**Association of Vehicle Systems International (AUVSI) Annual Conference, Denver, CO, Aug. 2010.**

# INNOVATIVE SOLUTIONS FOR COUNTER-MAV DEFENSE

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In today's terrorist-saturated war zones, protecting a forward operating location from an attack by a remote controlled micro air vehicle (MAV) carrying biological, chemical, or conventional weapons has become a focus of commanders at all levels of military command. The possibility of these attacks has also increased the relevance for homeland security applications within the United States. Research into innovative concepts across many engineering disciplines focused our efforts into researching, designing, and prototyping an unmanned system that can detect, track, and defend against an airborne terrorist attack. Solution space was limited to an air-to-air solution where the enemy aircraft is destroyed by a "friendly" MAV deployed from the base being attacked. Possible solutions include using a deployable net attached to an MAV, an MAV that uses aerosol glue or acid to destroy its enemy's control surfaces, proximity explosives, and MAV-borne electronic deterrents. The functional prototypes demonstrate two of the most promising neutralization capabilities.

## INTRODUCTION

Airborne terrorist threats have become a high priority for national defense contractors, the Department of Defense and the Department of Homeland Security. With the lowered cost and increased accessibility of small aircraft in today's world, terrorists have begun to capitalize on the chance to use small aircraft as weapons. Micro Air Vehicles (MAVs) have been equipped with a wide variety of conventional and non conventional weapons and used in terror attacks around the globe. In the interest of national security and base defense, research in defending against this increasing threat is necessary to properly protect military bases and other important assets. Capstone design work at the United States Air Force Academy has focused on an innovative solution to mitigate this "enemy MAV" threat, in order to drive further research for DoD and DHS applications. After rigorous customer needs analysis and concept generation, the cadet team proceeded with developing alpha-level prototypes for two different design concepts. The first design, called NetMAV, uses an airborne net attached to a radar and computer guided MAV to "catch" the enemy MAV. The second design, called SprayMAV, uses a similarly guided MAV to spray an acidic solution onto the enemy plane. The purpose of the spray is to degrade the flight control surfaces to the point that the enemy MAV becomes uncontrollable and crashes far from its intended target. Funding for research was provided by the Air Force Research Laboratories at Wright Patterson (AFRL/RB) and Eglin (AFRL/RW) Air Force Bases.

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## OBJECTIVES

The objectives for this project were focused on innovation and cost effective solutions to protect United States (US) military bases and high value civilian targets, such as outdoor sporting events or concerts from conventional (e.g. Explosives) and non-conventional (e.g. biological or chemical) MAV borne threats.

## CUSTOMER NEEDS

Customer needs research was focused around interviews conducted with members of the proposed customer base. Customers included members of the special operations forces and also the security forces (both military and civilian). Each potential "customer" was asked to rate the importance of the various customer needs as shown in Figure 1.

