

*ARMY RESEARCH LABORATORY*



## **Lighter-Than-Air and Pressurized Structures Technology for Unmanned Aerial Vehicles (UAVs)**

**by Harris Edge, Jason Collins, Ainsmar Brown, Michael Coatney,  
Beatrice Roget, Nathan Slegers, and Arthur Johnson**

**ARL-TR-5068**

**January 2010**

## **NOTICES**

### **Disclaimers**

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

# **Army Research Laboratory**

Aberdeen Proving Ground, MD 21005

---

---

**ARL-TR-5068**

**January 2010**

---

## **Lighter-Than-Air and Pressurized Structures Technology for Unmanned Aerial Vehicles (UAVs)**

**Harris Edge, Jason Collins, Ainsmar Brown, Michael Coatney,  
Beatrice Roget, Nathan Slegers, and Arthur Johnson  
Vehicle Technology Directorate, ARL**

## REPORT DOCUMENTATION PAGE

*Form Approved*  
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

**PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

<b>1. REPORT DATE (DD-MM-YYYY)</b> January 2010		<b>2. REPORT TYPE</b> DRI		<b>3. DATES COVERED (From - To)</b> October 2008–September 2009	
<b>4. TITLE AND SUBTITLE</b> Lighter-Than-Air and Pressurized Structures Technology for Unmanned Aerial Vehicles (UAVs)				<b>5a. CONTRACT NUMBER</b>	
				<b>5b. GRANT NUMBER</b>	
				<b>5c. PROGRAM ELEMENT NUMBER</b>	
<b>6. AUTHOR(S)</b> Harris Edge, Jason Collins, Ainsmar Brown, Michael Coatney, Beatrice Roget, Nathan Slegers, and Arthur Johnson				<b>5d. PROJECT NUMBER</b>	
				<b>5e. TASK NUMBER</b>	
				<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> U.S. Army Research Laboratory ATTN: RDRL-VTU Aberdeen Proving Ground, MD 21005				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>  ARL-TR-5068	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b>	
				<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>	
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b> Approved for public release; distribution unlimited.					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> Several areas of unmanned aerial vehicle (UAV) performance need to be improved for the next generation of UAVs to be used successfully in expanded future combat roles. This report describes the initial research to improve the performance of UAVs through lighter-than-air or pressurized structures-based (PSB) technologies. Basically, we examined how to construct the UAV in such a way that a considerable percentage of its weight will be supported by or composed of inflatable structures containing air or helium. In this way, PSB technology will reduce the amount of energy required to keep the UAV aloft, thus allowing the use of smaller, slower, and quieter motors. Using PSB technology in tandem with improving technologies in electronics, energy storage, and materials should provide a substantial increase over current UAV performance in areas of need to the military.					
<b>15. SUBJECT TERMS</b> Unmanned aerial vehicle, UAV, lighter than air, pressurized structure, hybrid vehicle					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>  UU	<b>18. NUMBER OF PAGES</b>  30	<b>19a. NAME OF RESPONSIBLE PERSON</b> Harris Edge
<b>a. REPORT</b> Unclassified	<b>b. ABSTRACT</b> Unclassified	<b>c. THIS PAGE</b> Unclassified			<b>19b. TELEPHONE NUMBER (Include area code)</b> (410) 278-4317

Standard Form 298 (Rev. 8/98)  
Prescribed by ANSI Std. Z39.18

---

## Contents

---

<b>List of Figures</b>	<b>iv</b>
<b>List of Tables</b>	<b>iv</b>
<b>1. Objective</b>	<b>1</b>
<b>2. Approach</b>	<b>1</b>
2.1 Introduction .....	1
2.2 Current UAV Pressurized Structures Research.....	2
2.3 Pressurized Structures Component Technologies .....	3
2.4 Materials and Manufacturing Technology .....	4
2.5 Propulsion for Pressurized Structures Vehicles .....	8
2.6 Integration of New Technologies for UAVs .....	11
2.7 Pressurized Structures UAV Concept .....	12
<b>3. Results</b>	<b>16</b>
3.1 Demonstration Vehicle Design .....	16
3.2 Demonstration Vehicle Control.....	18
<b>4. Conclusions</b>	<b>19</b>
<b>5. References</b>	<b>20</b>
<b>6. Transitions</b>	<b>21</b>
<b>List of Symbols, Abbreviations, and Acronyms</b>	<b>22</b>
<b>Distribution List</b>	<b>23</b>

---

## List of Figures

---

Figure 1. UAV with an inflatable wing. ....	2
Figure 2. High length-to-diameter (L/D) ratio envelope. ....	2
Figure 3. Festo AG Air ray with flapping wings. ....	2
Figure 4. Various pressurized structure concepts. ....	3
Figure 5. Material weight versus area. ....	5
Figure 6. Propulsion test stand drawing. ....	9
Figure 7. Response of test stand to impulse. ....	9
Figure 8. Propulsion hover performance with and without a duct. ....	10
Figure 9. Duct study physical characteristics. ....	10
Figure 10. Pressure contour examples for select ducts. ....	11
Figure 11. Software and algorithms for PSB UAVs. ....	12
Figure 12. PSB UAV concept vehicle. ....	12
Figure 13. UAV with three motor nacelles. ....	14
Figure 14. X-Plane simulation data for vehicle motors. ....	16
Figure 15. Quadrotor research vehicle. ....	17
Figure 16. One of two autopilot components. ....	18
Figure 17. Motor and thrust vectoring mechanism. ....	19

---

## List of Tables

---

Table 1. Results for specimens cut along the length of a roll of Cuben Fiber. ....	7
Table 2. Results for specimens cut along the width of a roll of Cuben Fiber. ....	7
Table 3. Computational data for ellipsoid envelopes. ....	13

---

## 1. Objective

---

The goals of this research are to investigate the various ways to employ pressurized structures-based (PSB) technology to improve unmanned aerial vehicle (UAV) performance, and build the capability to design, simulate, and quantify the benefits of PSB UAVs. The increase in performance should be measured by the increased capability of the UAV to perform missions of interest to the military. It should be noted that the use of PSB technology alone will not be sufficient to bring about increased UAV mission capability. To realize the benefits of pressurized structures, new materials, technologies, and techniques will need to be employed. For example, the UAV may be made lighter and partially buoyant by PSB technology, but without corresponding changes and/or improvements in the propulsion system to take advantage of the PSB airframe, it may still produce too much noise to allow the vehicle to be used for missions requiring stealth. Thus, this research includes investigations into all phases of aircraft design, materials, propulsion, control, and mission planning algorithms, etc., to bring about increased UAV performance.

---

## 2. Approach

---

### 2.1 Introduction

The current primary role for UAVs is reconnaissance, which is basically positioning sensors to obtain information. The UAV flown is likely to be a fixed-wing aircraft. Fixed-wing aircraft are currently the most efficient form of commercial off-the-shelf (COTS) UAVs. They provide the best current compromise between endurance, speed, and payload. As a reconnaissance and sensors platform, current fixed-wing aircraft can perform the basic tasks of following global positioning system (GPS) waypoints while obtaining video in an open area. However, this basic task can be performed with greater proficiency and stealth by vehicles with flight characteristics that can be provided by PSB technologies. PSB technology may provide vehicles capable of quiet and efficient hovering and slow forward flight with precision maneuvering. Basically, the UAV will be constructed in such a way that a considerable percentage of its weight will be supported by or composed of inflatable structures containing air or helium. PSB technology will reduce the amount of energy required to keep the UAV aloft, thus allowing the use of smaller, slower, and quieter motors. Using PSB technology in tandem with improving technologies in electronics, energy storage, and materials should provide a substantial increase over current UAV performance in areas of need to the military. Little experimental data exists for moderately sized UAVs constructed from pressurized structures. Thus, the first step is to build a predictive and design capability for such vehicles. This report documents this initial effort.

