TP13PUB53

Making the future. Together.

2013 TECHNICAL PAPER

2013 RTAM/SME DICK AUBIN DISTINGUISHED PAPER AWARD

VAST AUAV (Variable AirSpeed Telescoping Additive Unmanned Air Vehicle)[1]

authors
MICHAEL STERN and ELI COHEN
MIT Lincoln Laboratory
Lexington, MA

abstract
A low-cost, highly flexible and modular Variable AirSpeed Telescoping wing Additive manufactured Unmanned Aerial Vehicle (VAST AUAV) for atmospheric sensing is presented. A novel aerodynamic design was realized with a lightweight, efficient additive manufactured (AM) mechanical structure to meet performance requirements. The aerodynamic design features telescoping wings to permit both dash and loiter flight depending on the exposed wing area and airfoil. The aircraft structure was primarily fused deposition modeling (FDM) ABS-M30 with supplemental carbon fiber spars and commercial off the shelf (COTS) fasteners. The total weight of the aircraft was 7 lb (3.2 kg) with a maximum wingspan of 80 in. (2 m). The structure was designed to be easily assembled using only standard hand tools. The modular design permits rapid reconfiguration of the aircraft and the ability to swap payload while simplifying replacement of damaged parts, even in the field. Focus on frangible design prevents widespread damage and minimizes rebuild in the case of failure. Several test flights were completed demonstrating the structural integrity of the AM parts and the success of the overall design.

[1]This work is sponsored by the United States Air Force under Air Force contract number FA8721-05-C-0002. The opinions, interpretations, recommendations, and conclusions are those of the authors and are not necessarily endorsed by the United States Government.

terms
Unmanned aircraft, Aerial vehicle, Aerodynamic design, Modular design, Additive manufacturing, Fused deposition modeling

event
Rapid 2013 Conference and Exposition, Including 3D Imaging
SME
June 10-13, 2013
Pittsburgh, PA

SME
One SME Drive
Dearborn, MI 48128
313.425.3000
sme.org

VAST AUAV (Variable AirSpeed Telescoping Additive Unmanned Air Vehicle)[1]

Michael Stern and Eli Cohen

Abstract

We present a low cost, highly flexible and modular Variable AirSpeed Telescoping wing Additive manufactured Unmanned Aerial Vehicle (VAST AUAV) for atmospheric sensing. A novel aerodynamic design was realized with a lightweight, efficient additive manufactured (AM) mechanical structure to meet performance requirements. The aerodynamic design features telescoping wings to permit both dash and loiter flight depending on the exposed wing area and airfoil. The aircraft structure was primarily Fused Deposition Modeling (FDM) ABS-M30 with supplemental carbon fiber spars and Commercial off the Shelf (COTS) fasteners. The total weight of the aircraft was seven pounds with a maximum wingspan of 80”. We designed the structure to be easily assembled using only standard hand tools. The modular design permits rapid reconfiguration of the aircraft and the ability to swap payloads while simplifying replacement of damaged parts, even in the field. Focus on frangible design prevents widespread damage and minimizes rebuild in the case of failure. We completed several test flights demonstrating the structural integrity of the AM parts and the success of the overall design.

Introduction

Although additive manufacturing has been available for nearly three decades, it has been used almost exclusively as a tool for modeling and prototyping. However, in the last decade, the production of AM parts for end-use has become significant [1]. At the same time, consumer 3D printers have improved rapidly exciting the demand from hobbyists for functional printed parts. This shift in industrial use of AM combined with the emergence of consumer interest highlights the current transition of the technology: not only can AM continue to be used for rapid prototyping, but in some circumstances it can now also be used as a cost effective manufacturing technology.

The speed of development in AM has been impressive, particularly compared to recent innovation in the mature field of aircraft design. The timeline for manned aircraft development has slowed from a matter of months between concept and first flight in the 1940s to decades at

1 This work is sponsored by the Air Force under Air Force contract number FA8721-05-C-0002. The opinions, interpretations, recommendations, and conclusions are those of the authors and are not necessarily endorsed by the United States Government.

present; there is less tolerance for risk and only marginal improvement to be found using traditional design and fabrication techniques. Optimized aerodynamic structures are typically complex shapes, requiring skilled labor to fabricate. As a result, airplane designers have been constrained by manufacturing and fabricators have struggled to execute the more challenging airframe designs. The pressure to innovate without increasing risk led in part to the development of Unmanned Air Vehicles (UAVs). UAVs offer pilotless, smaller platforms with reduced cost and schedule. The US Army strategic plan for the next 25 years states that "aviation force mix shifts from being almost entirely manned to consisting of mostly unmanned and OPV (optionally piloted vehicle)" [2]. This shift in emphasis from piloted to unpiloted aircraft presents an opportunity for aircraft engineers to innovate substantially in airframe design and fabrication.