| | Context Catagories | Where | | | | | | When | | | | | | | | | Result |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Context Description | Desert | Jungle | Mountains | Urban | Rural | "Where" Wt | Rain | Dry | Night | Day | Windy | Calm | High Temp | Low Temp | "When" Wt | Overall Wt |
| | Usage Percentages | 0.3 | 0.1 | 0.6 | 0.6 | 0.4 | | 0.3 | 0.7 | 0.5 | 0.5 | 0.7 | 0.3 | 0.6 | 0.4 | | |
| Customer Needs (CN) | Affordable | 7 | 8 | 7 | 6 | 6 | 6.6 | 7 | 7 | 6 | 7 | 8 | 8 | 6 | 6 | 6.9 | 6.7 |
| | Appearance | 4 | 2 | 5 | 5 | 5 | 4.7 | 1 | 1 | 4 | 5 | 1 | 2 | 1 | 2 | 2.1 | 3.4 |
| | Manueverability | 5 | 5 | 7 | 7 | 9 | 7.0 | 5 | 5 | 8 | 8 | 9 | 7 | 8 | 8 | 7.4 | 7.2 |
| | Ease of Use | 9 | 8 | 9 | 9 | 9 | 9.0 | 9 | 7 | 9 | 7 | 9 | 6 | 8 | 8 | 7.9 | 8.4 |
| | Mobile | 9 | 9 | 9 | 9 | 9 | 9.0 | 8 | 6 | 8 | 6 | 6 | 5 | 8 | 8 | 6.8 | 7.9 |
| | Safety | 7 | 6 | 9 | 6 | 8 | 7.5 | 7 | 5 | 8 | 8 | 8 | 7 | 7 | 7 | 7.1 | 7.3 |
| | Size | 6 | 5 | 7 | 7 | 7 | 6.8 | 3 | 2 | 5 | 6 | 8 | 4 | 5 | 5 | 4.9 | 5.8 |
| | Weight | 3 | 3 | 3 | 5 | 6 | 4.2 | 5 | 3 | 5 | 5 | 8 | 4 | 5 | 5 | 5.1 | 4.7 |
| | Speed | 8 | 8 | 8 | 6 | 7 | 7.2 | 5 | 6 | 5 | 8 | 7 | 7 | 5 | 5 | 6.1 | 6.6 |
| | Endurance | 9 | 9 | 9 | 9 | 10 | 9.2 | 6 | 6 | 8 | 8 | 9 | 7 | 8 | 8 | 7.6 | 8.4 |
| | Distance From Target | 6 | 6 | 9 | 7 | 9 | 7.8 | 7 | 7 | 8 | 7 | 9 | 7 | 6 | 6 | 7.2 | 7.5 |
| | Durability | 9 | 9 | 9 | 7 | 8 | 8.2 | 10 | 10 | 9 | 9 | 10 | 9 | 10 | 10 | 9.7 | 8.9 |
| | Response Time | 10 | 10 | 10 | 10 | 10 | 10.0 | 10 | 9 | 10 | 9 | 9 | 9 | 9 | 9 | 9.2 | 9.6 |
| | Reusable | 6 | 6 | 6 | 6 | 6 | 6.0 | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 4 | 2.9 | 4.4 |
| | % of possible neutralizations | 10 | 10 | 10 | 10 | 10 | 10.0 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10.0 | 10.0 |
| | Collateral Damage | 5 | 5 | 5 | 5 | 5 | 5.0 | 4 | 4 | 5 | 5 | 4 | 6 | 7 | 4 | 4.9 | 4.9 |

**Figure 1 – Context Calculator for Quantifying Customer Preferences**

The context calculator[1] uses different possible scenarios where the MAV might be used in order to rate the customer needs against one another. After this comparison, the top customer needs were: high enemy neutralization rate, response time, durability, endurance and ease of use.

A House of Quality[2] was also used to rate customer needs against measurable objectives. The House of Quality rates the customer needs against measurable goals (design requirements) that are derived from the customer needs. For example, the measurable performance goal of "Response Time" is derived from the customer need "Rapid Deployment."