## 2.2 Current UAV Pressurized Structures Research

PSB UAVs may take a number of forms. This report discusses medium-sized UAVs with critical dimensions of ~10 ft; however, PSB technology can be applied to micro UAVs and larger UAVs. Pressurized structures can be used to augment or improve current UAV designs. Used in this way, pressurized structures can be used to replace components of UAVs. For example, the wings and fuselage of common UAV designs may be replaced with pressurized structures. An example of this is shown in figure 1 in which the wings of an aircraft are made from an inflatable frame. This type of approach is expected to improve the performance of UAVs slightly. It could also improve the portability of the UAV and possibly make assembly easier. Furthermore, it could reduce the cost of the UAV if the manufacturing techniques and materials are widely adapted. Greater increases in UAV performance may also be achieved through efficient and novel designs that take full advantage of the newer lightweight materials and buoyancy. Examples of such vehicles are shown in figures 2 and 3.



Figure 1. UAV with an inflatable wing.



Figure 2. High length-to-diameter (L/D) ratio envelope.



Figure 3. Festo AG Air ray with flapping wings.

These examples demonstrate a few of the different approaches that may be used to construct a vehicle with pressurized structures:

- *Replacement of Conventional Aircraft Components with Pressurized Structures* (figure 1): There are working examples produced by ILC Dover, which has performed much research on inflatable wings (*I*). Some key benefits of inflatable wings are increased portability and stowage and high acceleration survivability from a gun tube launch. ILC Dover has also performed research to vary the aspect ratio and camber of inflatable wings.
- *High Length-to-Diameter (L/D) Ratio Envelopes* (figure 2): Working examples of this form of vehicle have been produced by Hyperblimp. The keys to this design are its low drag and near-neutral buoyancy, which allow the vehicle to fly and maintain position using very little power. The vehicles are required to have a fairly high length in order to develop enough buoyancy for lift and payload. When there is little wind and the power is turned off, the vehicle descends very slowly. The vehicle produces lift for flight by slightly pitching the nose up. Hyperblimp vehicles are very good examples of the type of flight dynamics being sought for PSB UAVs.
- *Morphing Pressurized Structures* (figure 3): Working examples of this form of vehicle have been demonstrated by Festo AG. The pictured vehicle also operates at near-neutral buoyancy. Propulsion is provided by the “flapping” or “swimming” motion of fuselage appendages. Aerodynamic control is provided by changing or warping component shape. The morphing mechanisms can be servos, shape memory wire, electro-active polymers, pressurized gas, etc.

### 2.3 Pressurized Structures Component Technologies

Pressurized structure is a generalized term that describes an inflatable UAV component. There are many examples of pressurized structures used in aircraft. The blimp is the most obvious example. There are also examples of inflatable fixed-wing UAVs. Hybrid concepts have been proposed in which a blimp-like, helium-filled envelope is attached to a frame with helicopter rotors to perform heavy lift projects. Figure 4 shows PSB technology concepts that are under consideration for UAV construction.

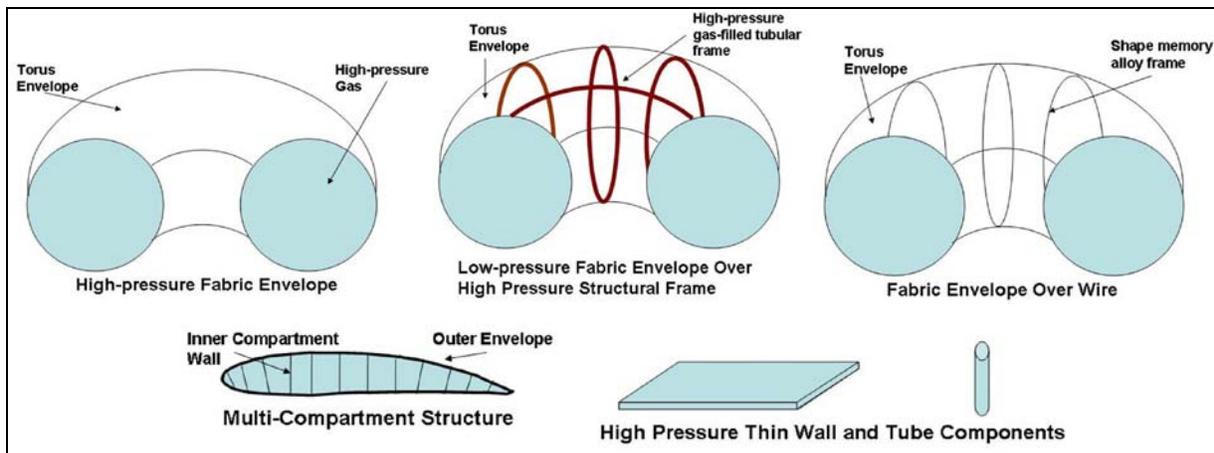


Figure 4. Various pressurized structure concepts.

Different types of UAV designs will require different types of pressurized structure solutions. For UAVs designed for moderate scale and cost, the high-pressure fabric envelope and fabric envelope over wire seem to be the most promising near-term solutions. The use of a high-pressure gas structural frame seems to be a promising means to build large, lightweight UAVs. Pressurized structures may be used to build conventional types of airframes, using an inflatable structure instead of materials such as foam and carbon fiber. For example, ILC Dover has produced UAVs with inflatable wings, which are beneficial in terms of storage and the wings' ability to change shape with variable camber (*I*). Software has been written to support this research to model the behavior of inflated beams constructed from thin fabrics. This software has not yet been validated for the current materials under consideration. However, this work was done in cooperation with Natick Soldier Research Development & Engineering Center (NSRDEC) and is based upon previous successful research in large-scale inflatable structures applications. Inflatable structures testing will be performed to validate the structural models.

## 2.4 Materials and Manufacturing Technology

Although there have been previous attempts and concepts using pressurized structures, there have not been many outdoor small-to-medium UAV designs. Aerostats are the most popular form of pressurized structures for military use, used primarily in persistent surveillance. One of the initial goals of this research is to develop inexpensive, moderately sized UAVs with critical dimensions of 10 ft (3 m) or smaller. Until fairly recently, it was difficult to realize the reduced weight benefits offered by pressurized structures for vehicles at this scale. One of the key reasons for that is materials technology. Today, one of the best current COTS solutions for durable envelope material is ripstop nylon infused with or bonded to a helium barrier, which is usually urethane based. Depending upon factors such as inflation pressure, cruise altitude, structural requirements, etc., ripstop nylon material weighs  $\sim 2.2\text{--}5$  oz/yd<sup>2</sup> (74.6–169.55 g/m<sup>2</sup>). This contrasts with some of the newer material candidates for envelopes such as Cuben Fiber\*, which weighs  $\sim 0.7\text{--}0.85$  oz/yd<sup>2</sup> (23.7–28.8 g/m<sup>2</sup>). To appreciate the potential weight savings, we compare the weight of an envelope made from nylon versus one composed of Cuben Fiber. A UAV with critical dimensions of 10 ft uses on the order of 100 ft<sup>2</sup> (9.3 m<sup>2</sup>) of envelope material. Figure 5 depicts the comparable weight savings of various materials. Notably, the weight savings of Cuben Fiber for this size of vehicle would be  $\sim 17\text{--}46$  oz (473–1309 g). Given that Cuben Fiber has strength comparable to Kevlar†, it may have a number of applications within a pressurized structure.

---

\* Cuben Fiber is a registered trademark of Cuben Fiber Corporation.

† Kevlar is a registered trademark of DuPont.