This paper explores a specific example in which AM technology was married with UAV development and final production. Two key parameters to minimize in UAV development are development time and airframe weight. Development time drives total cost, while airframe weight limits platform capabilities. These parameters align well with best practice utilization of AM where reductions in material use and production time are highly valued.

Variable Speed Weather Sensing AUAV

This project was developed to solve a weather sensing challenge: create a small UAV capable of performing both Lagrangian and Eulerian sampling within a cloud. Lagrangian sampling requires the aircraft to stay stationary with respect to the moving air mass while Eulerian sampling requires the aircraft to stay stationary with respect to a point above the ground. The challenge was put forth by a researcher at MIT's Earth, Atmospheric and Planetary Sciences Department who was interested in measuring sub-mesoscale weather phenomena. The objective was to have a single UAV fly slowly with the airflow, approximately 8 mph, to facilitate Lagrangian sampling and then transform to a high speed configuration flying against the airflow, at up to 75 mph, to facilitate Eulerian sampling.

Figure 1: VAST AUAV during flight testing.

An additional objective focused on the exploration of AM and modular design to provide rapid development of future payload-specific UAVs. Additive manufactured UAVs (AUAVs) provide an opportunity for quick, one-off airframe designs that permit flight-testing of specific payloads and missions without the burden of existing airframe limitations or integration constraints. Given the relative youth of both UAVs and AM, the intersecting AUAV field has only recently started to be explored. The VAST (Variable AirSpeed Telescoping Wing) AUAV project provided an opportunity to conduct research in this new area. The aircraft was flown successfully, as shown in Figure 1, demonstrating the performance of the design and the vehicles airworthiness.

Previous Additive Unmanned Air Vehicles (AUAVs)

The authors know of three additively manufactured unmanned fixed wing aircraft: SULSA from the University of Southampton in the UK, MUAV testbed from University of Malaysia Pahang, and "Wendy," from the University of Virginia. These three aircraft employ different manufacturing processes, as well as design methodologies.

The SULSA aircraft was produced by Selective Laser Sintering (SLS) in nylon and was printed in five major portions with no external fasteners required. The wings featured an internal stiffening structure and drainage holes to remove excess powder from the production process. Notably, SULSA features an elliptical wing, a design that, while aerodynamically very efficient, has been notoriously difficult to fabricate. By implementing modern AM processes, SULSA achieved a complex wing geometry with no added manufacturing overhead [3].

Both aircraft from the University of Malaysia aircraft and the "Wendy" aircraft from the University of Virginia were based on Commercial Off The Shelf (COTS) Remote Control (RC) aircraft design and fabricated using Fused Deposition Modeling (FDM). They both utilized traditional RC airplane construction techniques with 3D printed parts as replacements for those typically made from balsa or light plywood. A vinyl skin was applied by hand to the completed AM airframe skeleton [4][5].

In designing the VAST AUAV, we strove to utilize a combination of AM and COTS components to create an easily assembled high performance vehicle. Like "Wendy", VAST was fabricated using FDM, although the design approach, modularity, and internal structure differentiate the vehicles. While using a different AM technology from SULSA, we leveraged the printing process similarly to enable the final assembly of VAST without skilled labor.

Design for Additive Manufacturing (DFAM)

The application of AM to UAV design provided an opportunity to experiment with both the fabrication methodology and the design of the aircraft. The creation of an AUAV removes the challenge of fabrication, opening up the design space. Further, AM provides the designer with the freedom to prototype multiple iterations of an AUAV quickly without requiring substantial fabrication effort. These benefits enabled us to take greater mechanical, aerodynamic and AM fabrication risks in the development of the VAST AUAV.

Design Process

Whereas traditional manufacturing technologies require a shift between the prototype and production phases, AM provides a seamless transition from development to final fabrication. Effort invested during the prototype phase considering manufacturability, assembly, and analysis apply directly to the production parts, eliminating the need for additional design and testing to facilitate final production as shown in Figure 2.

