The Design, Manufacturing, and Testing of a Novel Blended Wing Body Multirotor UAV for Public Safety Applications

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ABSTRACT

Virginia Tech's Uncrewed Systems Lab (USL) has begun development of a small quadcopter with a novel aerodynamic design intended for public health and safety applications. An ever-increasing number of regulations against Chinese technology in the US has forced many public safety agencies to ground their fleets and seek new alternatives. The USL team and our partners wish to fill this hole in the market. The final product is envisioned as being a monocoque composite blended wing body (BWB) quadcopter, compatible with a wide range of payload types and comprised of only non-Chinese components. Based on market research and a literature review, the team believes that these features will significantly enhance the aerodynamic efficiency, structural reliability, repairability, and versatility of our product compared to currently available solutions, and that these features are what the customer base need in their solution.

Thus far, the USL has already shown that the design has significantly better energy efficiency than comparable vehicles due to its unique, wing-shaped fuselage. A prototype was designed and constructed for proof of concept and configuration testing. Proof of concept testing showed great promise. The prototype was flight tested and compared to a Holybro S500, and found to be significantly more energy efficient, particularly at higher speeds. This is highly promising, and thus, work will continue on optimizing and maturing this design. The next steps include arm configuration testing and downselection followed by building a composite prototype. The team at VT's USL has high hopes for making this an actual product that will be profitable and beneficial to society by catering to public safety and law enforcement customers in the United States.

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1. Understanding the Problem

1.1. Introduction

Virginia Tech's Uncrewed Systems Lab is in the early stages of designing, testing, manufacturing, and marketing a novel small multirotor design. The concept is a monocoque blended wing body quadcopter, compatible with a wide range of payload types and comprised of only non-Chinese components. The team believes that these features will significantly enhance the aerodynamic efficiency, structural reliability, repairability, and versatility of our product compared to currently available solutions. Customers in US government-affiliated public safety and research sectors are the primary targeted customer base. They are in great need of such a product, particularly in light of recent and seemingly ever-expanding legislation regarding Chinese technology in the US [1]. This report covers two aspects of this ongoing project: our understanding of the problem, and the design, manufacturing, and testing of the first prototype of our proposed solution. Special emphasis is placed on fuselage structural design and manufacturing, and the results of initial flight testing.

This first prototype is an arm configuration testbed and proof of concept. Due to the lack of literature surrounding BWB multirotors, and the difficulty of modeling the complex aerodynamics of such aircraft with readily accessible software, the USL team decided to design and build a 3D-printed prototype to prove that a wing-shaped fuselage had beneficial aerodynamic attributes. It was also designed such that the arms are attached to the fuselage with easily swappable 3D-printed brackets so different arm configurations can be tested on the same fuselage to determine the optimal arm length and positioning. At this point, initial flight testing for proof of concept has been conducted and is analyzed in this report. Arm configuration testing and downselection is the next step in the maturation of this design. The final product is envisioned as being a sleek composite structure with arms that blend into the wing.

The USL team believes this concept has great promise because it combines the benefits of multirotors and airplanes. Multirotors are capable of vertical takeoff and landing (VTOL) as well as hovering, which are hugely beneficial features for customers who may not always have access to a large, hard, flat surface to take off from, or who need to fly in a somewhat enclosed area like a city, or who need to perform tasks like inspections or surveillance for which they may need to maintain the aircraft's position for some period of time. However, conventional small uncrewed

or remotely piloted aircraft have significantly greater energy efficiency, which leads to greater range, endurance, and payload capacity. Our design combines the invaluable features of multirotors with some of the aerodynamic benefits of airplanes, and further enhances these aerodynamic benefits by incorporating BWB structures to create a more efficient multirotor for our customer base.

1.2. Genesis of the Problem

Small unmanned and remotely piloted aircraft can be mission critical to health and safety professionals and researchers, however, nearly all of the drones they are currently using are manufactured in China, or use Chinese components, which presents a national security risk [2].