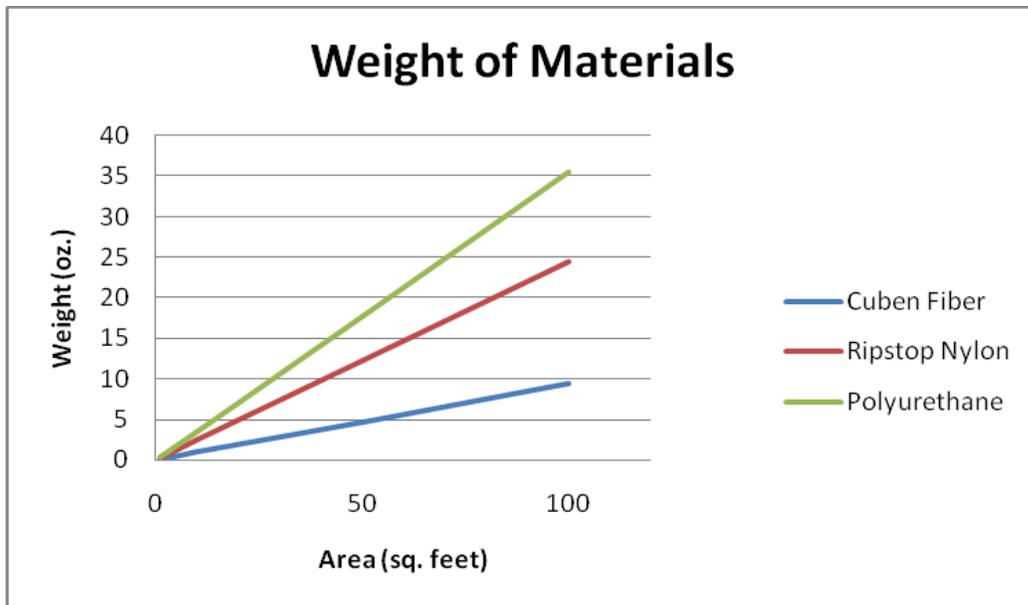


Figure 5. Material weight versus area.

Cuben Fiber is a form of ultra-high molecular weight polyethylene (UHMWPE) and is produced by Cubic Tech Corp. While very light and very strong, UHMWPE-based fabrics require special techniques to form air-tight, if not helium-tight, seals. In addition, there are some proposed designs that may require high pressure seals, and it is difficult to make a seal that is comparable to the strength and low weight of Cuben Fiber.

A large effort was made to ensure that fabrics such as Cuben Fiber could be used to manufacture PSB airframes. For vehicles with critical dimensions under 10 ft in length, the combined characteristics of weight and strength in UHMWPE-based fabrics are required to have high percentages of buoyancy. Cubic Tech helped to ensure that the manufacturing techniques would be available to produce a moderately sized UAV with a high percentage of buoyancy; however, some of these techniques have recently been developed and are considered proprietary. Cubic Tech can produce Cuben Fiber in any number of thicknesses and in different fiber orientations. Cuben Fiber is primarily used as sails for racing sail boats, but it has been used in a number of applications from kites to armor. Cuben Fiber alone is somewhat porous to helium. When made into a thin fabric, Cuben Fiber requires the application of a helium barrier. Cubic Tech is currently developing helium barriers. The helium barrier for the material purchased for the research used in this report was a metalized film.

In addition to making custom-designed UHMWPE-based fabrics, Cubic Tech also specializes in constructing items from Cuben Fiber-based products. There is a point during the Cuben Fiber manufacturing process when the fabric may be formed into a three-dimensional shape. This allows the vehicle to be formed with relatively few seams, a design which keeps the added weight from the seams and adhesives low and allows the strength of the fuselage to be roughly

the strength of the Cuben Fiber material, which is exceptional. The opportunity for a reduced number of seams also allows for the possibility of very smooth aerodynamic fuselage construction.

The primary difficulty in establishing the viability of an aircraft composed of Cuben Fiber is making sure that the seam strength is comparable to the material strength. Four methods have been identified as being viable choices for producing quality seams:

1. Adhesives can be used to produce a seam with Cuben Fiber with varying degrees of success. Thus far, there have only been two adhesives found that provide adequate strength for prototype fuselage fabrication. The two adhesives are of the same formulation, one standard thickness and the other thin, Bondit B45TH and B45, respectively. Further, the two adhesives should be used together to form a seam. The standard formulation should be used to glue one surface of the Cuben Fiber to another, and then a thin coat of the thin formulation should be applied over the juncture as a preventative measure to resist peeling.
2. One of the standard methods for producing Cuben Fiber seams is to use ultrasonic bonding or welding, combined with a specially designed adhesive. This is the method commonly used to produce sails. Time and funding did not allow proper testing of this option. This method works well for making sails, which require a much thicker fabric material than what would be used for the initial small UAV designs. The thin gauge material required for light UAVs, along with the requirement for an air or helium gas impermeable barrier, means that the industry standard equipment would need to be calibrated for this use. Industry-standard equipment costs ~\$20,000. While lower-end ultrasonic welders cost on the order of \$5,000, there is no guarantee that the welding process would not damage the thin gauge material and that it would be compatible with an impermeable gas barrier. We anticipate that a custom-calibrated ultrasonic welder would work for some seams.
3. Laser-enhanced bonding has been demonstrated to work on Cuben Fiber. This technology was developed under the Small Business Innovative Research (SBIR) program with NSRDEC. The SBIR funding was for developing gas impermeable seams for chemical-biological suits. In this method a laser, along with a small amount of specially formulated adhesive, is used to fuse a seam. A specially designed machine was developed for this bonding method and it was demonstrated to work on a number of difficult-to-bond materials. The company that developed the equipment, Ten Bar Ranch LLC, is unlikely to be funded for continued development under the NSRDEC SBIR program. Another source for this bonding technique has not been found.
4. Plasma treatment of UHMWPE-based materials may provide better adhesion properties. Researchers at the U.S. Army Research Laboratory (ARL), Aberdeen Proving Ground, MD, Dr. Daphne Pappas and Dr. Andres Bujanda, have been modifying the surface properties of materials by exposing them to plasma. Limited exposure to plasma should allow better surface bonding properties with little change to the bulk material properties.

Recently, they have applied this process to Dyneema and Cuben Fiber. This research is currently underway. The early results appear promising, but many future experiments will be needed to verify the benefits of this approach.

In addition, Cubic Tech has experience constructing items from Cuben Fiber that require seams. Currently, their procedure for producing seams in thin gauge fabric is considered proprietary, which implies that Cubic Tech would need to produce the manufactured item.

Tests are underway on the material properties for Cuben Fiber and structures composed of Cuben Fiber. Tables 1 and 2 show data for tests performed at North Carolina A & T State University for this research (2). The data are for a sample of Cuben Fiber that has a metalized helium barrier. The fiber orientation is orthogonal and runs parallel and perpendicular to the length of the roll; Cubic Tech can provide fabric with fibers in different orientations. The samples for this test were 1 in wide.

Table 1. Results for specimens cut along the length of a roll of Cuben Fiber.

<b>Specimen</b>	<b>Breaking Factor (lb/in)</b>	<b>Percent Elongation at Break (%)</b>
Metalized-length-1	90.55	4.57
Metalized-length-2	111.02	4.51
Metalized-length-3	110.24	4.64
Metalized-length-4	113.93	4.64
Metalized-length-5	112.41	4.21
Average	107.63	4.51
Standard deviation	9.65	0.18

Table 2. Results for specimens cut along the width of a roll of Cuben Fiber.

<b>Specimen</b>	<b>Breaking Factor (lb/in)</b>	<b>Percent Elongation at Break (%)</b>
Metalized-width-1	111.81	4.67
Metalized-width-2	125.95	4.61
Metalized-width-3	105.42	4.57
Metalized-width-4	106.35	4.47
Metalized-width-5	110.17	4.51
Average	111.94	4.57
Standard deviation	8.26	0.08

Most tests show promising physical characteristics for Cuben Fiber. The thin sheets of Cuben Fiber may be tightly compressed and will still maintain their strength, indicating that if properly designed, an inflatable UAV would have a low volume when deflated. There is still a question of whether a helium barrier fused to the Cuben Fiber would maintain its integrity when tightly

folded. There is some indication that creep would take place in Cuben Fiber if inflation pressures were too high. These results, along with the results of future experiments, will be used to validate software that will be written to predict the performance of inflated structures.