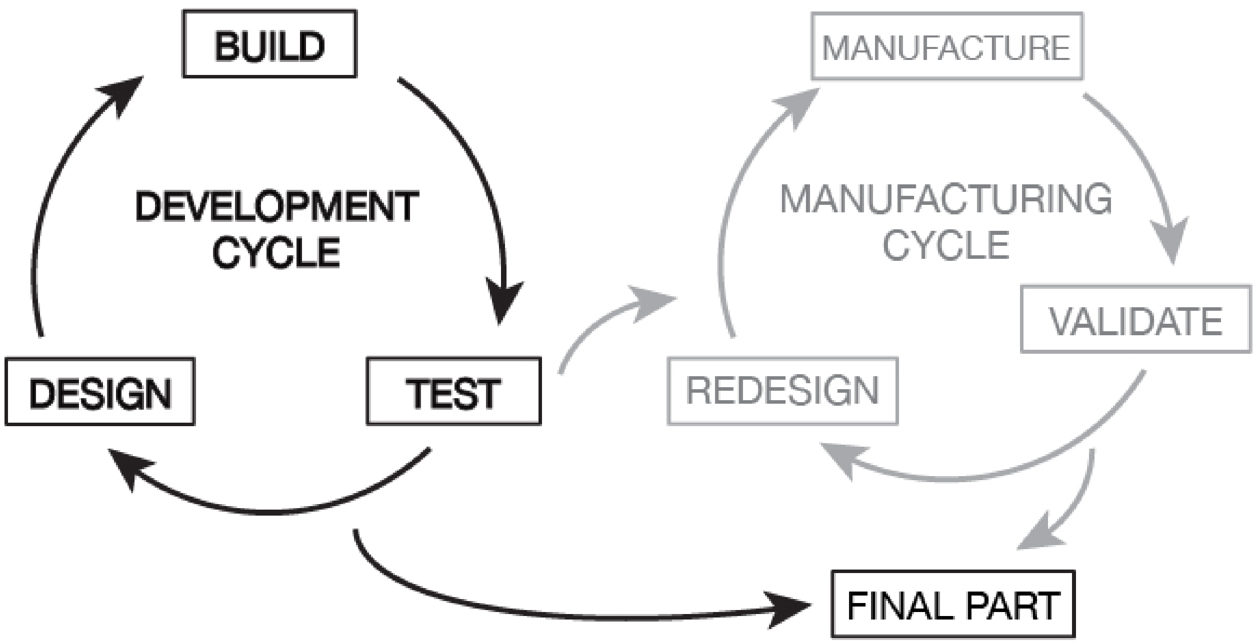

Figure 2: Design cycles for both AM and conventionally manufactured parts. AM requires only the development cycle while conventional manufacturing also requires a manufacturing cycle.

By reducing the barriers in the transition from prototype to production, AM enables an alternate design mentality in which engineers remain in the design phase longer, thus permitting greater system design flexibility.

The nature of AM encourages a change from the traditional serialized waterfall design process to an iterative spiral model. Similar to best practices in software development, a design can be built and tested in days or weeks, permitting several opportunities for improvements informed both by testing and by ongoing analysis results [6]. When a design is determined complete, the validated prototype instantly becomes the first production part.

Guidelines for Design

To design effectively for AM, engineers must be intimately aware of AM technology-specific constraints. Due to the youth of the technology and the diversity of the systems and software available, users must often experimentally determine many of the system constraints. The VAST AUAV was manufactured using the Stratasys 400MC in ABS-M30, which produces parts using FDM, a material extrusion process. Every AM technology has a number of associated design considerations. Here special focus is paid to FDM, although many of these following considerations apply to other processes as well:

Part Orientation

- The orientation of a part during the printing process impacts many of its final characteristics; the layer deposition process creates an inherent anisotropy in the part, which may adversely affect its strength properties.
- Depending on orientation, some features will require support material.
- At small scales, print orientation can affect figure error on shapes, such as circles.

Digital Design

- Every part has a resolution of a discrete size that is dictated by a physical constant, such the diameter of the extrusion nozzle.
- For small-scale or thin-walled parts, the overall dimensions of the piece can be only a small multiple of the extrusion bead width.
- The vertical build direction resolution is limited by the layer height.