Over the past several years, there's been "a real shift in the US," according to Scott Kennedy, a China specialist at the Center for Strategic & International Studies. Fear about China being "out to replace the US" has now become fear that China is "infecting local and state governments" [3]. As a result, the US government has placed Chinese technology under more and more scrutiny. Most commercial off-the-shelf quadcopters are made in China or are at least made with Chinese components. This includes DJI's quadcopters, which are by far the most popular in the world [4].

On May 24th of 2017, the US Navy released a memorandum entitled, "Operational risks with Regards to the DJI Family of Products". A day later, the Army Research Laboratory at Aberdeen Proving Grounds in Maryland completed a classified study entitled, "DJI UAS Technology Threat and User Vulnerabilities". As a direct result of these two references, the US Army discontinued its use of DJI products in August 2017 [5].

In 2018, the US Department of Justice began its "China Initiative" under former President Donald Trump's Attorney General Jeff Sessions to counter rising concerns about Chinese espionage and threats to US national security [6].

In 2019, the Department of the Interior also grounded its entire fleet of about 800 drones because of security concerns. All of them were manufactured in China or were made with Chinese components, and at least 15% of them were DJI drones [7]. Months later, after an internal review,

the Department of the Interior made the decision to continue keeping its fleet grounded, except during emergencies like wildfires, citing “national security interests” [8].

In 2020, congress passed the National Defense Authorization Act for Fiscal Year 2020, which forbade the Department of Defense (DoD) from purchasing drones manufactured in China or made with certain Chinese components, such as Chinese flight controllers, radios, and cameras [9]. Then, just before leaving office in 2021, former President Trump signed Executive Order 13981, which forbade the federal government from purchasing Chinese unmanned aerial systems (UAS) [10]. Shortly thereafter, the DoD released an official statement, “that systems produced by Da Jiang Innovations (DJI) pose potential threats to national security” [11].

The Biden administration famously began cracking down on China’s technological development around 2022. Clete Williams, former Deputy Assistant to the President for International Economics and Deputy Director of the National Economic Council during the Trump administration, went so far as to say “[The Biden] administration views Chinese indigenous innovation as a per se national security threat ... and that is a big leap from where we’ve ever been before” [12].

Now, in 2023, anti-Chinese policies have begun trickling down to the local and state government levels. As of April 5th, Florida’s government agencies are no longer permitted to operate drones made in countries of concern, including China. This has had significant consequences for government-affiliated public safety workers and researchers. Miami Dade Fire Rescue Captain Luis Valerino told *Forbes* that the new drones his department has purchased to replace the old DJI systems “simply aren’t as good” and that it feels like his fire department has been “pushed back five years.” State universities also need to purchase new UAV systems. Cassandra Farley, University of Florida’s director of research integrity, testified that it will cost $1-2 million to replace its research drones. Even mosquito control workers have been affected; they previously used DJI drones to survey and monitor mosquito habitats, but they may now be forced to send people into habitats with snakes and alligators to perform these surveys [1].

Earlier this month, a similar piece of legislation was passed in Arkansas [13]. The USL team believes that it is highly likely that this trend will continue. A hole is opening in the market. Our product will fill it.

1.3. Market Research

The USL team needed to perform market research to ensure that the product will adequately fill the hole in the market. The market in question is the public safety and law enforcement market. This research played a vital role in defining our system requirements, design drivers, and measures of merit.

The usage of unmanned aircraft or drones in the public safety and law enforcement sectors has expanded rapidly, and despite the increase in bans of Chinese-made drones, the number of public safety agencies with drones has increased every year (Figure 1).

