COMPOSITE MATERIALS FOR MICRO AIR VEHICLES

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ABSTRACT

This paper will discuss the development of the University of Florida's Micro Air Vehicle concept. A series of flexible wing based aircraft that possess highly desirable flight characteristics were developed. Since computational methods to accurately model flight at the low Reynolds numbers associated with this scale are still under development, our effort has relied heavily on trial and error. Hence a time efficient method was developed to rapidly produce prototype designs. The airframe and wings are fabricated using a unique process that incorporates carbon fiber composite construction. Prototypes can be fabricated in around five man-hours, allowing many design revisions to be tested in a short period of time. The resulting aircraft are far more durable, yet lighter, than their conventional counterparts. This process allows for thorough testing of each design in order to determine what changes were required on the next prototype. The use of carbon fiber allows for wing flexibility without sacrificing durability. *The construction methods developed for this project were the enabling technology that allowed us to implement our designs.* The resulting aircraft were the winning entries in the International Micro Air Vehicle Competition for the past two years. Details of the construction method are provided in this paper along with a background on our flexible wing concept.

KEY WORDS: Micro Air Vehicles (MAVs), Composite Materials, Flexible Wings

1. INTRODUCTION

Micro air vehicles, or "MAVs", are designated by DARPA as a class of aircraft with a maximum size of 6 inches and are capable of operating at speeds of 25 mph or less (Mueller, T. J. 2000). The concept is for a small, inexpensive and expendable platform that can be used for surveillance and measurement missions in situations where larger vehicles are not practical. For example, they can be used for small unit battlefield surveillance, mapping out the extent of chemical/radiation spills or viral outbreaks as well as more routine applications such as monitoring crops or wildlife distributions. Many potential uses involve launching large numbers of MAVs to secure the necessary coverage with the intrinsically "close up" type of maneuvering allowed by a micro-sized aircraft. In some applications, MAVs could be used in swarms or sent to a pre-designated grid to collect and transmit data. Practical applications of MAVs are becoming more achievable with the ever-decreasing size and weight of the payload components that can include video cameras, chemical sensors, electronics, and communication devices. Only a few years ago the thought of a 6-inch flying machine equipped with a functional video camera was science fiction. Today it is a reality.

It is well known that in the Reynolds number range between 10,000 and 100,000, which corresponds to the MAV size range identified by DARPA, the aerodynamic performance of conventional airfoils is dramatically reduced. Figure 1 illustrates this phenomenon in a plot that describes the marked drop in the lift to drag performance as a function of Reynolds number for all smooth, rigid airfoils. This plot clearly illustrates that the design rules that have been adopted for large aircraft cannot be scaled down to the MAV scale. With smooth, rigid wings in this Reynolds number range, the laminar flow that prevails is easily separated, creating large separation bubbles, especially at higher angles of attack (Mueller, T. J.,1985). Flow separation leads to sudden increases in drag and loss of efficiency.