| | CN Weight (from Excel) | Effictiveness rate(killsper trial) | Response Time (min) | Turn Radius (feet) | Operator Safety (# of injuries) | Speed (mph) | Max time aloft (hrs) | Range (feet) | Durability (% of part failures per mission) | Size (feet) | Weight (lbs) | Radius of Area Affected (Feet) | Cost ($) | UAV | Aegis missile defense system |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| % of Neutralizations | 10 | 3 | 0 | 1 | 0 | 2 | 3 | 2 | 0 | 1 | -1 | 0 | 2 | 3 | -3 |
| Rapid Deployment | 10 | 3 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | -1 | -2 | 0 | 1 | -1 | -3 |
| Manueverability | 7 | 1 | 0 | 3 | 0 | -2 | -1 | -1 | 0 | -2 | -1 | 0 | 1 | -2 | 1 |
| Safety | 8 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 3 | 3 |
| Speed | 7 | 1 | 2 | -1 | 0 | 3 | -2 | -1 | -1 | 1 | 0 | 0 | 1 | 2 | 2 |
| Endurance | 8 | 2 | 0 | 0 | 0 | -3 | 3 | 0 | 1 | 2 | 1 | 0 | 1 | 3 | 2 |
| Distance from Target | 8 | 1 | 0 | 0 | 1 | 0 | 1 | 3 | 0 | 0 | 1 | 2 | 1 | 3 | 1 |
| Durability | 8 | 0 | 0 | -1 | 0 | -1 | 0 | 0 | 3 | 0 | 0 | 0 | 1 | 1 | 1 |
| Reusable | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | 3 | 3 |
| Cost | 7 | 0 | 0 | 0 | 0 | -1 | -1 | -1 | 3 | -1 | -2 | 0 | 3 | -3 | -3 |
| Appearance | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 3 |
| Ease of Use | 8 | 2 | 0 | 2 | 1 | -1 | 1 | 1 | 1 | 2 | 1 | 0 | 1 | -1 | 2 |
| Mobile | 8 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | -3 | -3 | 0 | 0 | -2 | -2 |
| Collateral Damage | 5 | 0 | -1 | 0 | 0 | 0 | -1 | -1 | 0 | 0 | 0 | 3 | 0 | | |
| Technical Difficulty | | 8 | 5 | 4 | 2 | 2 | 4 | 3 | 4 | 6 | 6 | 10 | 1 | | |
| Present Value | | 85% | 1 | | 0 | 30 | | 0.5 | | | | 1000 | | | |
| Target Value | | 100% | 0.33 | | 0 | 45 | | 5 | 0% | | | 0 | | | |
| Importance | | 121.7 | 45.44 | 32.75 | 40.27 | -21.6 | 37.118 | 24.978 | 63 | -4.41 | -50 | 31.5 | 115.4 | | |

**Figure 2 – Partial House of Quality for the Anti-MAV System**

## ASSUMPTIONS

In order to create an innovative solution, efforts were focused on airborne anti-MAV systems. Previous work in the DoD Black Dart program has proven the difficulty or complexity of using large land based weapons systems. We assumed that the enemy would use a MAV with a wingspan between 2 and 6 feet and with a top speed of ~30 mph. These assumptions are based on research of currently available MAV technology and widely available R/C aircraft. Although detection, tagging and tracking will be involved in the overall process of enemy MAV defeat, we focused our efforts specifically on the neutralization portion of the problem (see Figure 3). In that light, the purpose of the team's design efforts was to develop a wide range of neutralization concepts and work to show the feasibility of the two most promising concepts through analysis and prototyping.

However, some information regarding the tracking function is critical to our design. The Merlin Bird Tracker is a COTS product that is used by airports to track bird locations. It has the ability to track birds at 4 miles distance. Using that distance, and assuming the enemy MAV is moving at 30 MPH, we calculate we would have approximately 9 minutes between "first alert" from the radar system and the arrival of the enemy MAV on target. We are using a factor of safety of 3 for this work and therefore we are assuming we have 3 minutes to neutralize the enemy MAV. Furthermore, the resolution of the radar is quoted at 4 feet. Assuming we are using a military GSP based system for the tracking function, we will use a value of 3-16 feet for that system's sensitivity. Therefore, we will set a design requirement for the separation distance between the friendly and enemy MAVs of 7-20 feet.