Support Material Plan

- Support material is wasteful: it takes additional material and time to create and must be removed and thrown away after fabrication, requiring handing and processing time.
- The further above the build plane a supported feature is, the more detrimental, since support material propagates through the entire height of the print. High support often results in dramatically increases build times.
- Depending on geometry, support material may not be required to bridge small gaps. For example, a typically supported feature, such as a horizontal hole, may often be built support-free with only minor distortion.

Overhanging Structures

- The machine can create self-supporting overhangs up to a specific angle; in the case of our printer, this angle is roughly 45 degrees from the vertical axis.
- The part may be reoriented to eliminate problematic overhangs. Here, the tradeoff between the two potential configurations must be evaluated-- changes may not necessarily reduce support but instead shift it to another location, or the support may be reduced but the build may take longer.

Knowledge of these guidelines for AM was an integral part of the design process for the VAST AUAV. A strong understanding of the system constraints both allowed us to create advanced structures as well as reduce the build time of other parts drastically. The application and refinement of these guidelines was key element in the success of the VAST project.

Aircraft Design

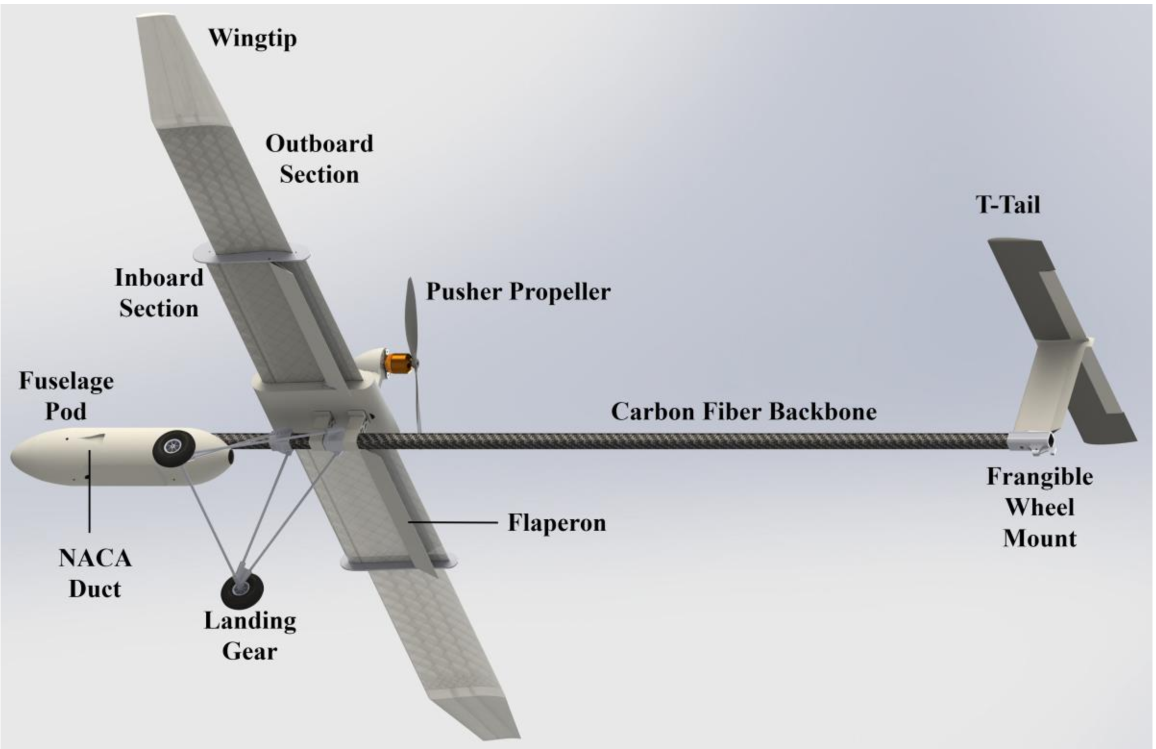

Figure 3: VAST AUAV rendering showing major components.

The aircraft consists of three major assembles, shown in Figure 3, all mounted to a central carbon fiber backbone. From fore to aft, these sections are the fuselage pod; the wings, including the propulsion system; and the tail.

Fuselage

The fuselage was a modular three-piece design: a nose cone, a center body of variable length, and a tail fairing. The midsection was sized to hold the battery pack, radio equipment, autopilot, and weather-sensing payload. Well defined interfaces between the three sections permitted rapid redesign and swap of any of the segments to accommodate new hardware. This configuration permitted changes in payload or an increase in battery pack size to be implemented without affecting the overall airframe design. AM capabilities allowed for the inclusion of a dimensionally accurate NACA inlet (low drag intake developed by the National Advisory Committee for Aeronautics) on each side of the fuselage to introduce cooling air into the battery compartment with minimal additional drag.