Overall, the newer class of UHMWPE-based materials in their many forms, Dyneema, Spectra, Cuben Fiber, etc., has the strength and weight properties required for building UAVs with PSB technologies. Also, construction using such structures can allow a high percentage of buoyancy for vehicles of < 8 ft in critical length. The primary obstacle to using pressurized structures made with UHMWPE-based materials (and materials with similar properties) to construct UAVs appears to be developing manufacturing techniques and new vehicle designs that can take advantage of the material's properties.

## **2.5 Propulsion for Pressurized Structures Vehicles**

It was decided early on that the vehicles designed should have the ability to hover and perform short/vertical takeoff and landing (SVTOL). In addition, the vehicle propulsion system should be made as efficient and quiet as possible. In terms of basic vehicle design philosophy for VTOL and hovering aircraft, the propulsion systems can be classified as being centrally located, like a ducted fan UAV, or distributed or pod-based, like a quadrotor. Each type of propulsion system has its merits and some aircraft designs may have elements of both. Both of these types of propulsion systems will be investigated for their use in PSB UAVs.

The initial tests for the propulsion controls were made with an ARL-funded microcontroller-based autopilot. A test stand was built with two propulsion pods mounted in a similar manner to the UAV model developed for X-Plane. The autopilot was mounted on the test stand such that it shared the angular orientation of the motors. Each motor drove a variable pitch propeller. The autopilot was able to control both the motor speed and propeller pitch to control the roll angle of the test stand using a simple proportional-derivative controller. Figures 6 and 7 show the test stand and a graph showing the propulsion system returning the roll to 0 after several impulses have been imparted to the test stand (3). Although the variable pitch propellers allowed for quick precise control of attitude, at some motor speeds, it only generated 50% of the thrust of a similar diameter fixed-pitch propeller. The COTS variable-pitch propeller was designed for acrobatic performance, not efficiency. The tests were successful, but it showed that, in order to maximize efficiency, custom-designed propellers or ducted fans would be needed. We anticipate that, for the precision maneuvering that will be attempted, a more complex control algorithm, such as model-predictive control, will be used (4). This type of control has also been previously used with the autopilot. The precise control afforded by this type of propulsion can be used by vehicles with larger surface areas to maintain tight tolerances of attitude, which can translate into efficient use of body-lift aerodynamics to contribute to low-energy hover flight.

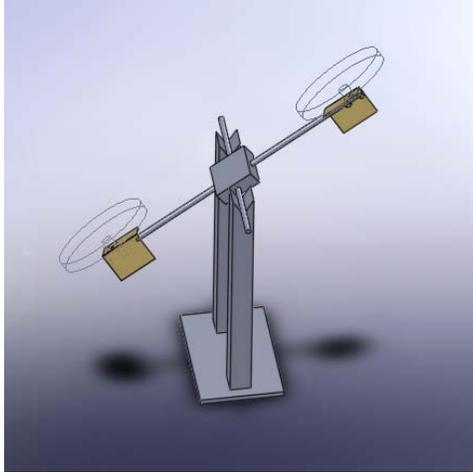


Figure 6. Propulsion test stand drawing.

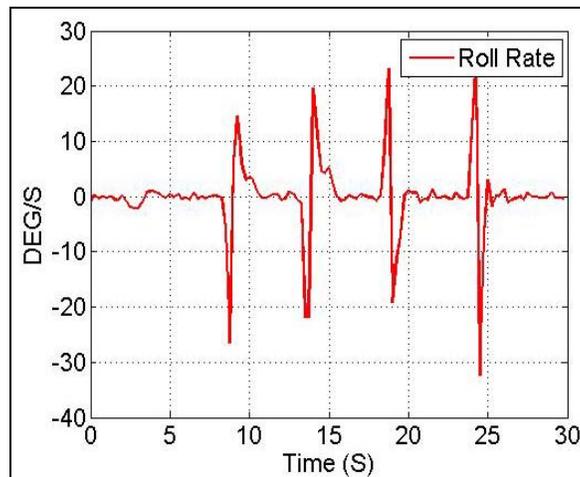


Figure 7. Response of test stand to impulse.

In an attempt to find a quieter, more efficient propulsion system for pressurized structures vehicles, a study was performed to find the benefits of using ducted fans. In general, a well-designed shroud or fan duct improves the performance of a propeller (5). However, as with other areas of aircraft design for smaller UAVs, there is little experimental data for the size of aircraft under consideration for the initial PSB aircraft designs. There are also a number of tradeoffs that must be considered for this propulsion system. One of the goals of this research is to reduce the noise generated by UAVs. One way to reduce the noise is to reduce the power expended for flight. The tradeoff for the type of duct used for this scale of vehicle is whether the added mass of the duct is worth the increased efficiency of the propulsion system. The advantage of a PSB fuselage is that if the duct or shroud can be integrated or formed from a pressurized structure, the added weight penalty should be quite small. Figure 8 is from a study by Roget that demonstrates the potential benefits of using a well-designed duct with a propeller (6). The data presented in

figure 8 are for a hovering rotor 0.6 ft in radius with a varied solidity of 0.05 to 0.3, and a collective angle varying from 5° to 30°. The data demonstrate that for a given input power, the ducted rotor provides more thrust.

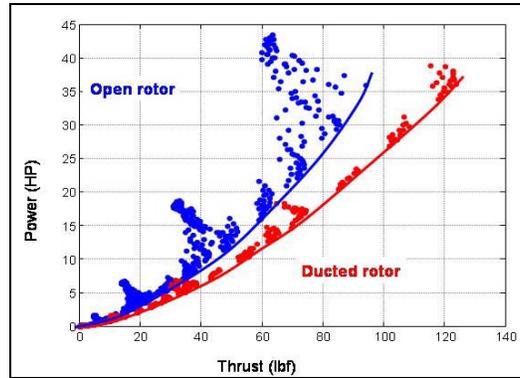


Figure 8. Propulsion hover performance with and without a duct.

As stated previously, the duct must be well designed in order to realize increased efficiency. A parametric study was performed to give an indication of the duct traits required to optimize propulsion performance for a PSB vehicle. Figure 9, from the Roget study, depicts the parameters of the duct study. The shapes of the investigated ducts range from a rotor diameter of  $R = 30$  in to a duct length ratio of  $0.2 \times$  the diameter to  $2 \times$  the diameter. Figure 10 shows examples of computed flow fields of different duct lengths and shapes. The Roget study indicates that excessive duct lengths incur an efficiency penalty due to viscous drag. To ensure a moderate performance increase, the duct should be short in length, with a divergent shape. The diffuser angle does affect performance. Performance increases as the diffuser angle increases from  $0^\circ$  to  $10^\circ$ . There does not appear to be improvement beyond  $10^\circ$  of divergence in the diffuser angle. It is anticipated that experiments will be performed to obtain data and provide validation of these results for smaller ducted fans.

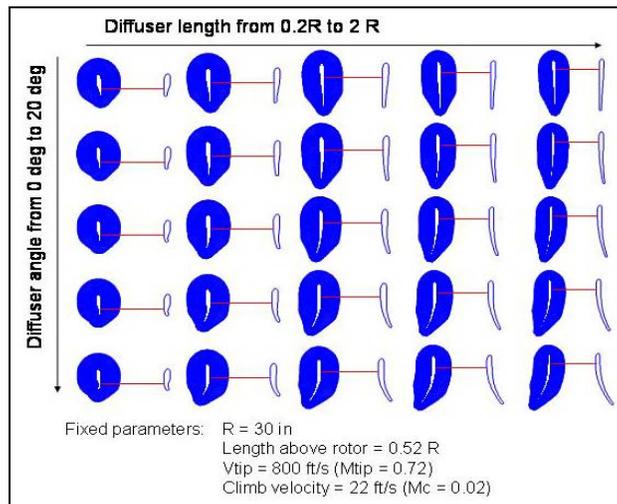


Figure 9. Duct study physical characteristics.