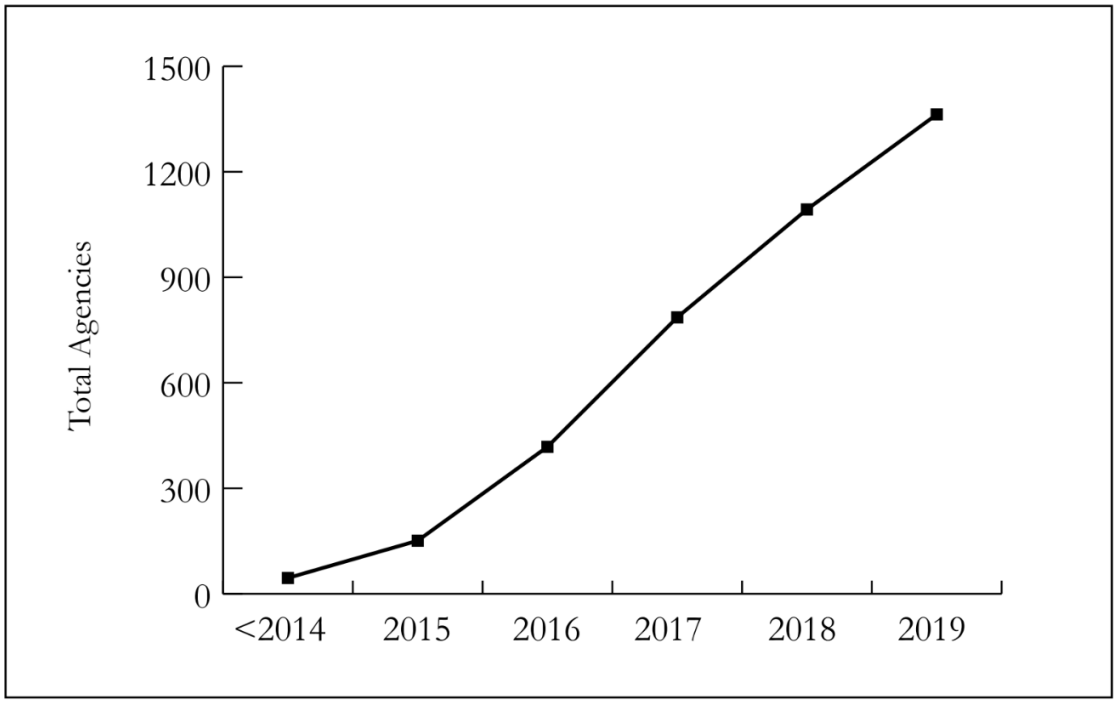

Figure 1: Total Number of Public Safety Agencies with Drones by Year [14]

However, the rate at which new agencies adopt drones has taken a sharp downturn since 2017 (Figure 2). This may be tied to the increase in regulations regarding Chinese technology, especially because about 90% of public safety agencies that use drones use drones made by DJI [14].