Wings and Propulsion

Aft of the fuselage, the wings are mounted above the carbon fiber backbone of the aircraft. To meet the loiter and dash performance requirements, the outboard section of the wings can retract inward or extend outward to vary the wing area and, proportionally, lift. Central to the wing assembly was the wingbox which serves to provide mounting features to connect the wings and the carbon backbone together, as well as house the wing extension system. The wing extension system was driven by a lead screw, which extends and retracts the outboard wing section along carbon fiber spars that are inserted during the assembly phase. The wingbox also serves as the mount for the motor and propeller. Unlike many conventional aircraft that feature the propeller on the front of the fuselage, a pusher configuration was chosen to provide unperturbed air to the sensor payload mounted in the fuselage. The high mounting of the motor was necessary for the propeller to clear the backbone without resorting to a twin-boom tail design, which would have added design complexity.

The wing sections were constrained to 16” in length; the greatest dimension in any of the primary axes of the Fortus 400MC. The initial aerodynamic design consisted of a half wing comprised of a 16” inboard section, a 16” outboard section, and a canted 9” wingtip section. This basic wing design was iteratively simulated with Computational Fluid Dynamics (CFD) tools to predict lift and drag over a range of operating conditions. The NACA 4-digit series of airfoils was searched for wing profiles that would meet the low- and high-speed requirements. Shown in Figure 4, the NACA 5415 was chosen for the inboard wing section and NACA 6608 was chosen for the outboard wing section.

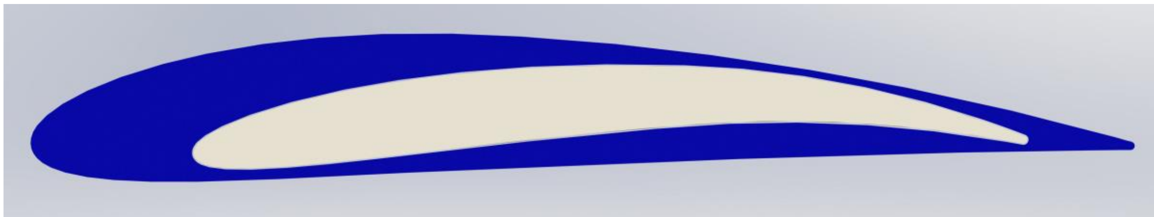

Figure 4: Cross sections of the NACA 5415 inboard section and NACA 6608 outboard section shown nested as occurs during the telescoping process.

In an effort to reduce design complexity, control surfaces were included only on the inboard section of the wings. This decision decoupled control surface actuation and wing telescoping. The nesting airfoils required for wing telescoping left insufficient room for conventional ailerons. Known as a flaperons, the inner flap sections were mounted on the lower surface of the wing. They were linked to an aileron input from the pilot and were activated in opposition to effect a roll as well as in unison to act as flaps.

Tail

The VAST AUAV featured a T-tail. In high angle of attack, slow flight, the deployed external flaps and discrete transition from the inboard wing section to the wingbox both generated a large wake of turbulent flow, as shown in Figure 5. To maintain tail authority, the elevator was mounted in a T-tail configuration atop the rudder, keeping it above the wake and in the energized flow from the high-mounted propeller. Although the T-tail is less efficient structurally than a conventional tail, it was critical to maintaining positive control authority given the flow conditions.

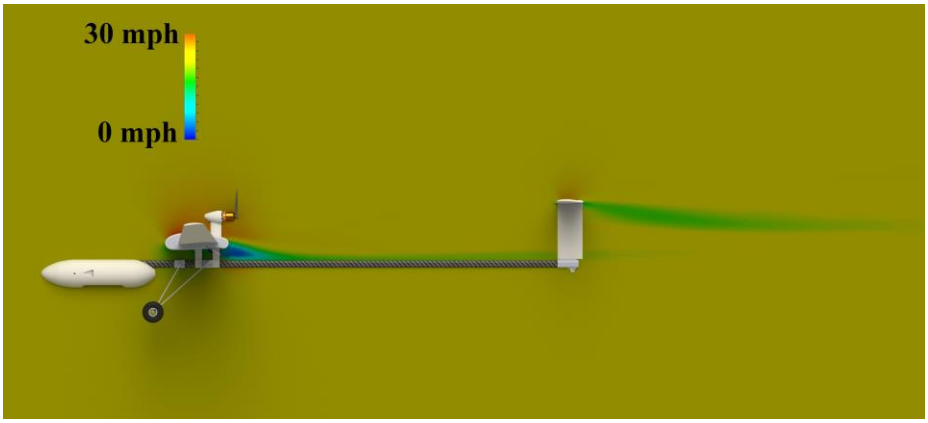

Figure 5: CFD calculation of airflow interaction between wings and tail during flight, airspeed represented by color.

