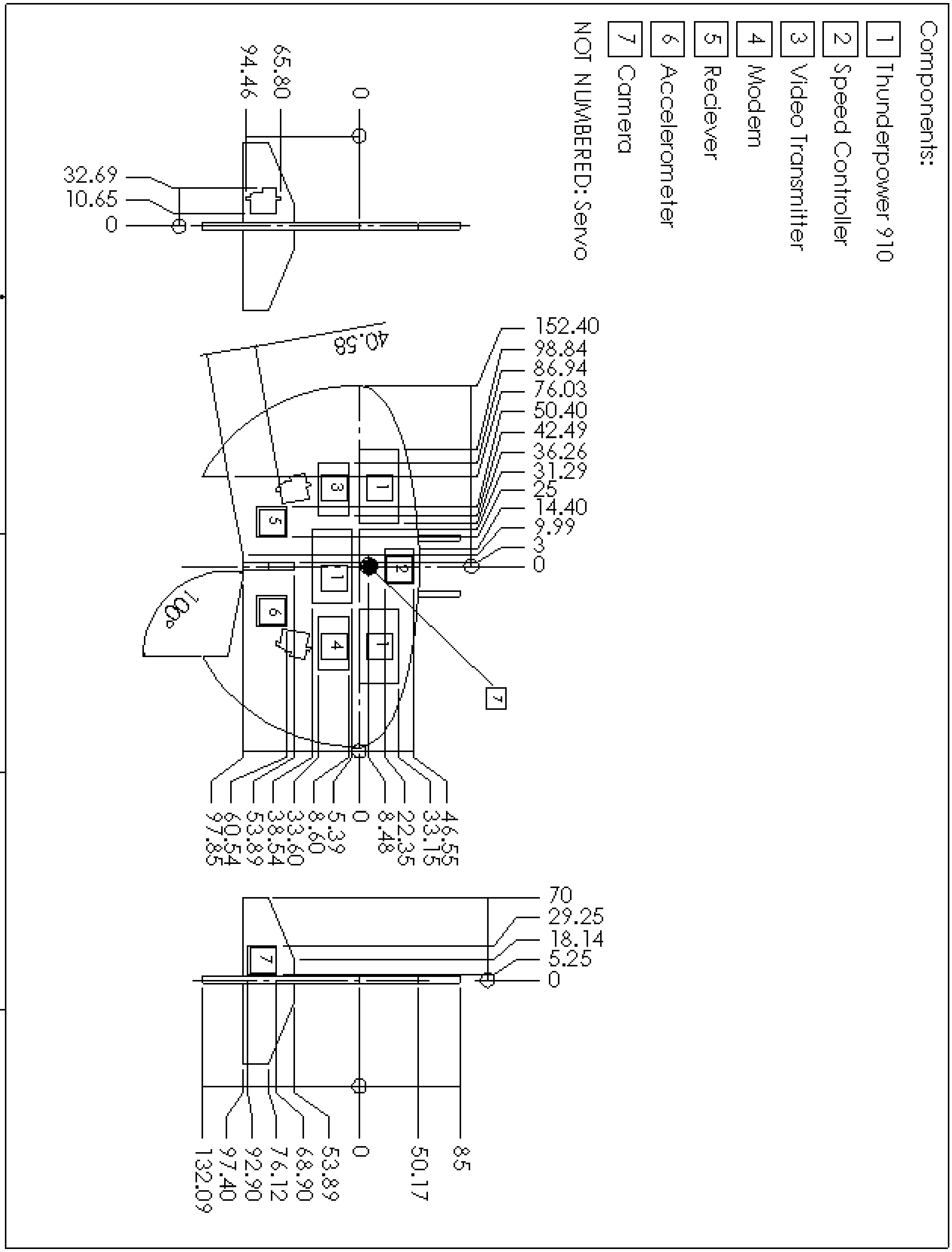
[4]Krashanitsa, R., Platanitis, G., Silin, D., Shkarayev, S., Aerodynamics and Controls Design for Autonomous Micro Air Vehicles, AIAA-2006-6639, AIAA Atmospheric Flight Mechanics Conference and Exhibit, Keystone, Colorado, Aug. 21-24, 17 p., 2006.

[5]Shkarayev, S., Moschetta, J. M., and Bataille, B., "Aerodynamic Design of VTOL Micro Air Vehicles," The 3[rd] US-European Competition and Workshop on Micro Air Vehicles, September 2007, Toulouse, France.

[6](Sergi Bermůdez i Badia, Ulysses Bernardet, Alexis Guanella, Pawel Pyk, Paul,F.M.J. Verschure, 2007) "A Biologically Based Chemo-Sensing UAV for Humanitarian Demining". Advanced Robotic Systems

XV. Appendixes




Components:
1 Thunderpower 910
2 Speed Controller
3 Video Transmitter
4 Modem
5 Reciever
6 Accelerometer
7 Camera
NOT NUMBERED: Servo
152.40
98.84
86.94
76.03
50.40
42.49
36.26
31.29
25
14.40
9.99
3
0
40.58
46.55
33.15
22.35
8.48
0
5.39
8.60
33.60
38.54
53.89
60.54
97.85
70
29.25
18.14
5.25
0
85
50.17
0
53.89
68.90
76.12
92.90
97.40
132.09
65.80
94.46
32.69
10.65
0