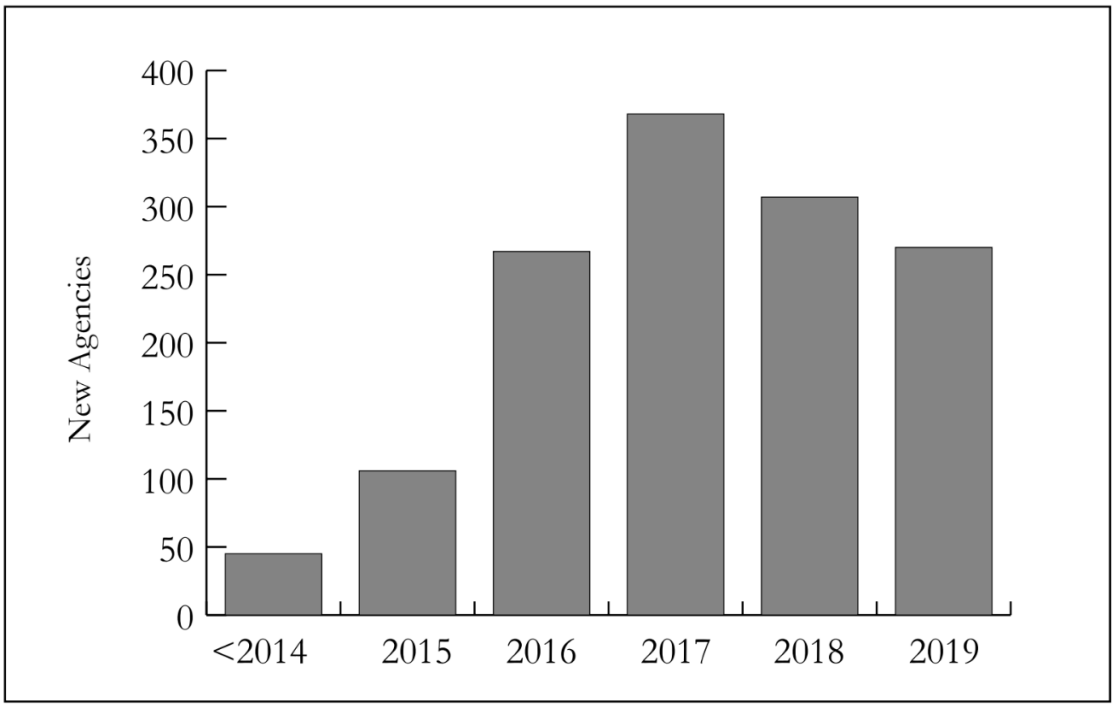

Figure 2: New Public Safety Agencies with Drones by Year [14]

Within the public safety sector, drones are most commonly used for law enforcement, followed by fire and rescue and emergency management (Figure 3)

Mission	Agency Count	Percent of Total*
Law Enforcement	1,103	70%
Fire and Rescue	326	20%
Emergency Management	149	10%

Figure 3: Public Safety Agencies with Drones by Mission [14]

Within law enforcement, the most common use cases include search and rescue, crime scene photography and reconstruction, investigating armed and dangerous suspects, disaster response, and traffic collision reconstruction (Figure 4).

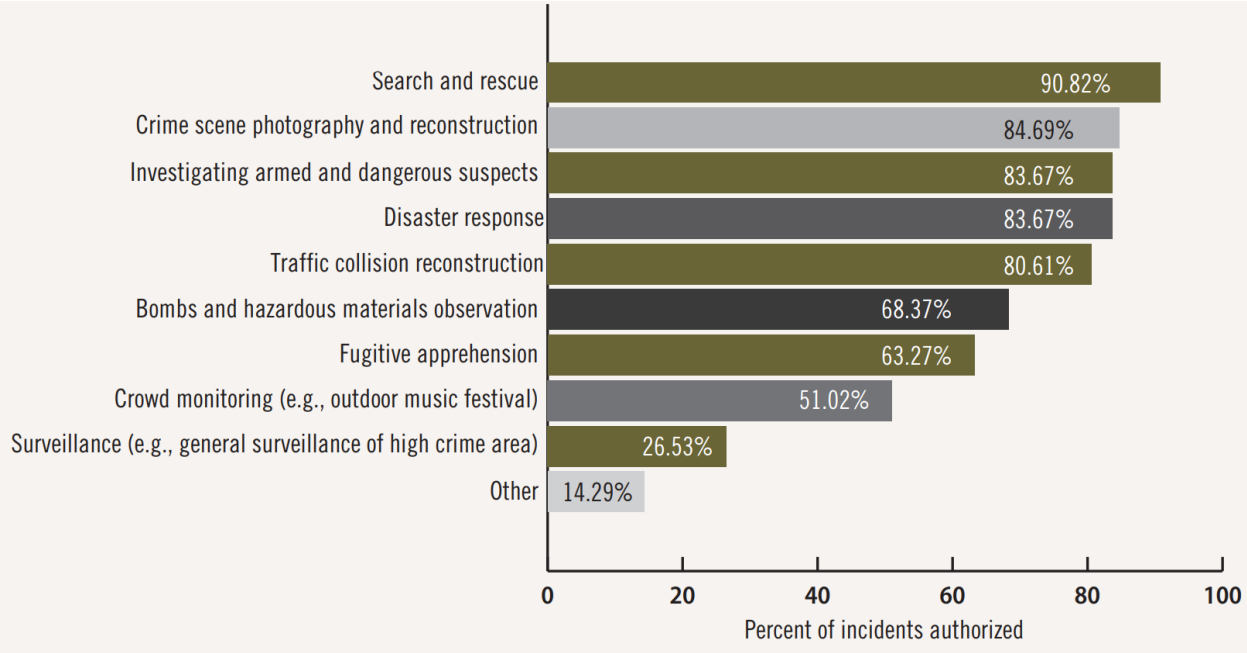

Figure 4: Incidents Authorized for Drone Use [15]

Most, if not all, of these applications require the drone to be equipped with a camera for video or photography, thus our product should be easily compatible with a variety of cameras for photography, videoing, and thermal imaging. Some of these applications, such as search and rescue, also potentially require the drone to remain aloft for a fairly long period of time and cover a good deal of ground. This is why the USL decided to explore the concept of a blended wing body quadcopter.