The horizontal and vertical stabilizers were mounted far enough aft to provide adequate stability margin with the wings either retracted or extended. To compensate for the increased stability in high-speed flight, the control surfaces on the tail are oversized to allow for sufficient maneuverability.

Final Aircraft Specifications

The aerodynamic design of the VAST UAV was intrinsically linked to the fabrication technologies used in its creation. Maximum part size and achievable part weights directly drove the initial aircraft sizing and performance requirements. Final aircraft dimensions and specifications follow in Table 1.

Parameter	Value
Wing Span (Extended)	80 in
Wing Area (Extended)	503 in^2
Wing Span (Retracted)	56 in
Wing Area (Retracted)	366 in^2
Stall Speed (Extended)	7 mph
Maximum Speed (Retracted)	60 mph
Weight	7 lbs
Battery	2x 5400mAh 11.1v LiPo
Motor	AXI 2820/10 Brushless (300 W)
Endurance (Best Cruise)	1 hour

Table 1: VAST UAV specifications.

Modularity

The VAST AUAV featured a decoupled modular design, which greatly benefited the design process. The three major aircraft units, fuselage, wings, and tail, each consist of multiple subassemblies. This increased part count, as compared to a more integrated design, lowered initial manufacturing overhead as no one part, or prototype of a part, cost as much as printing an assembly. Because any part could be printed in less than 24 hours, greater design risks could be taken and every part could be treated as a learning opportunity. Furthermore, common interfaces between parts and within major systems allowed multiple designers to collaborate simultaneously on each major assembly.

The division of parts or assemblies into smaller modules positively impacted the fabrication process as well. For fabrication, the print orientation was varied between parts within the same assembly, reducing the amount of support needed, which in turn reduced build times. Additionally, the modular design was more conducive to integrating COTS components. Incorporating carbon fiber spars into the wing structure would have been more difficult in an integrated design with a monolithic wing and fewer access points.

Payload flexibility was also derived from the modular design of the VAST AUAV. Many small UAVs have very tight tolerances for weight and balance. Swapping payloads or reconfiguring battery packs frequently requires ballasting the aircraft to achieve the correct center of gravity. The separate structures of the VAST AUAV allowed for relative repositioning of the major assemblies along the body tube with no additional weight penalty, enabling great variability in payload size and weight.

Modularity accelerated the flight-testing phase of aircraft development. Initial flights demonstrated poor roll authority due to the inboard-mounted flaperons. Larger flaps were designed, printed, and integrated into the existing flap interface within days, allowing for quick follow-up flights. Other aerodynamic adjustments were also simple to implement, such as modifying the incidence and washout of the wings and wing tips.

Finally, by separating the aircraft into sub-modules, we were able to create a frangible design with specific failure zones such that only a subset of parts would need to be refabricated or replaced in the event of a crash. The landing gear was one such example. In the initial design, the tail gear was incorporated into the tail assembly. During the first landing, the tail gear connection failed, rendering the entire tail inoperable. Future designs incorporated a break point in the tail gear interface which permitted the tail gear to snap off in a hard landing, protecting the tail assembly and allowing new gear to be field-fitted.

Despite the many benefits to modularity described above, we encountered a number of drawbacks. Foremost, modularity comes at a price of performance: a more integrated design would likely be lighter and stiffer. Additionally, the AM footprint of a modular design, with more parts, exceeds that of an integrated design, necessitating a greater number of prints. Finally, assembling a modular design requires more touch labor than an integrated design.

The freedom to experiment and take greater risks was afforded by the modular design and contributed to the innovation and experimentation that was instrumental in the development of the VAST AUAV. Here, the benefits of the modular design outweigh the drawbacks.