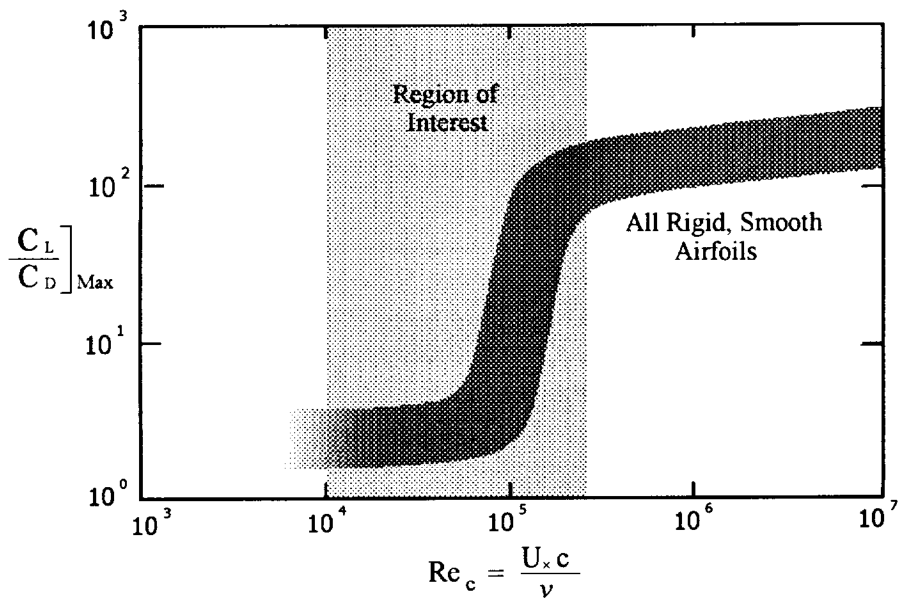


Fig. 1. Dependence of L/D on Reynolds Number

In nature, the relationship between Reynolds number and aerodynamic efficiency can be observed in birds where large species soar for extended periods of time while small birds have to flap vigorously (at high frequency) to remain airborne. The Reynolds numbers of the larger species are well above 100,000 whereas hummingbirds would fly at below 10,000 if they attempted to soar. Additionally, the wing loading for small birds must be less than that for large birds.

Another major obstacle for flight at this small scale is the diminished stability and control characteristics that accompany the small mass moments of inertia of these tiny aircraft. Also, the velocity scale of the turbulence naturally exhibited by the atmosphere is comparable to the flight speed of these vehicles. Therefore, variations in airspeed over the wing can be large, and can even cause variations from one wing to the other, leading to difficulty in maintaining smooth flight. These factors make control of these aircraft difficult, both for a remote operator or an on-board autopilot. Other technical challenges associated with flight on the 6-inch scale include the need to provide reliable propulsion and miniaturization of components including the electronics and actuators for the control surfaces.

In the quest to develop practical MAVs, two approaches have been followed so far. The first and most popular is to configure the airframe as a lifting body or flying wing using conventional propeller driven thrust. In this approach, the emphasis is to increase the relative area of the lifting surface while decreasing drag, directly addressing the decrease in the aerodynamic efficiency, and ignoring issues of stability and control. In order for these designs to fly at all, active stability augmentation systems are usually required. In nature, however, there are no examples of lifting bodies or flying wings. All birds and bats have well defined wings and a fuselage. The second approach that has been explored on the MAV scale is the direct mimicry of birds (Ellington, C. P., 1984 and Frampton et al, 2000). By flapping, birds produce both lift and thrust. Researchers have demonstrated flapping mechanisms in the lab environment, but have yet to produce practical controlled flight vehicles. Complex control issues and high power consumption remain as formidable challenges for this type of MAV.

Previous studies, documented in Shyy et al. (1996, 1997, 1999), Smith and Shyy (1995), and Jenkins et al. (1998), indicate that an alternate approach, specifically allowing the lifting surface to deform, can lead to more favorable aerodynamic performance in a fluctuating low Reynolds number environment. These findings helped lead to the University of Florida's flexible wing concept, which we have been applying to successful MAVs over the past two years. We utilize conventional propeller driven thrust in combination with an adaptive-shape, flexible wing that adapts to flight conditions and also develops a stable limit cycle oscillation during flight. We believe that the behavior of our flexible wing may be a technology that will lead to more practical micro air vehicles in the future.

Our wings were developed to produce smooth flight even in gusty wind conditions. It is our view that in order to produce the best overall flight characteristics, one must first start with an airplane that is intrinsically stable. This is accomplished via the adaptive nature of the wing as well as its natural oscillation. Our aircraft can be flown by novice to average RC pilots, without the aid of gyro enhanced stabilization. We have demonstrated the merits of these MAVs at the International Micro Air Vehicle Competition by winning the event the last two years in a row. We have successfully demonstrated MAVs with a maximum dimension as small as 5-inches.

2. FLEXIBLE WING MICRO AIR VEHICLE

The development of our flexible wing utilizes a combination of biologically inspired design and the use of modern composite materials. The wing is thin and undercambered as are those of small birds and bats. The micro air vehicle that we have developed is constructed with a carbon fiber skeleton and thin membrane materials. In the fuselage we use a low stretch, tough mono-film covering and on the wing we use an extensible latex rubber membrane. The configuration is a departure from the traditional flying wing or lifting body design. It has a distinct fuselage and wing, more similar to that of birds and bats. The MAV shown in Fig. 2 is the product of more than one year of design iteration using flight tests and pilot feedback as the primary method of evaluation. Figure 3 shows video footage taken from the ground of our 6 inch MAV. The insert shows the view from the on-board video camera.