From the lab's prior research, the USL also found that there are certain law enforcement drone applications for which there is great need, but currently no adequate solution. For example, law enforcement officers expressed interest in having drones with the ability to automatically follow running fugitives. Currently, drones must be flown manually in fugitive apprehension missions.

While law enforcement makes up the bulk of our intended customer base, there are opportunities to serve fire safety, EMS, and other public safety customers that are worth exploring because they have some unique needs that are not adequately fulfilled by currently available solutions. For example, EMS workers have expressed interest in using drones to drop off emergency medical supplies, first responders have expressed interest in having drones that can perform radiation source localization, and other public safety workers have expressed interest in using drones for gas sampling. This means that it would be highly beneficial for our product to have

hardware, electrical, and software standards that allow it to be compatible with a wide range of payload types.

Overall sturdiness, ease of use, and ease of maintenance and repair were also highly valued features because they increase the longevity and decrease user frustration with the product. Ease of maintenance and repair is also closely intertwined with ease of swapping out different payloads, which has already been established as a highly desired feature. Thus, these features will also be incorporated into the design.

To summarize, the customers primarily need a non-Chinese drone with a long range and high endurance that is compatible with many types of payloads and is easy to use and repair. Specifically, based on prior research, the product must have a flight duration of more than 25 minutes for a 1kg payload, and a flight duration of more than 15 minutes for a 2kg payload. The remainder of this paper is about how the USL team's design will be aerodynamically optimized such that it best meets these requirements. The other requirements are outside the scope of this paper but will be addressed in future work.

1.4. Review of Literature

1.4.1. Introduction

Our product needs to be able to fly for relatively long periods of time in order to complete our customers' missions. Thus, ways of optimizing the product's efficiency, and in turn, its flight time were sought. Using an airfoil-shaped fuselage to generate additional lift and blending the interface between the fuselage and the arms to reduce form drag at these junctions was our solution. The result can be thought of as a blended wing body (BWB) quadcopter design.

Leaders in the aerospace industry have called blended wing body aircraft "game-changers" ever since the late 1980s [16]. Despite this, only 3 blended wing body aircraft are currently in service, all of which are for military applications [17]. Before developing our own BWB design, the team thought it prudent to gain a more complete understanding of the pros and cons of such aircraft in order to determine if the issues that have historically prevented BWBs from seeing wide-spread adoption would be barriers to our success as well.

The earliest groundbreaking piece of literature on BWBs was H. R. Liebeck's 2003 paper, "Design of the Blended Wing Body Subsonic Transport" [18]. The paper chronicles the technical development of the BWB concept over nearly a decade, starting with a three-year study conducted by NASA and McDonnel Douglas in conjunction with university groups between the years of 1994 and 1997, moving into BWB design constraints, and ending with a description of Boeing's most advanced BWB baseline design of the time.

1.4.2. The 1994 Study

In his summary of the 1994-1997 study, Liebeck explains the first two challenges associated with BWBs: passenger emergency egress and cabin pressure loading. Passenger emergency egress is a challenge because, according to the square-cube law, "the surface area per passenger available for emergency egress decreases with increasing passenger count." Cabin pressure loading is a challenge because pressure loads are most efficiently carried in hoop tension. To address these challenges, the team considered using a cabin consisting of multiple, overlapping circular cylinders. It was a double-decker cabin, with three circular cylinders comprising the bottom level, and one comprising the top. Passengers were able to egress from both the top and bottom levels, which helped with egress concerns. However, "clearly, the concept was headed back to a conventional tube and wing configuration." Thus, the team opted to abandon the overlapping circular cylinder cabin design. They chose "to assume that an alternate efficient structural concept could be developed". He goes on to explain that, unlike a wing, which rarely experiences its design load, the pressure cabin experiences its design pressure load every flight, and thus, based on fatigue alone, the centerbody ought to be constructed from composites. Re-designing the aircraft without the circular cylinder constraint resulted in a design that reduced total wetted area by 33% and had a nearly elliptical spanload, which "implied a substantial improvement in aerodynamic efficiency."