Specific Examples from the VAST AUAV

To illustrate some of the design principles described in the design for additive manufacturing section, two components of the aircraft are described in more detail. These designs were created in an effort to develop efficient structures and served as learning tools for developing AM design guidelines.

Fuselage

The fuselage had the potential for efficient AM fabrication because, when oriented upright, it was a vertical cylinder with no overhanging areas. The wall thickness was minimized to reduce weight, but was limited by control software which required closed contours to be at least two beads thick. When printed at this limit, the thin-wall fuselage sections were at risk of buckling during handing and assembly. To address this, internal ribs were added to the cylindrical shell. The initial rib design had a traditional rectangular cross-section, which required support material and was therefore undesirable. The rib cross section was redesigned to utilize the 45-degree self-supporting angle, enabling it to be fabricated without support, as shown in Figure 6.

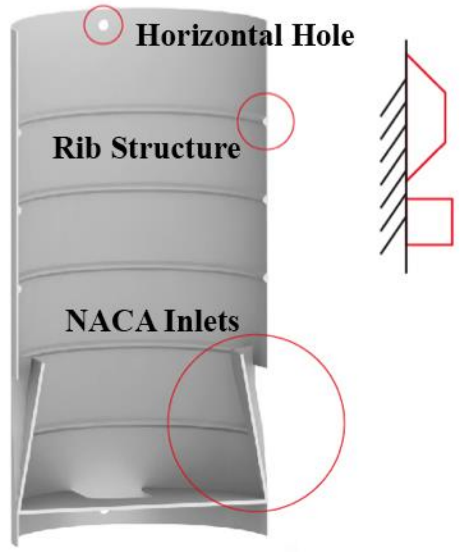

Figure 6: Left: photo rendering of fuselage cross section: from top to bottom, horizontal hole, internal rib, NACA duct. Right: self-supporting rib design and original rectangular rib profile requiring support.

The NACA duct in the fuselage required support material because the geometry of the duct was the priority. To keep the support to a minimum, the height of the NACA duct from the end of the fuselage was reduced. With the fuselage oriented duct end down, during the print all the support material was kept near the base. At the top of the fuselage during the build, there were two mounting holes that were perpendicular to the print direction. As these holes were small, 0.175" diameter, it was possible to let the material bridge the small gap with only minor distortion of the shape of the hole, again reducing the support.

These changes to the fuselage had a substantial effect, reducing the build time of the part from over fifteen hours to eight and a half. The modifications for manufacturing outlined above required few compromises while contributing to a lightweight and quick-printing part.

Cellular Wing Design

Figure 7: Outboard wing section, showing self-supporting angle and decreased cell size at top surface.

The cellular wing design internal structure incorporated into the VAST AUAV was based off of work done by Stratasys. Shown in Figure 7, it contained an internal fill consisting of closed-cell diamonds covered by a two bead thick skin. This pattern enabled the low density construction without requiring support material by keeping all overhanging structures to 45 degrees. To span the top area of the wing support-free, the cellular size was locally decreased, reducing the unsupported spans and enabling a bridging similar to the holes in the fuselage described above.

The vertical build orientation places airfoil cross-sections in-plane with the build eliminating any stepping error of the airfoil. Unfortunately, printing vertically introduces the potential for the wing to delaminate between layers when under bending loads. To compensate for this, the wing design included conventional spar materials. The printed wing section featured clearance holes printed for the spars. After the part was built, carbon fiber tubes were inserted. This composite wing design was lightweight, simple to assemble, and robust.

Spar and Skin Wing Design

In an effort to further reduce the wing weight, a lighter version was created where the cellular internal structure was removed, leaving only the passages for the spars with vertical ribs connecting them to the skin, as shown in Figure 8.

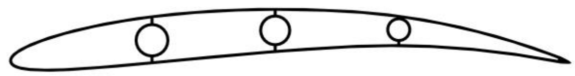

Figure 8: Rendering of the cross section of the spar and skin wing design.

This change cut the weight by approximately 20 percent, placing increased importance on the carbon fiber spars for strength. Unfortunately, wings of this type were less stiff and liable to distort in cross section between spars depending on the magnitude and location of applied loads. Therefore, the vehicle was fabricated with the heavier but more robust cellular design.

Wing Testing

Mechanical testing to failure was performed on multiple wings structures generated during this project. The two distinct internal geometries were compared to each other and to the Stratasys pre-programmed sparse fill as a control. For this comparison, five different variations of the wing design were tested: cellular wing with and without carbon reinforcement, spar and skin wing with and without reinforcement and sparse fill wing without reinforcement. Each wing was evaluated based on the print times, part weight, maximum load at failure.