The shape of the wing allows for the maximum lifting surface while staying within a 6-inch diameter sphere. In order to define the design space for our flexible wing we built numerous prototypes to learn how the geometry of the carbon fiber skeleton affects the flight characteristics.

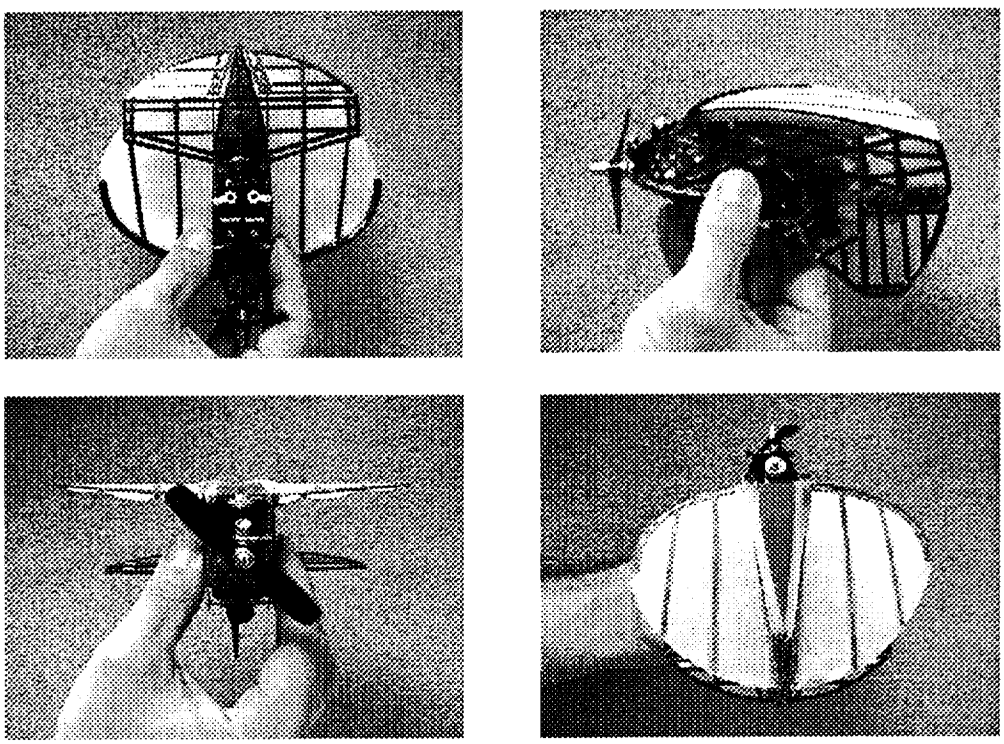


Fig. 2. The 6-inch maximum dimension MAV with video camera.

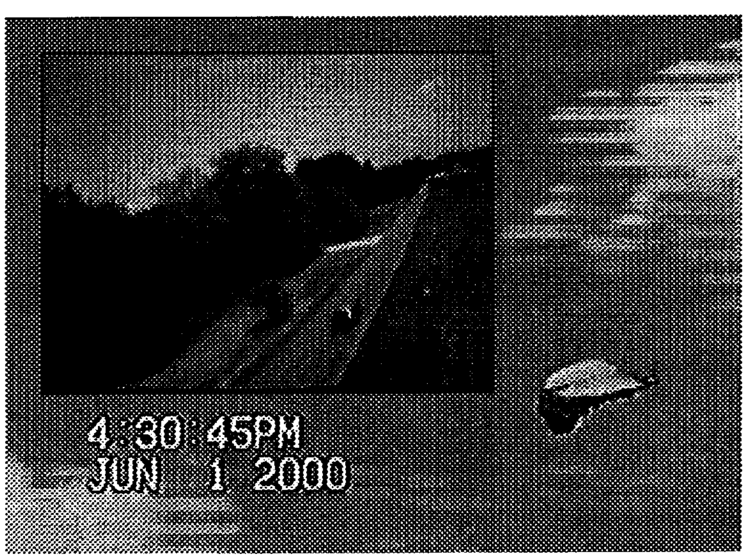


Fig. 3. View of MAV from the ground and video footage from on board.

In order to explore the limit of current technologies and to facilitate vehicle development in a timely fashion, our strategy to date has been to use off-the-shelf components. The servos, receivers, batteries, motor, video cameras and transmitters used in the prototype MAV can all be purchased via mail order. A fully equipped (with video camera and transmitter) aircraft costs less than $500.