However, the design also had a longitudinal static margin of -15%, implying that this aircraft would require a fly-by-wire control system to help the pilot maintain control. This issue was not unique to this particular BWB; later studies have shown that BWB generally aircraft have not only decreased longitudinal stability, but also directional stability and damping [19].

Despite the various challenges, the team believed that BWBs showed a great deal of promise.

1.4.3. BWB Design Constraints

Liebeck then goes on explain that the thickness to chord ratio of a BWB must be on the order of 17% in order to fit passengers, cargo, and systems within the wing. This is much higher than is typical for transonic airfoils, such as those typically used for airliners. This results in a much larger wingspan than a comparable tube-and-wing configuration, which may present airport compatibility issues and facilitate the need for folding wings. BWBs also have lower wing loading compared to tube and wing configurations, which leaves them more susceptible to gust and wake turbulence, which may also be problematic at airports.

Additionally, Liebeck explains that BWBs have the potential to be more complex and costly to manufacture, maintain, and repair for several reasons [20]. Much of the structure will need to be made from composites, the geometry is more complex than a conventional tube and wing, and due to the novelty of such designs, it is difficult to estimate the weight and cost of BWB structures, especially the cabin [21]. All of these factors increase the risk of investing in BWB structures.

1.4.4. The Boeing BWB-450 Baseline Design

Liebeck then launches into a discussion of Boeing's BWB-459 baseline airplane. This aircraft design was created as a direct result of the prior NASA and McDonnell Douglas study. The team's primary goal was to determine how BWB performance stacked up against tube and wing performance. The key measures of merit were fuel burn and takeoff weight.

The structural definition of the centerbody and its associated pressure vessel was key to determining if BWBs had a takeoff weight advantage. They compared several structural concepts and settled on a skin/stringer outer surface with internal ribs with Y braces where they meet the skin. These braces reduce the bending moment on the skin caused by the internal pressure. The pressure vessel was comprised of upper and lower surface panels, a rounded leading edge that also served as the front spar, a rear main spar, and internal ribs. The structure was developed and verified using finite element analyses and assumed to be made of composites. They then compared the structural weight fractions of the BWB-450 with a generic tube and wing design

also made from composites with approximately the same number of passengers, range, and similarly advanced technologies. Boeing found that the fuselage weight of the BWB-450 was 21% higher than the tube and wing design, but overall takeoff weight was 11% lower.

To quantify the improvements in fuel burn, the team compared two aircraft: their BWB design, and an Airbus A380-700, both meeting approximately the same requirements. The “most striking” result of this entire study was that the BWB-450 obtained an impressive 32% lower fuel burn per seat.

1.4.5. Summary of Pros and Cons

In summary, BWBs have the following benefits:

1. Greater aerodynamic efficiency, resulting in:
    a. Lower fuel burn
    b. Lower takeoff weight for the same payload

And the following downsides:

2. Difficulty satisfying passenger emergency egress requirements.
3. Non-circular pressure vessel, resulting in a weight penalty.
4. Potential for poor airport compatibility due to greater wingspan and gust sensitivity.
5. Poor stability and control, requiring a more complex flight control system.
6. Manufacturing, maintenance, and repair concerns, including a reliance on composites and challenges associated with the novelty of the design.

The benefits translate directly into greater energy efficiency, which is exactly what the team was hoping for. By adopting a BWB design, our quadcopter should be able to fly longer and with greater payload than comparable vehicles.

As for the downsides, nearly all of them become irrelevant at the scale of small UAVs. Passenger egress is irrelevant. Fuselage pressurization is irrelevant. Compatibility with airport infrastructure is irrelevant. As for manufacturing, maintenance, and repair, while the USL does intend to use composites for the final design, fabricating composites on this small of a scale is

significantly easier, and repair and maintenance will be as simple as taking the top of the quadcopter off and changing out whatever is broken.

The only concerns that potentially remain applicable at our scale are those pertaining to stability and control. And, it is also possible that there may be some BWB-associated challenges that are unique to aircraft of our size or unique to VTOL BWBs. So next, the team looked at more recent studies pertaining to BWB-type aircraft that are on a scale more similar to our own.