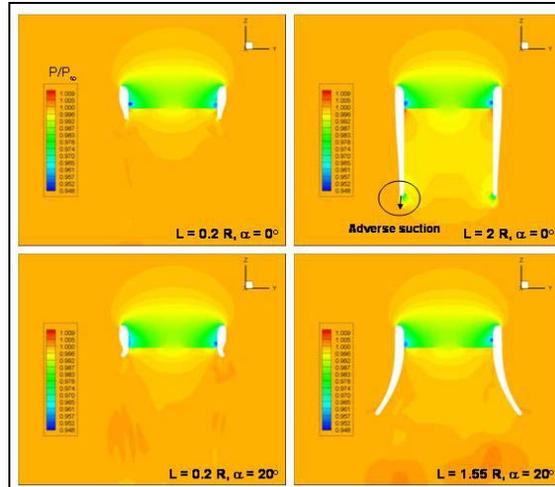


Figure 10. Pressure contour examples for select ducts.

## 2.6 Integration of New Technologies for UAVs

As stated previously, it will take a number of new and/or improved technologies in combination with the PSB airframe to produce a UAV that will increase mission capability. For example, solar cells may be used to augment power. Aircraft that have low drag and high-percentage buoyancy may be able to stay aloft during daylight hours using a combination of solar energy, high-efficiency batteries and/or fuel-cells, and effective energy-management algorithms.

Although today's autopilots may be quite small, they are often designed to control typical radio-control components. Future autopilots are likely to be smaller. However, for a PSB UAV, the size of the autopilot may not be the primary factor when it comes to weight; it may be the wires connecting the autopilot and batteries to the UAV aerodynamic controls, propulsion system, and sensors. One way to overcome this is to use a distributed autopilot that is placed in strategic areas of the UAV and operates equipment in its vicinity. UAVs that are required to stay aloft for only an hour or two do not require the software and control algorithms of a vehicle that may operate for half a day in an urban environment. Thus, sensor-laden PSB UAVs designed to stay aloft for extended periods of time may have high computational requirements just to perform their mission. For example, algorithms such as optic flow may be required for navigation in urban environments. A number of higher-level algorithms will need to be developed to efficiently manage extended-duration PSB missions.

PSB UAVs may come in a number of forms. At this time, it is difficult to define a set of attributes for mid-sized PSB UAVs. Figures 11 and 12 depict some of the technologies that will be developed or integrated into the pressurized structures vehicle. A case-study vehicle, seen in figure 12, is a good practical model of a simple concept for extending the performance of UAVs with an envelope-on-frame design using lightweight envelopes composed of Cuben Fiber.

<p><b>Current Autopilot Control for Conventional UAV</b></p> <ul style="list-style-type: none"> <li>Stabilize aircraft</li> <li>Navigate through waypoint</li> <li>Monitor battery/fuel</li> <li>Monitor communications link</li> </ul> <p><b>Future Autopilot Control for PSB UAV</b></p> <ul style="list-style-type: none"> <li>Stabilize aircraft <ul style="list-style-type: none"> <li>-maximum efficiency for forward flight and hover</li> <li>-precision hover for targeting/observation (peek through window scenario)</li> <li>-transition between multiple flight modes</li> </ul> </li> <li>Navigate through waypoint <ul style="list-style-type: none"> <li>-planning for acoustic stealth</li> <li>-planning for visual stealth</li> <li>-thermal detection and soaring</li> </ul> </li> <li>Manage power <ul style="list-style-type: none"> <li>-solar battery recharging</li> <li>-“windmill” battery recharging</li> </ul> </li> <li>Monitor communications link <ul style="list-style-type: none"> <li>-persistent networking</li> </ul> </li> </ul>
--

Figure 11. Software and algorithms for PSB UAVs.

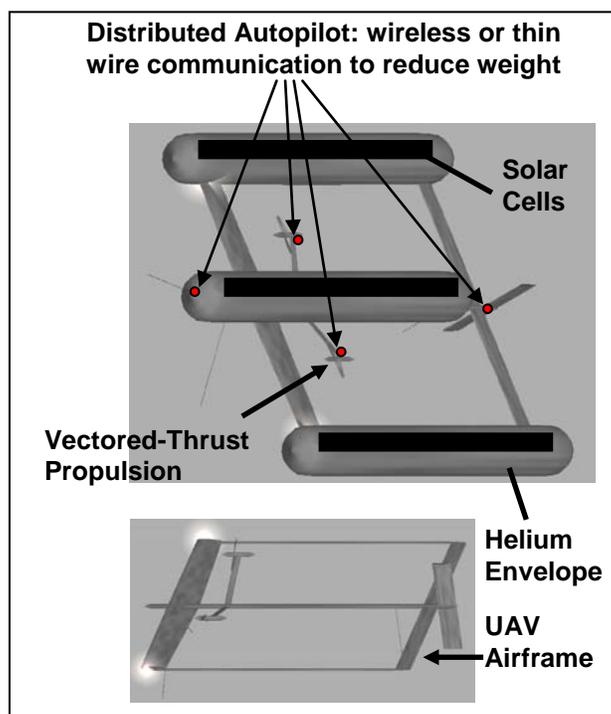


Figure 12. PSB UAV concept vehicle.

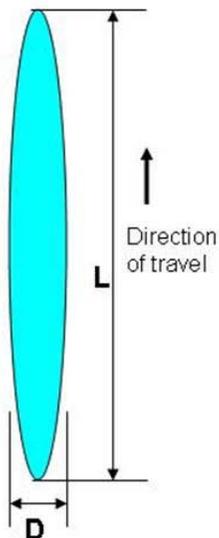
## 2.7 Pressurized Structures UAV Concept

The goals of this research are to investigate the various ways to employ PSB technology to improve UAV performance. The increase in performance should be measured by the increased capability of the UAV to perform missions of interest to the military. As previously noted, the

use of PSB technology alone will not be sufficient to produce increased UAV mission capability. In order to realize the benefits of pressurized structures, new materials, technologies, and techniques will need to be employed. For example, the UAV may be made lighter and partially buoyant by PSB technology. However, without corresponding changes and/or improvements in the propulsion system to take advantage of the PSB airframe, it may still produce too much noise to allow the vehicle to be used for missions requiring stealth. Thus, this research includes investigations into all phases of aircraft design, materials, propulsion, control, and mission planning algorithms, etc., to increase UAV performance.

There are significant tradeoffs required to make this approach work. One of the more important tradeoffs in designing lighter-than-air vehicles is buoyancy versus drag (7). To increase buoyancy, one must increase volume. For a given length, as one increases the volume of an envelope, one must increase the cross-sectional area and, thus, the drag. The drag determines key characteristics of the mission profile, vehicle speed, and power requirements. By looking at an analytical analysis of a common shape used for lighter-than-air vehicles, a body-of-revolution ellipsoid, one can readily see the relationship between volume, drag, and power to sustain flight. In addition, the relationship of power to noise gives an indication of the percentage of noise that can be reduced by using lighter pressurized structures. Table 3 is indicative of the characteristic values used in the design of a lighter-than-air envelope. This table shows computed values for a typical body-of-revolution ellipsoid with a characteristic length of 8.2 ft (2.5 m) within the current design specification.

Table 3. Computational data for ellipsoid envelopes.