Our typical 6-inch MAV flies at airspeeds between 15 and 35 mph and can fly for up to five minutes. The overall flying weight is 55 grams with a useful payload of an additional 28 grams. For our competition MAVs, we use most of the payload for our video camera and transmitter, which total to about 16 grams.

The flexible nature of the wings can provide several non-obvious advantages over their conventional rigid counterparts. The wings fabricated with a carbon fiber skeleton and extensible latex rubber skin have the ability to adapt to the airflow to provide smoother flight. This is accomplished via the passive mechanism of adaptive washout. In sailing vessels adaptive washout is produced through twist of the sail. This greatly extends the wind range of the sail and produces more constant thrust (lift), even in gusty wind conditions. In the wings that we have designed, the shape changes as a function of the airspeed and the angle of attack. The adaptive washout is produced through extension of the membrane and twisting of the framework, resulting in angle of attack changes along the length of the wing in response to air speed and overall angle of attack. For example, as the plane hits a head-on wind gust the airspeed suddenly increases. The increased airspeed causes a shape change in the wing which decreases the lifting efficiency, but because the airspeed in the gust is higher, the wing maintains nearly the same lift. Once the airspeed decreases, the wing recovers to the original configuration. If there is a decrease in the relative airspeed, the angle of attack increases and the wing becomes more efficient and near constant lift is restored. The net result is a wing that flies with exceptional smoothness, even in gusty wind conditions. The adaptive washout mechanism is subtle and must be tuned into the wings in order to work effectively. We have built hundreds of wing configurations and have been able to produce many wings with remarkably smooth flying characteristics. Figure 5 illustrates the flexible nature of our wing.

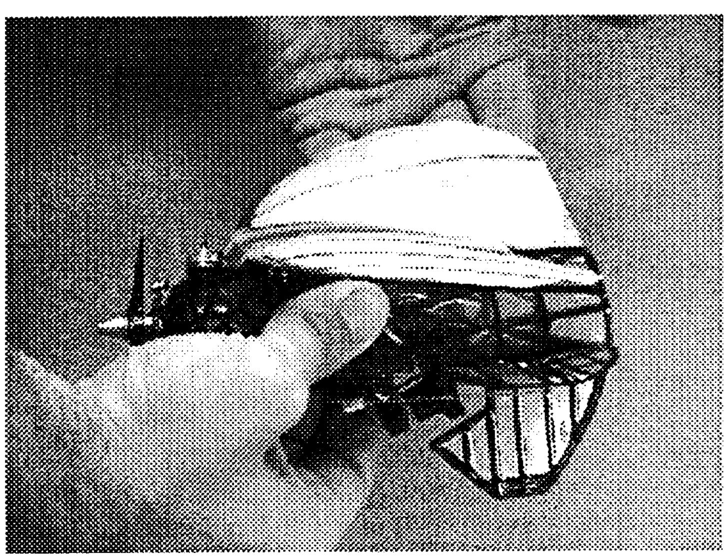


Fig. 5. The wings flex, even under small aerodynamic loads.

For aircraft with very small inertia, as in the case of MAVs, changes in wing loading can immediately affect the flight path. As the aircraft becomes smaller and lighter the need for suppressing the effects of wind gusts becomes more critical, especially if it is to be used as a camera platform. Additionally, as the airspeed of the vehicle decreases, wind gusts become a larger percentage of the mean airspeed of the vehicle. For example, our 6-inch aircraft flies between 15 and 35 mph. On a typical day the wind speed can vary by more than 10 mph. For rigid wings, the lift can easily vary by 50% or more over the short period of time during the gust. To make matters more critical, gusts are not always head-on. Since control of these aircraft is one of the most important hurdles, it is critical to suppress unwanted and sudden changes in direction, elevation and orientation.

In nature, birds and bats display a similar form of adaptive washout. This passive mechanism can be observed on windy days by large soaring birds. The feathers at the wing tips flair to accommodate sudden changes in airspeed. To some extent, our design approach has been biologically inspired. We have observed both birds and bats and have designed our wings to have similar characteristics.