To determine maximum load at failure, each outboard test wing section was placed into the end of an inboard wing section to restrain it as would be expected in flight. The outboard section was loaded at its midpoint, a simplification of flight aerodynamic forces. Weight was added gradually until the wing section failed. Table 2 lists the specifications and results for each sample wing section.

Internal Structure	Print Time (hr:mm)	Part Weight (lbs)	Max Load at Failure (lbs)	Strength-to-Weight (lbs/lbs)
Sparse Fill	16:49	0.53	36	68
Cellular Fill – Carbon Spars	13:31	0.29	32	110
Cellular Fill	13:31	0.26	18	72
Spar and Skin – Carbon Spars	8:33	0.24	27	120
Spar and Skin	8:33	0.20	13	63

Table 2: Comparison of performance for multiple wing designs.

From the results, it was seen that the three designs unsupported by carbon fiber reinforcement all had similar strength-to-weight ratios. Notably, the different internal wing geometries enabled the fabrication of far lighter structures than pre-programmed fills that came with Stratasys software. The addition of the carbon fiber reinforcing spars greatly enhanced the bending strength of the sample, providing an average increase of 90% in strength and 70% in the strength- to- weight ratio of the wings. These improvements in strength demonstrate the capability of carbon fiber spars to combat the anisotropy of the wings, as well as the potential for highly efficient composite structures by combining conventional and AM materials.

Conclusion

The VAST AUAV has made a number of advancements in AM UAV design. It was the first airplane constructed with material extrusion that requires no skilled labor to assemble. Successful flight testing of the airplane validated the aerodynamic performance of the vehicle. Additionally, the wing testing conducted showed the high strength-to-weight potential for AM parts and the enhanced strength that can be generated by combining conventional materials with AM. As additive manufacturing continues to advance, we expect that it will increasingly be used to prototype and fabricate UAVs, helping to enable a new category of custom, small-run AUAVs that can be parametrically modified to match a specific mission.

The VAST AUAV project has also served as an opportunity to investigate the considerations for design for additive manufacturing with a material extrusion FDM process. There has been an opportunity to highlight the benefits of a development process for AM end-use parts, where time spent on the prototype both through analysis and validation applies to the production level part as well. During this project, we have also had the opportunity to create a set of guidelines for designing with AM. These guidelines are applicable not only for the FDM AUAV construction here, but also over a wide range of systems and an even wider range of projects. Finally, this airplane serves as an example of constraints that exist in additive manufacturing and techniques that can be used to design efficiently within this space.

Acknowledgments

We would like to thank our whole team: Aaron Cusher, Caroline Lamb, Molly Gutcher, Kyle Oman, and Walter Zukowski. We would also like to thank the MIT Lincoln Laboratory Advanced Concepts Committee for providing the funding for this project.

References

[1] Wohlers, Terry T. *Wohlers Report 2012: Additive Manufacturing and 3D Printing State of the Industry: Annual Worldwide Progress Report*. Fort Collins, CO: Wohlers Associates, 2012. 181 pp. Print.

[2] Trimble, Stephen. "US Army predicts shift to nearly all unmanned aircraft by 2035." *Flightglobal.com*. Flight International, 16 Apr. 2010. Web. 8 Apr. 2013. <http://www.flightglobal.com/news/articles/us-army-predicts-shift-to-nearly-all-unmanned-aircraft-by-2035-340692/>.

[3] "Southampton University Laser Sintered Aircraft." *Decision Environments for Complex Designs (DECODE)*. University of Southampton, n.d. Web. 8 Apr. 2013.

[4] Senese, Mike. "Want a Flying Drone? These Students 3D-Printed Their Own Wired.com." *Wired Design*. Wired, 28 Nov. 2012. Web. 8 Apr. 2013.

[5] Bin Taha, Zahri, Vin Cent Tai, and Phen Chiak See. "Design and Manufacture of a Miniature UAV using 3D Rapid Prototyping." *Advanced Materials Research* 308-310 (2011): 1426-1435. Web. 25 Mar. 2013.

[6] Boehm, Barry W. "A Spiral Model of Software Development and Enhancement." *ACM SIGSOFT Software Engineering Notes* 11.4 (1986): 14-24. *Web of Science*. Web.