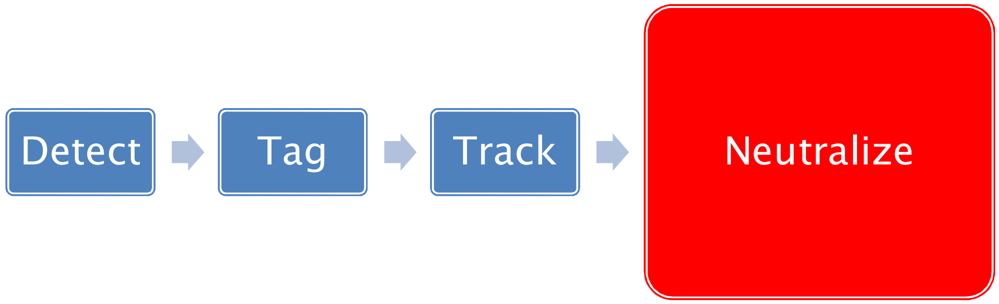


**Figure 3 – Enemy MAV Defeat process Showing our Emphasis on Neutralization**

## CONCEPT GENERATION

After customer needs were determined, the team used a suite of concept generation techniques[3] to generate ideas for prototyping, the end result of which were the SprayMAV and NetMAV concepts. Using this concept generation suite, we were able to generate over 80 unique concepts for neutralization. Figure 4 shows the list of potential concepts.


**Figure 4 – Initial Concepts for Anti-MAV Systems**

The concepts were narrowed using engineering judgment and considerations such as budget, time for development, and legality. Many of the concepts were either too big, too expensive, or used technology that is not currently available. A modified Pugh Method[2] was used to make the final ranking for the concepts. The SprayMAV and NetMAV concepts came through as the two designs that met all customer needs, met the team objectives, and were inexpensive enough to develop within the team's budget.

**SPRAYMAV**

One of our primary concepts for neutralizing a threat was spraying acid, or some other corrosive substance from one MAV onto another, thus degrading its flight control surfaces and causing the plane to crash (Figure 5). The benefits of this system include its low weight, allowing it to be carried by a wide range of MAVs, the low cost of building the system (since all components are COTS) and finally, the system durability. Additionally, this system could be adapted to spray a wide range of liquids for varying purposes, making it versatile. However, the idea is not without issues. For example, the amount of liquid which can be carried within an MAV is severely limited based on both weight and volume constraints. Also, varying flight and weather conditions will change the way in which the acid falls and spreads out after being sprayed. A nozzle design providing maximum coverage can be used, but there is no way to completely avoid dealing with the variability of nature. Finally, there is not one perfect solution for an acid which can sufficiently degrade every material. Each acid has certain materials which it will degrade, but no single acid can sufficiently degrade all materials within the allowed timeframe.

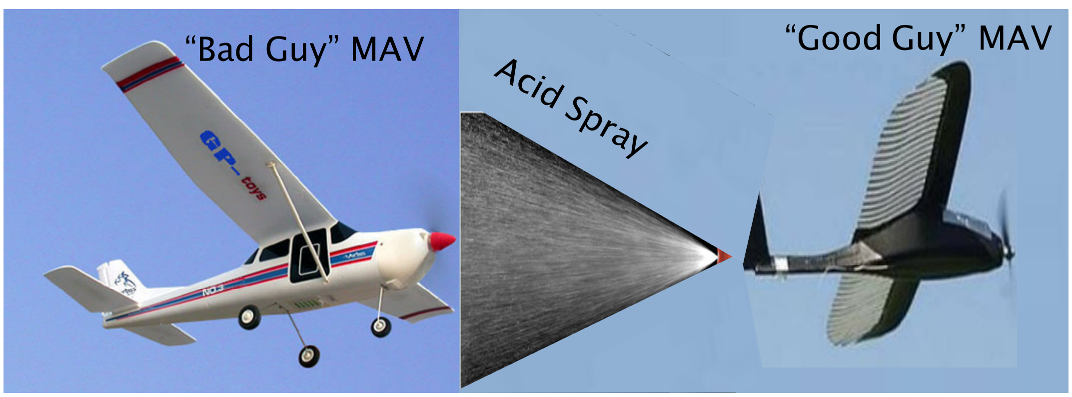


**Figure 5 – Basic "SprayMAV" Concept**

In order to test this concept the team needed to pick a test aircraft which the spraying prototype could be placed in for testing. The two planes considered for use were the Dynam ICanFly and the Multiplex Easy Glider Pro. These planes were based on their advertised stability and payload capabilities which would allow the team which had no prior experience with small planes to prototype and test the concept. The Dynam model allowed the team to place the prototype inside the plane, however it had a smaller wingspan and was generally less stable. The Multiplex model was much more stable with a six foot wingspan, however there was no room inside the plane itself which the prototype could fit in, so on this model it had to be fixed to the outside or the fuselage.