3. MICRO AIR VEHICLE COMPETITION

In 1997 the University of Florida established and hosted the First International Micro Air Vehicle Competition. The objective was to fly the smallest aircraft (by maximum linear dimension) and demonstrate its capabilities by completing a nominal mission. There were two categories in the competition, surveillance and payload. In the surveillance category, the competitors were to return an image to the launch area of a 1.5-meter alphanumeric symbol surrounded by a 1-meter high wall that was placed on the ground 600 meters from the launch area. The aircraft needed to be flown through a video camera/transmitter, since the target was so far from the launch area. In the payload category the aircraft were required to carry a two-ounce block of aluminum for two minutes and land on the field. In the first two years of the competition, Steven Morris from MLB company won the surveillance competition. His smallest aircraft had a maximum dimension of 14.5 inches. In 1999 the University of Florida entered its first flexible wing aircraft. That year we won both the surveillance and payload categories using a 12-inch maximum dimension aircraft. In May 2000, the competition was hosted by Arizona State University at Fort Huachuca, Arizona at a field elevation of one mile. Once again, with designs that utilized the flexible wing concept, the University of Florida won both categories of the competition with a 10-inch aircraft in the surveillance competition and an 11-inch aircraft in the payload category.

In addition to MAVs intended for the competition, we have flight tested other MAVs that were as small as 5 inches. Our 6 inch MAV can be flown by an average RC pilot and can fly for more than five minutes, and is capable of aerobatic maneuvers including axial rolls, loops and hovering flight. We have also produced the worlds smallest aircraft (5-inch maximum dimension) built with off the shelf components and the world's smallest aircraft without active stability control.

4. COMPOSITE CONSTRUCTION METHODS

Thus far we have relied on an Edisonian approach to design our aircraft. No mathematical models would have lead to the development of our new concept. Our philosophy was simply to build many designs and flight-test them while carefully observing their flight characteristics. In order to use this approach we made some significant advances in the construction methods so that design iterations could be made quickly and each design could be thoroughly tested. *The construction methods developed for this project were the enabling technology that allowed us to implement our designs.* We make our airframes using unidirectional carbon fiber prepreg, Kevlar thread, and tough mono-film materials. Most of the materials are integrated and vacuum bag cured all at once. Each aircraft can be designed, built and ready to fly within five man-hours. The resulting MAVs are nearly indestructible (since they have no landing gear this is a must), yet are lighter than the conventional balsa wood counterpart. Each design is flight-tested and evaluated by the pilots and observers for flight characteristics including stability of flight, payload capacity and maneuverability.

The following step-by-step construction techniques used to fabricate a MAV fuselage and wing are described here.

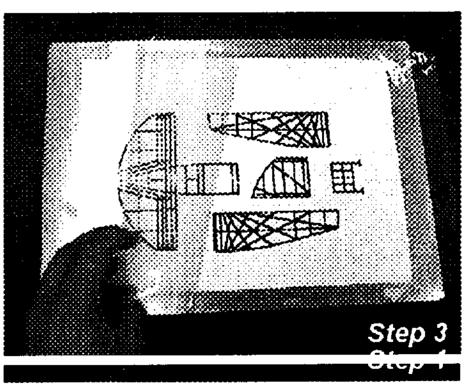
4.1 Fuselage Construction

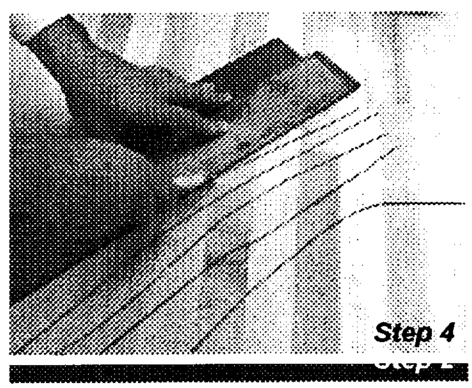
Step 1. A drawing is made of the fuselage panels to act as a guide for placement of the carbon fiber

Step 2. The drawing is taped onto the flat tool.

Step 3. Transparent skin material (Vacuum bag material) is then placed over the drawing

Step 4. Unidirectional carbon fiber tape is cut into long narrow tacky strips.