L/D, L=8.2ft L=2.5m	Vol ft <sup>3</sup> (m <sup>3</sup> )	Cd (in direction of travel)	Lift lb (N)	Power hp
2	65.0 (2.05)	0.479	4.713 (20.97)	0.698
3	31.8 (0.90)	0.381	2.078 (9.24)	0.244
4	18.0 (0.51)	0.316	1.178 (5.24)	0.116
5	11.5 (0.33)	0.284	0.754 (3.35)	0.066
6	8.12 (0.23)	0.281	0.532 (2.37)	0.046

Within table 3 are computed values for envelopes of the same length (L), but varying diameters (D). Also included are values for computed volume, drag coefficient, lift or buoyancy if the envelopes were filled with helium, and the power that is required to move them through the air at

20 mph (32.2 kph) based on analytic solutions. The table was prepared to illustrate the tradeoffs applicable to a number of pressurized structure designs. The important item to note is that the drag coefficient for forward flight changes moderately. However, the power to maintain a steady velocity of 20 mph changes quite a bit between an L/D of 3 and 4. Another point to note is that the lift from buoyancy suffers for a high L/D. However, it can be partially recovered by the aerodynamic lift generated when the body is flown at small positive angles of attack (8). Further, table 3 shows the compromises that must be made to take advantage of buoyancy, while still maintaining reasonable speeds. It also indicates that an L/D greater than 5 would provide the best aerodynamics for power efficiency at 20-mph flight speeds. A patent was recently granted in 2007 for airships with L/D greater than 9 that exploit low drag. However, the lift from buoyancy is diminished for higher L/D. One compromise that may work for these types of envelopes is to use multiple envelopes.

Pressurized structures could be used in common aircraft design or be used in yet-to-be-imagined designs. For brevity, one concept of a PSB research vehicle is discussed. Figure 12 depicts a concept that tries to exploit the benefits of the simple high L/D envelope. It is a concept for a research aircraft that may be used to test a number of the ideas previously discussed.

The aircraft is an envelope-on-frame design. This means that there is a simple lightweight reconfigurable frame most likely constructed with a carbon fiber or plastic spine with wings, elevator, and rudder that supports one or multiple envelopes. In the future, the spine may be replaced with a high-pressure structure. For this concept research aircraft, it was determined that the frame should be capable of sustaining flight in the event of envelope failure. Models of the frame with and without envelopes were created and flown in the well-established X-Plane flight simulator to ensure they were stable in forward flight. A Federal Aviation Administration (FAA)-certified version of X-Plane is available in Meyer (9). These models, shown in figures 12 and 13, have wingspans of 8 ft (2.44 m), and each envelope has a length of 10 ft (3.05 m) and a diameter of 1.5 ft (0.46 m).

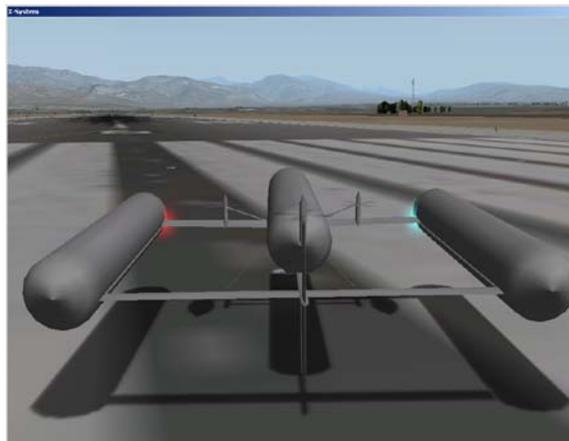


Figure 13. UAV with three motor nacelles.

This design is quite flexible in the manner it can be configured. It can be scaled up or down in dimension and maintain very similar flight characteristics. A number of different envelope shapes and construction types can be tested. The number of envelopes and propulsion devices may be varied as well. Furthermore, different types of propulsion systems may be adapted and attached to the frame or envelopes in different locations using different techniques.

The aircraft is currently modeled with variable pitch propellers on motor nacelles that can be rotated forward and aft. Unfortunately, X-Plane does not allow the nacelles to vector the thrust left or right. Roll control may still be performed by varying propeller pitch or motor speed between the left and right propulsion pods. (Currently, the propeller pitch and motor speeds for the left and right motors are identical.) With only two propellers mounted near the center of gravity, the aircraft is only marginally stable while hovering and does not hover well with the nacelles rotated upward and normal to the wind. It does exhibit very good slow forward speed flying qualities in simulation.

The X-Plane model is designed to be flexible and reconfigurable to test different energy management concepts for PSB aircraft such as solar power and wind energy recovery. For example, the envelopes provide sufficient area to mount enough solar cells to power the propulsion system. Solar cells from PowerFilm Inc. were tested for compatibility with potential power components. It was not anticipated that the solar cells would generate a lot of heat. Under full sunlight, the solar cells can reach over 140 °F, which forces special design considerations for the envelopes. A method may be found to use the heat to aid vehicle efficiency. The PowerFilm solar cells provide 3.04 W/ft<sup>2</sup> (32.72 W/m<sup>2</sup>). If 10 ft<sup>2</sup> (0.929 m<sup>2</sup>) of surface area for solar cells were placed on each envelope, then 304 W of power could be generated.

PowerFilm offers a version of its solar cells for radio-control aircraft. They weigh approximately 1.16 oz/ft<sup>2</sup> (35.53 g/m<sup>2</sup>), making the total weight of the solar cells 34.8 oz (986.58 g). The solar cells produce significant power, but they also weigh quite a bit. More solar cells could be added to the wings if more power were required. However, data from X-Plane simulations indicate that, for the envelope-on-frame design, 260 W of power are required for sustained speeds of 25 mph (40.2 kph). Depending upon the mission, this design should be capable of long-endurance flights during daylight hours.

Different variations of the vehicles can be produced to test different concepts. For instance, the version of the envelope-on-frame vehicle with three motors (figure 13) proved to be more stable during hover. Figure 14 showed how the three motor speeds varied during a climb to 200 ft. This provides beneficial information about the controls and energy usage for comparison of concepts. Although a three-motor version can provide the capability for hovering, it would require additional modifications for extended flight duration, such as larger helium envelopes.