The team built a prototype of the spray system which was compatible with both the Dynam and Multiplex models (Figure 6).

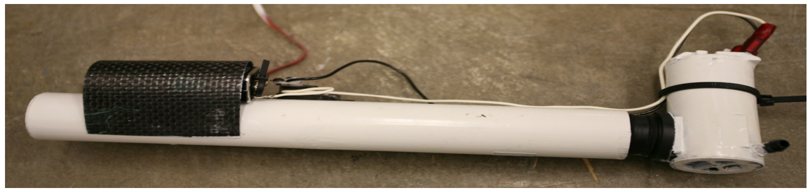

**Figure 6 – Prototype of Spray System**

An 8” by ¾” PVC pipe was used to contain the fluid in the system. A windshield wiper fluid pump powered by a 9V battery was used to spray the acid, while the other side of the tube was capped with a combination of foam and hard plastic. This combination was lifted slightly to break the seal when the prototype was spraying, thus eliminating the issue of creating a vacuum when the liquid was sprayed. The long and skinny shape of the prototype was picked so that it could fit inside the Dynam model, and so that it could be easily adapted to fly, attached to the Multiplex model and still be streamlined (Figure 7). Keeping the weight of this prototype low was critical since both the total weight and the center of gravity affect how the planes fly. This effect is enhanced since the planes are quite small.

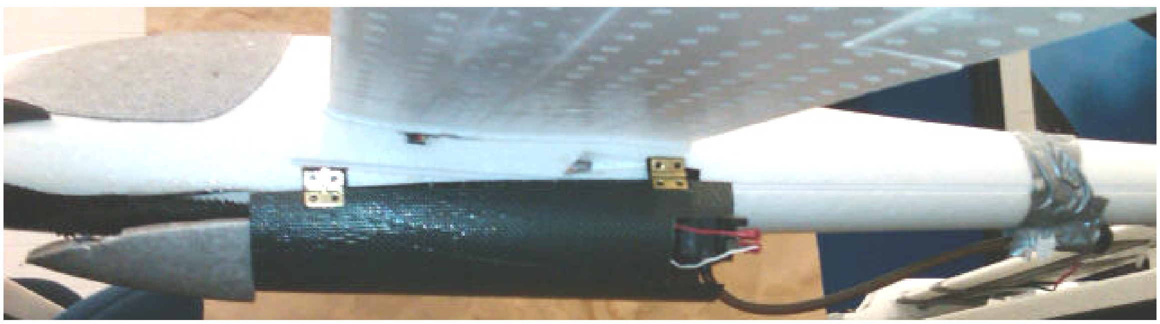

**Figure 7 –SprayMAV System Attached to Multiplex Aircraft**

The operations concept for the SprayMAV is generally straightforward. A spray system will be mounted onto an existing MAV platform. The system’s capabilities (volumetric capacity, spray intensity, etc.) will vary depending on the host platform’s payload capabilities. Once a threat is detected by the modified bird-detection radar, the UAV will be launched towards the adversary. A flight path will be set so that the defending MAV will fly above the attacking MAV with a separation of 10-20 feet. Once the MAVs are within approximately 30 feet of each other, the spray system will be activated. It will continue to spray until the MAVs have flown approximately 30 feet past each other. This buffer zone compensates for imprecision in the bird-detection radar and varying weather conditions which could change the direction in which the acid flows after being sprayed.