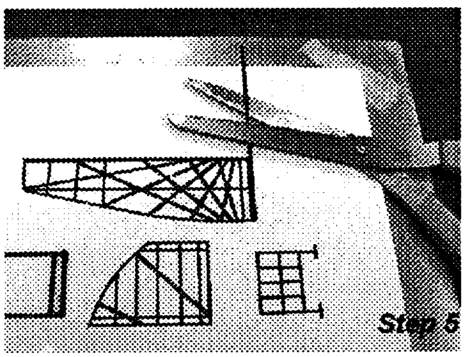


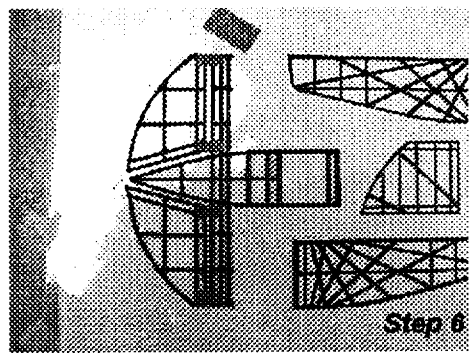
Step 5. The carbon fiber strips are placed on the transparent skin material manually using the drawing as a guide or by automated process. Multiple layers are used in places where high stiffness is required. Overlap at the corners assures a mechanically sound joint.

Step 6. Hinge material is placed between layers of carbon fiber at the location of the control surfaces.

Step 7. Nonporous Teflon release film is then placed over the assembly.

Step 8. The assembly is then placed into a vacuum bag and subsequently into a vacuum oven for cure.


Step 5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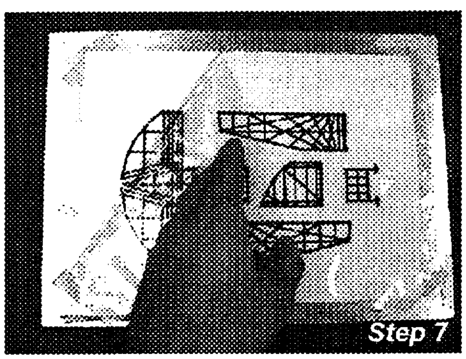
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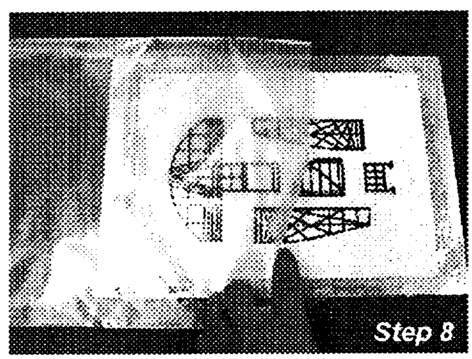
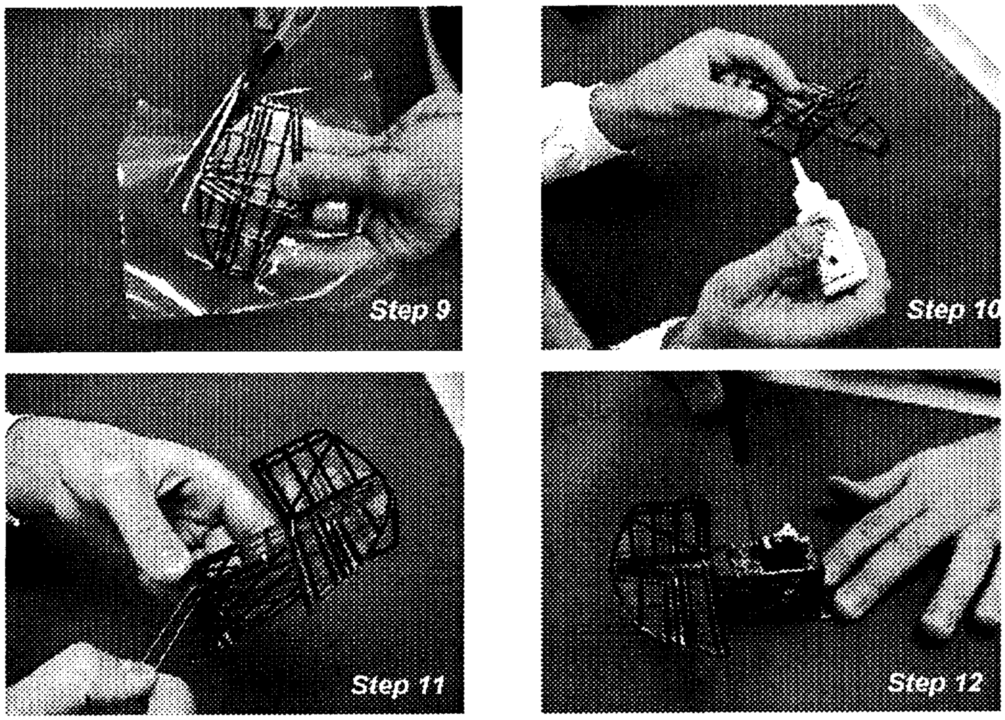

Step 8

Step 9. After the cure cycle is complete, the parts are removed from the bag. The fuselage panels are then cut out.