1.4.6. Smaller-Scale Concepts

The world of small, remotely piloted vehicles seems to be poised in the perfect position to take advantage of blended wing structures. However, there is a dearth of literature in this area. Two sources of interest were uncovered: Xiao et al.'s 2021 study entitled "A Lifting Wing Fixed on Multirotor UAVs for Long Flight Ranges", and a product, simply called "The Flying Wing", produced by a company called VTOL Technologies.

Xiao et al. designed, built, and tested a small BWB unmanned aerial vehicle (UAV), about 85cm diagonally and weighing about 2kg [22]. Their primary objective, much like ours, was to determine if the range and payload of multirotor UAVs could be significantly improved by enhancing their aerodynamic efficiency. They took a pre-existing Skywalker X5 RC BWB aircraft, cut off the ends of the wings, and mounted it on a set of propellers and landing legs, resulting in a design rather similar to our own. However, the Skywalker X5 has a rounded fuselage that blends into the wings, unlike our design, which has a pure flying wing fuselage. Additionally, Xiao et al. tilted the propellers on their prototype 10 degrees away from the fuselage on the lateral-vertical plane. This was done to improve yaw control performance, particularly in crosswind conditions. They also optimized the mounting angle of their fuselage via numerical methods to maximize the vehicle's flight range in cruise. They flew the vehicle with and without the BWB fuselage and found that, at their cruise speed of 15m/s, the BWB version saved 50.14% power compared to the more conventional configuration. They concluded the effect of the propellers and the effect of the BWB fuselage were almost decoupled. The aircraft was controlled with a conventional multirotor UAV controller, and only experienced controllability issues at speeds above 20m/s. No other issues with the BWB design were mentioned in this study.

Additionally, VTOL Technologies' Flying Wing was of great interest to us [23]. The Flying Wing is a composite tilt-rotor quadcopter with a fuselage comprised of a wing with flaperons and an avionics and payload bay underneath it. It was designed to be an alternative to the manned helicopters and foot personnel that are currently used to inspect things like oil pipelines, railroads, electric lines, offshore wind farms, etc., while being faster, less expensive, and more consistent. It cruises around 33m/s, and VTOL Technologies claims it has performance times of up to 4 times longer than comparable rotary wing platforms.

Although there is very little literature regarding small multirotor BWBs, the two sources found gave us a great deal of hope for our own design! They both indicate that opting for an aerodynamic fuselage design can lead to significant gains in efficiency, which is exactly what we were hoping for. Although, stability and control remain a potential concern at high speeds. Additionally, The Flying Wing suggests that there may be a place in the market for BWB quadcopters, which is fantastic because we aspire to turn this project into a business if it is as successful as we hope. These two sources, and the research that went into finding these two sources, showed us that there is a promising and largely untapped design space to explore. We have, and will continue to explore it with our new prototype test bed.

2. Prototype of the Proposed Solution with Substantiating Technical Details

2.1. Prototype Overview

The team decided to make a 3D printed prototype of our initial proposed solution to use as a proof of concept and configuration test bed (Figure 5 & Figure 6). It was designed such that the arms are attached to the fuselage with easily swappable 3D-printed brackets so different arm configurations can be tested on the same fuselage, which will later be used to determine the optimal arm length and positioning. The arms themselves are carbon fiber tubes, which can easily be cut to different lengths. The prototype is about 60 cm by 36 cm including the arms and weighs about 1105 g without a battery. The prototype was flight tested and compared with the Holybro S500. Our prototype is a similar size and weight to the Holybro S500 and uses the same electronics, making the S500 a good comparator. To design and manufacture this prototype, we split into two teams: one working predominantly on the arm bracket design, and one working

predominantly on the fuselage. This paper focuses on the fuselage and the analysis of the flight test data that came from the completed prototype.