Tests of acid effectiveness were conducted. We first tested Aqua Regia, a mixture of Hydrochloric and Nitric Acids. We tested this acid on specimens of Styrofoam, Balsa Wood, and Carbon Fiber/Kevlar composite weaves. These materials were chosen based on their common use in the construction of COTS MAVs. Unfortunately, the team found that Aqua Regia, although highly acidic, did not have the corrosive ability to sufficiently degrade any of the materials within the required time frame. Because there are only approximately three minutes between contact with the enemy and the time they are over the target, any substance used must act within this time frame. Next we tested concentrated solutions of Nitric and Sulfuric acid. Although some degradation effects were noted, there was not sufficient effect on the materials within the time frame allowed. Finally, the team tested acetone on Styrofoam. This solution was extremely effective, and required less than 10 mL of the liquid to completely degrade a representative airfoil. Figure 8 shows the structural degradation of the airfoil.

**Figure 8 – Structural Degradation of Styrofoam Airfoil From 10 ml of Acetone**

Note that another promising chemical to consider is Perchloric acid. Research indicates that this may have the quick degradation performance across a number of common materials used for MAV airfoils. However, testing Perchloric Acid is a very closely controlled and dangerous process. As a result we did not perform these tests.

A critical question regarding the spray MAV concept is the volume and endurance of the stream. How long the acid needs to be spayed depends on the type of liquid that is used. Because no fluid will degrade every material the team decided that acetone was the most robust solution for us to use in our prototype. Because approximately 80% of the COTS RC planes are made of some type of Styrofoam, acetone has reasonable applicability to the problem. Also, it was the obvious choice because it quickly degrades the material of interest. The amount of fluid needed is minimal, with 5-10mL needed to degrade an airfoil to an extent that should cause structural failure or at least significantly lower aerodynamic performance.

The system we developed can spray a continuous stream for 15 seconds. This proved to be sufficient time for several "passes" against the target. Assuming a 30 mph flight speed, a 5 second spray will cover over 200 feet providing abundant coverage. The selected spray device consists of two streams that come out in a V pattern. The time required for disabling the enemy MAV depends on the type of fluid used. In testing the acetone, it took approximately 30 seconds for the acid to eat through the entire airfoil.

**NETMAV**

The NetMAV concept involves packaging a net on the friendly MAV, and deploying the net just prior to passing the enemy MAV. The enemy MAV is simply caught in the net and, as a result, is brought to the ground. The strategy is shown in flight in Figure 9.

**Figure 9 – NetMAV Concept Shown in Action**

The net is custom made and has a trapezoidal shape with the short section that is attached to the aircraft being 6 feet long. The bottom of the net is three times this long (i.e. 18 feet) in order to facilitate a tri-fold initial folding strategy. The net is approximately 20 feet long. The top length of 6 feet was chosen to conform to the wing span of the aircraft we were using to demonstrate the concept. The square holes in the net are designed to have a diagonal of approximately 25 inches. This holes size was determined based on a study of COTS RC Aircraft size and payload capacity. With this hole size we believe there is a very small possibility that an enemy MAV will pass through the net without being "caught".