Step 10. The parts are glued together with cyanoacrylate adhesive.

Step 11. Kevlar thread is used to lash the parts together. Without lashing, the glue joints would fail.

Step 12. The motor, servos, receiver, control rods and horns are installed.



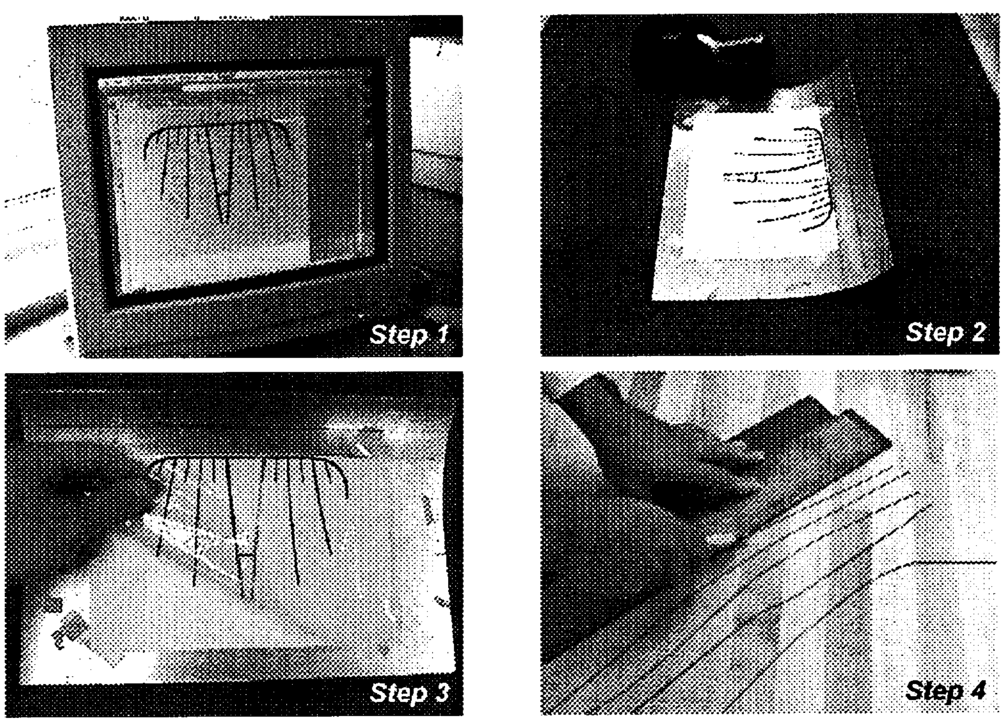
4.2 Wing Construction

Step 1. A drawing is made of the wing planform to act as a guide for carbon fiber placement.

Step 2. The drawing is taped onto a curved tool.

Step 4. A layer of nonporous Teflon release film is placed over the drawing.

Step 4. Unidirectional carbon fiber tape is cut into long narrow tacky strips.

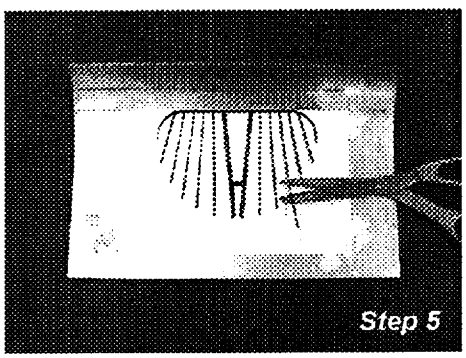


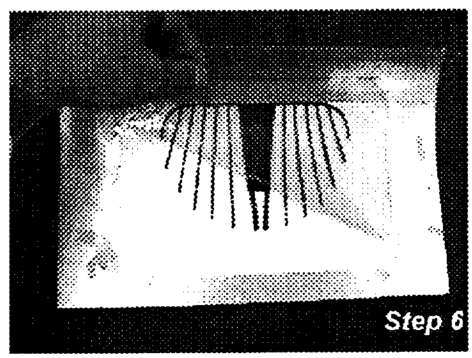
Step 5. The carbon fiber strips are placed on the release film using the drawing as a guide. Multiple layers are used in places where high stiffness is required. Overlap at the corners assures a mechanically sound joint.