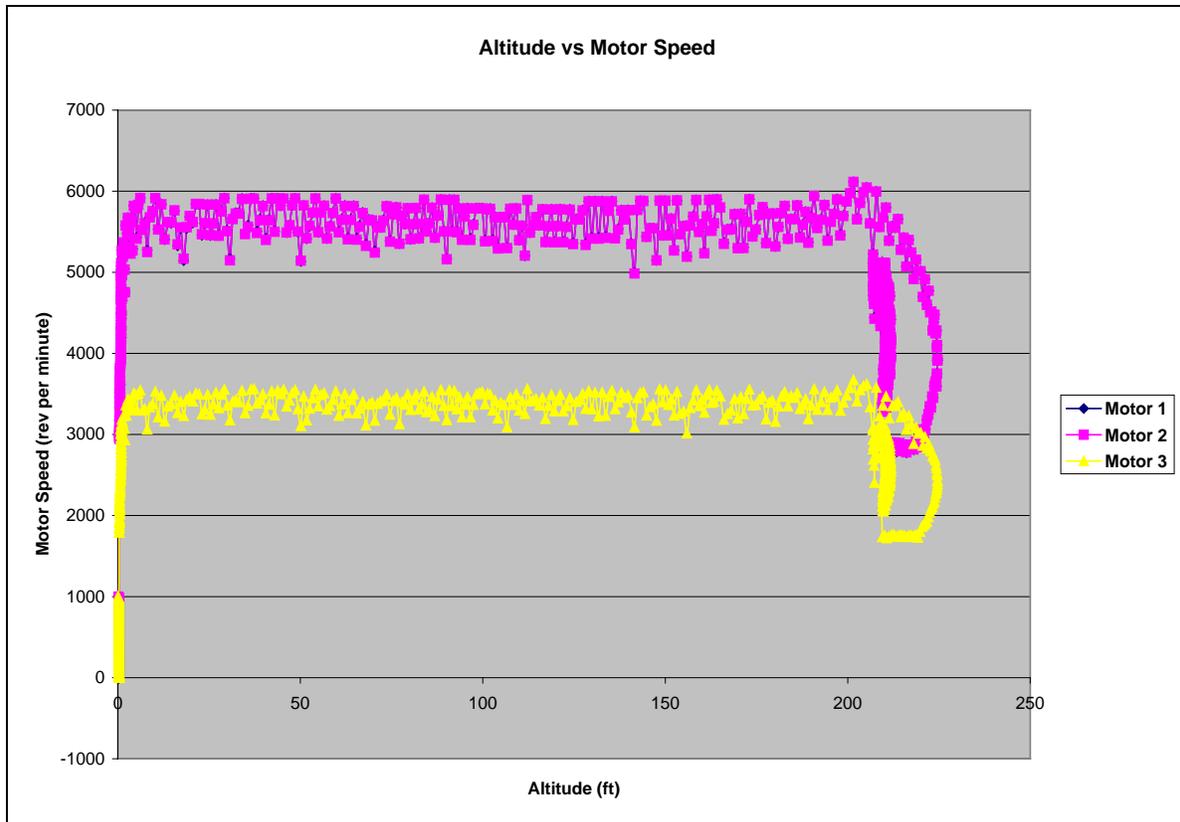


Figure 14. X-Plane simulation data for vehicle motors.

---

### 3. Results

#### 3.1 Demonstration Vehicle Design

After gathering data, information, and software tools for vehicle design, some vehicle configurations emerged as likely candidates for testing manufacturing, design, propulsion, and control concepts. There was only enough time to build one. The design that was built was an octagonal envelope-based quadrotor (figure 15). There were a number of reasons for choosing this design. First, since this research was on lighter-than-air technologies, a design was chosen that would maximize buoyancy—saucer shapes are one of the most volumetrically efficient shapes. In addition, the octagonal helium envelope was relatively easy to manufacture. The envelope was built in-house so modern envelope building techniques were not used. The envelope should not be inflated much higher than slightly above atmospheric pressure. The quadrotor configuration allowed the testing of the propulsion pod concept. This design also allowed the testing of vectored thrust control.

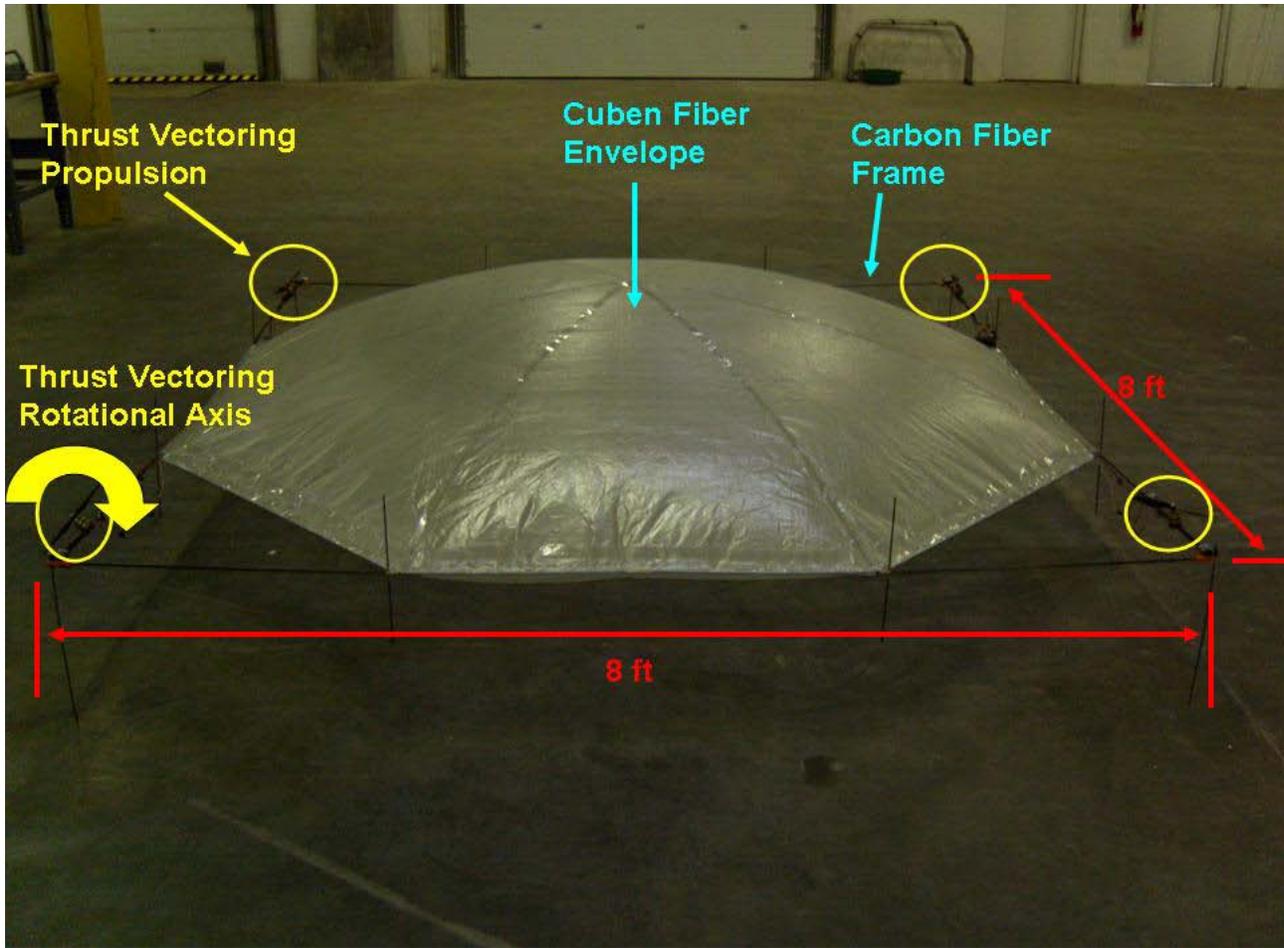


Figure 15. Quadrotor research vehicle.

One of the benefits of using pressurized structures is that they can serve as the backbone or hub of a vehicle structure while being nearly weightless. When the helium envelope is inflated and no batteries are mounted, the vehicle is buoyant and can float. The current design weighed 2.95 lb without batteries and helium. The vehicle weighed 3.70 lb with batteries and without helium. When the vehicle had batteries mounted and the envelope was inflated with helium, it weighed 6 oz. The vehicle was 8 ft long and 8 ft wide, and the envelope was 2 ft in depth. The vehicle produced much more thrust than was required. The four motors can produce ~6 lb of thrust using the current batteries. Thus, the vehicle could be made lighter by reducing the motor size and/or reducing the number of motors. For the initial tests, having excess thrust was preferred. The vehicle's lightweight construction could be attributed to the integration of the frame with the envelope and the envelope being constructed from Cuben Fiber. The envelope essentially had a sleeve that surrounds its perimeter that allowed carbon fiber rods to be inserted. The individual carbon fiber rods were held together around the perimeter by hollow brass

connectors. The carbon fiber tubes were thin and hollow; however, once the envelope was inflated, the tension supplied by the envelope helped to stiffen the carbon fiber frame, and in return, the carbon fiber tubes provided a structure that kept the envelope shape consistent.

### 3.2 Demonstration Vehicle Control

The quadrotor design also presented an opportunity to test the distributed autopilot concept. For this vehicle two microcontroller-based autopilot modules were used to control the aircraft. One of the modules is shown in figure 16. The autopilot modules communicated through Bluetooth transceivers. Each autopilot module controlled two of the four motors and two of the four servos, which allowed the wiring to be much shorter and the battery weight to be distributed as well. The distributed autopilot was a further evolution of the current ARL-funded open-pilot architecture. The original autopilot was designed by Dr. Nathan Slegers of the University of Huntsville, AL. The modifications to produce a distributed autopilot were initiated by the requirements of this research.