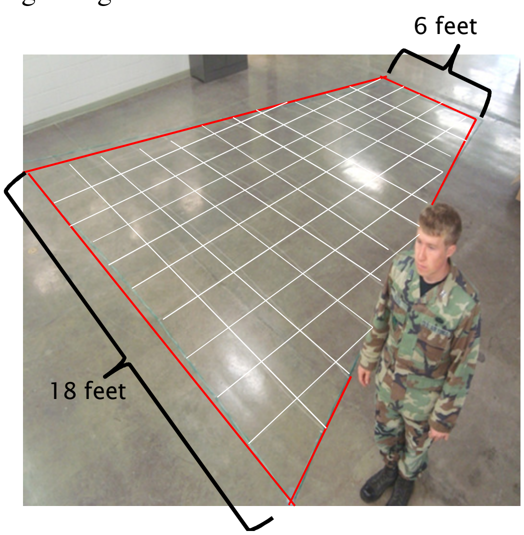


**Figure 10 – Net in its Fully Deployed Configuration**

Once the net has been tri-folded into a 6' x 20' size it is folded using an accordion type pattern into its stowed state. In this stowed state it has roughly a 3 inch diameter. The stowed net is then attached to the aircraft under the wings approximately at the center of gravity. This keeps the basic aerodynamic stability variables such as static margin intact. The in-flight deployment (release of the net) uses a single servo under the fuselage of the aircraft to release the servo arms from the webbing that is used to hold the net. This causes the net to unfold from the wings and be dragged below the aircraft. In order to keep the 18 feet edge of the net spread out after in-flight deployment, the 18 feet section is divided into 3 sections, each 6 foot in length. A very light, stiff rod (carbon fiber is the preferred material) is attached to each 6-foot section. The straightening of the three, 6-foot sections from their tri-folded pattern is facilitated by coil springs attached between each of the three rods

The aircraft used for demonstration of the NetMAV concept was chosen based on airspace limitations and payload requirements. The Multiplex Easy Glider Pro was approved for flying in USAFA airspace, and it had the highest payload potential of the approved aircraft. The aircraft has a six foot wingspan and an electric drive power pack providing thrust through a propeller (see Figure 11).

**Figure 11 - Multiplex Easy Glider Pro Aircraft**

The net and deployment system weighed approximately 1 lb. This was close to the payload capacity of the aircraft, but proved light enough for positive test results. We found that the optimum speed to fly the net was 15-25 mph. Somewhat to our surprise, the aircraft maintained reasonable flight controllability with the net deployed.

Using only visual flight controls, we were able to successfully capture the enemy MAV with the NetMAVsystem. We anticipate that the next iteration of the design would incorporate an automated tracking system for maneuvering the NetMAV to the proper location adjacent to the enemy MAV for deployment of the net and resulting capture of the enemy MAV.

**CONCLUSION**

COTS MAVs could potentially be used by the enemy to deliver explosive, biological or chemical agents. In simulations, protecting against this enemy threat has proven to be difficult. Although successful tests have been done using advanced weapons systems against this threat, these advanced weapons may not always be available when and where an enemy attacks. In light of this, a simple, reliable anti-MAV system is sought. Cadets at the US Air Force Academy in coordination with students at the University of Texas, have developed two potential concepts for defeating this threat. One concept uses a friendly MAV to spray acid onto the enemy MAV during flight. Initial prototypes show that spraying acetone in small quantities will significantly degrade the Styrofoam wings of an enemy MAV. The other concept uses a net deployed from the friendly

MAV to capture the enemy MAV. This concept was also demonstrated to be effective in initial testing.

## ACKNOWLEDGMENTS

This work is partially supported by a grant from the Air Force Research Labs (AFRL/RW, Eglin Air Force Base and AFRL/RB, Wright Patterson Air Force Base) and, in part, by the University of Texas at Austin Cockrell School of Engineering and the Cullen Trust Endowed Professorship in Engineering No. 1. Particular thanks go to Dr Greg Abate, Dr Mikel Miller, Dr Greg Reich, Capt Robert Walker and Dr Greg Parker at AFRL/RB. In addition, we acknowledge the support of the Department of Engineering Mechanics at the U.S. Air Force Academy as well as the financial support of the Dean's Assessment Funding Program. Any opinions, findings, or recommendations are those of the authors and do not necessarily reflect the views of the sponsors or the US Air Force.

## REFERENCES

1. Green, M., Jensen, D., Seepersad, C., Wood, K., "Design for Frontier Contexts: Classroom Assessment of a New Design Methodology with Humanitarian Applications", International Journal of Engineering Education, Vol. 25, No. 5, 2009.
2. Otto, K., Wood, K., Product Design: Techniques in Reverse Engineering and New Product Development, Prentice Hall, 2001.
3. Jensen, D., Weaver, J., Wood, K., Wood, J., Lindsey, J., "Techniques to Enhance Concept Generation and Develop Creativity", *ASEE Annual Conference*, Austin, TX, June 2009.