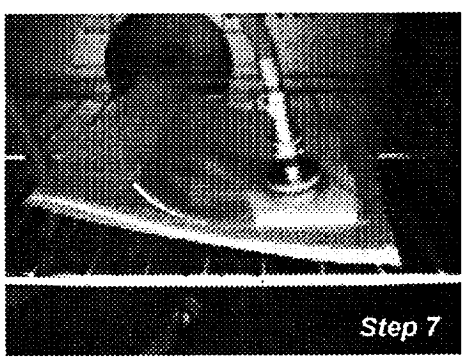
Step 6. Nonporous Teflon release film is then placed over the assembly.

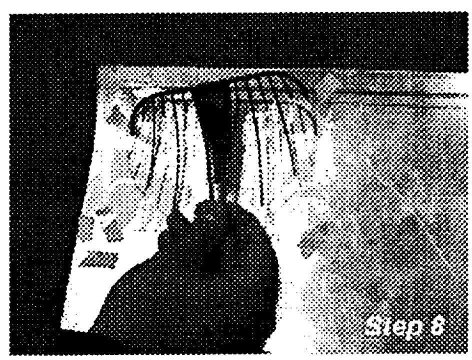
Step 7. The assembly is then placed into a vacuum bag and subsequently into a vacuum oven for cure.

Step 8. After the cure cycle is complete, the carbon fiber wing skeleton in separated from the tool.







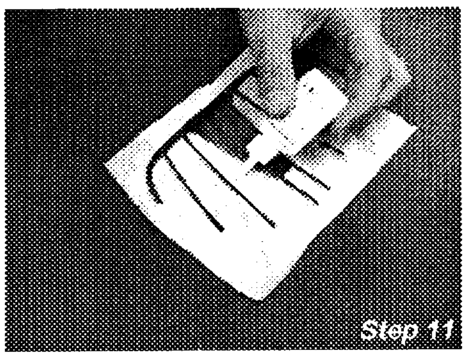


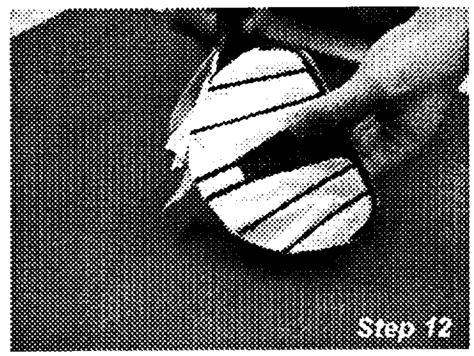
Step 9. Spray mount adhesive is applied to the skeleton.

Step 10. Thin latex rubber material is then applied to the wing.

Step 11. Cyanoacrylate adhesive is used to reinforce the bond line.

Step 12. Excess latex rubber is trimmed away.





CONCLUSION

A novel design for Micro Air Vehicles (MAVs) has been developed at the University of Florida. The design has been proven successful, winning both the 1999 and 2000 International MAV competitions sponsored by the National Science Foundation and Lockheed Martin. Above all, lightweight construction was required of this process since wing loading issues are critical on the MAV scale. Other considerations for creating the process were speed of fabrication to allow for rapid iteration of prototypes, durability to allow for thorough flight testing without down time for repair, and flexibility to facilitate the investigation of our flexible wing concept. The key technology that allowed us to meet all of these requirements was the use of carbon fiber composite materials. Using this process, an entire flight vehicle can be constructed in only 5 man-hours. Currently, these vehicles are made using only off the shelf components (electronics, servos, motor, batteries, etc.). The smallest of these vehicles which has been successfully flight tested to date has a maximum dimension of 5 inches and can be flown by an average hobby R/C pilot. The flexible wing has been shown to exhibit excellent control characteristics to help overcome the problems associated with the magnitude of wind gusts on the MAV scale. It has also been shown to exhibit reduced susceptibility to flow separation at higher angles of attack. The construction techniques using carbon fiber composites were the enabling technology that led to the successful development of these vehicles.

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