The vehicle had eight control inputs. There were four motors and the throttle could be controlled on each motor independently. Also, each motor could be rotated about an axis to allow the propellers to be tilted from the vertical axis. A motor and thrust vectoring mechanism are shown in figure 17. The aircraft controls are still undergoing programming. Thus far, pitch, roll, and yaw stabilization have been demonstrated.

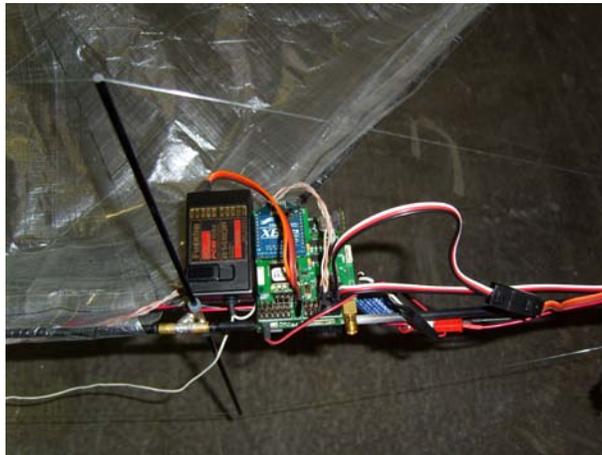


Figure 16. One of two autopilot components.

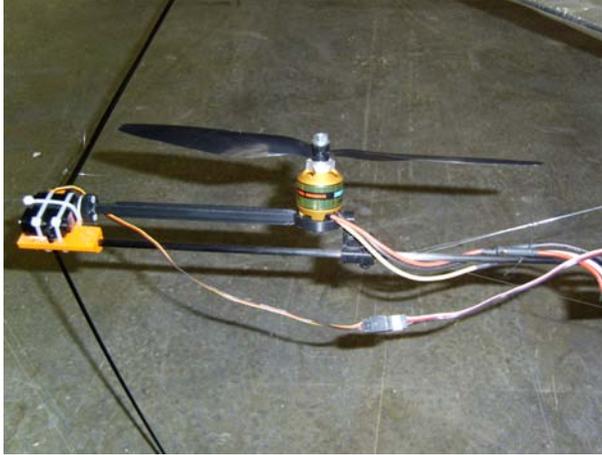


Figure 17. Motor and thrust vectoring mechanism.

---

## 4. Conclusions

---

This report showed initial research for applications of pressurized structures in UAVs. Pressurized structures have promise as a technology to extend the mission capabilities of future UAVs. A number of issues must be overcome, but newer materials and construction techniques, combined with current miniaturization of electronics and improving energy storage options, should allow new UAV designs that would be optimal sensor platforms for future military operations.

UHMWPE-based fabrics appear to be a very good option for producing PSB vehicles. While, it remains to be seen what the cost in terms of material and manufacturing effort would ultimately be for this type of vehicle, the weight and strength of these fabrics allow a substantial reduction in vehicle mass. The technology for manufacturing airframes composed of pressurized structures using UHMWPE-based fabrics exists, but it will require significant time and effort to perfect the technology and integrate it.

The current research aircraft that was constructed for this effort will be used to ascertain the benefits of buoyancy for mid-sized UAVs. It demonstrated the innovative use of modern lightweight fabrics to construct UAVs with a high percentage of buoyancy. Very little experimental data for buoyant vehicles of this size exist, thus, this work was an important milestone for this research. The vehicle will be used to validate the simulation tools that are being accumulated for pressurized structures research. The results of some of those simulations were presented in this report. With the experimental data provided herein and other upcoming pressurized structures research vehicles, a comprehensive study can be made of potential vehicle performance for a number of designs.

---

## 5. References

---

1. Cadogan, D.; Smith, T.; Uhelsky, F.; MacKusick, M. Morphing Inflatable Wing Development for Compact Package Unmanned Aerial Vehicles. *The 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Palm Springs, CA, April 2004, AIAA-2004-1807.
2. Skujins, J.; Shivakumar, K. *Tension Testing of Cuben Fiber Balloon Fabric: Metalized and Non-Metalized*; U.S. Army Research Laboratory external communication with North Carolina A&T University, Greensboro, NC, May 2009.
3. Edge, H.; Nixon, M.; Janas, A.; Ross, W.; Collins, J. Pressurized Structure Technology for UAVs. *Proceedings of the 2008 Army Science Conference*, Orlando FL, December 2008.
4. Slegers, N.; Kyle, J.; Costello, M. Nonlinear Model Predictive Control Technique for Unmanned Air Vehicles. *J. of Guidance Control and Dynamics* **2006**, 29 (5), 1179–1188, ISSN: 0731-5090.
5. Black, D.; Wainauski, H.; Rohrbach, C. Shrouded Propellers – A Comprehensive Performance Study. *The AIAA 5th Annual Meeting and Technical Display*, Philadelphia, PA, October, 1968, AIAA-68-994.
6. Roget, B. *Effect of Diffuser Design on Ducted Rotor Hover Performance*; U.S. Army Research Laboratory external communication with National Institute of Aeronautics, Langley, VA, June 2009.
7. Konstantinov, L. *The Basics of Gas and Heat Airship Theory*, Montgolfier, ed.; Aeroplast, Kyiv, Ukraine, 2003.
8. Costello, M. Extended Range of a Gun Launched Smart Projectile Using Canards. *9th Annual Gun Dynamics Symposium*, McLean, VA, November 1998.
9. Meyer, A. X-Plane Manual; <http://x-plane.com/contact.html> (accessed August 2007).

---

## **6. Transitions**

---

The Director's Research Initiative, "Lighter-Than-Air Technology for UAVs," is part of a Vehicle Test Directorate (VTD) mission program, called "Pressurized Structure for UAVs." It was determined that pressurized structures was a more suitable description that allowed for a broader range of research applications, such as parafoils for NSRDEC. The pressurized structures research is also part of a Technology Program Agreement (TPA) with NSRDEC. Under the TPA, NSRDEC will receive results from the pressurized structures program, and ARL will benefit from research and expertise at NSRDEC and have access to their experimental facilities.

---

## List of Symbols, Abbreviations, and Acronyms

---

ARL	U.S. Army Research Laboratory
COTS	commercial off-the-shelf
FAA	Federal Aviation Administration
GPS	global positioning system
L/D	length-to-diameter
NSRDEC	Natick Soldier Research Development & Engineering Center
PSB	pressurized structures-based
SBIR	Small Business Innovative Research
SVTOL	short/vertical takeoff and landing
UAV	unmanned aerial vehicle
UHMWPE	ultra-high molecular weight polyethylene

No. of Copies	Organization
1 ELEC	ADMNSTR DEFNS TECHL INFO CTR ATTN DTIC OCP 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1 CD	US ARMY RSRCH LAB ATTN RDRL CIM G T LANDFRIED BLDG 4600 ABERDEEN PROVING GROUND MD 21005-5066
3 CDS	US ARMY RSRCH LAB ATTN IMNE ALC HRR MAIL & RECORDS MGMT ATTN RDRL CIM L TECHL LIB ATTN RDRL CIM P TECHL PUB ADELPHI MD 20783-1197
10 HC <sub>s</sub>	US ARMY RSRCH LAB ATTN RDRL VT M NIXON ATTN RDRL VTM M COATNEY D LYE ATTN RDRL VTU H EDGE (3 COPIES) J COLLINS A BROWN S WILKERSON ABERDEEN PROVING GROUND MD 21005-5066

TOTAL: 15 (1 ELEC, 4 CD<sub>s</sub>, 10 HC<sub>s</sub> )

INTENTIONALLY LEFT BLANK.