Figure 5: The Prototype

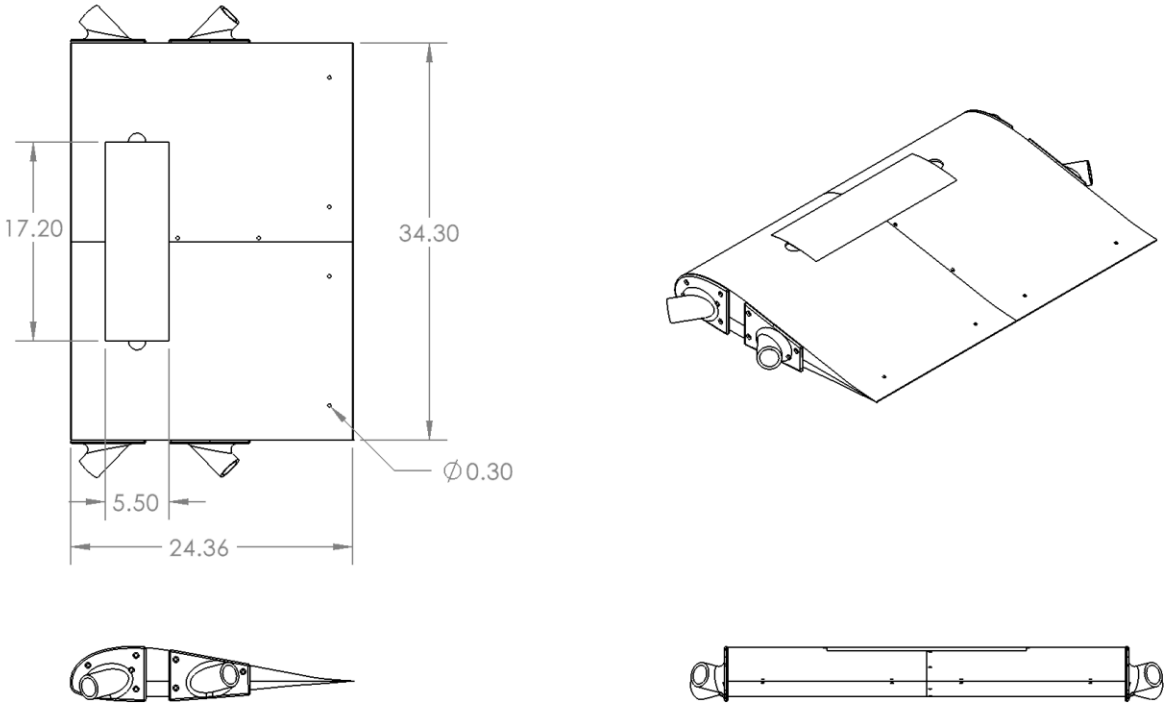

Figure 6: 3-View Drawing of the 3D Printed Parts of the Prototype (Units in cm)

2.2. Fuselage Design

An ARA-D 20% airfoil was selected for the fuselage. A major driver of this decision was the high thickness of this airfoil. The chord was restricted to 24.36cm due to 3D printer size constraints, and the battery is 3.5cm tall. A 24.36cm chord ARA-D 20% airfoil was just thick enough to fit the battery, while also accounting for the thickness of the walls of the walls of the airfoil (Figure 7).

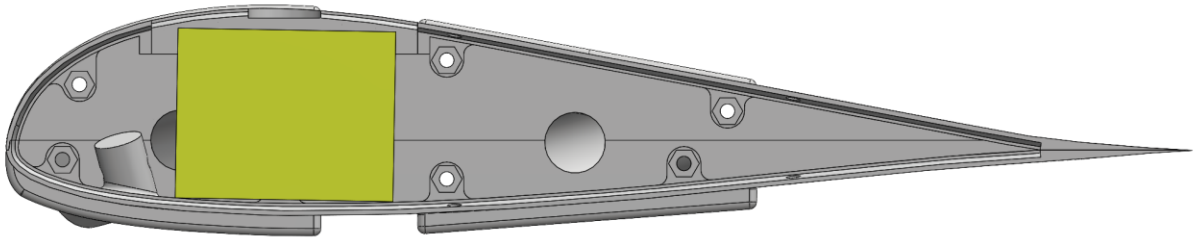

Figure 7: Cutaway Side View of the Prototype, Battery in Yellow

The team initially wanted to print the fuselage in two parts: a top half and a bottom half, so that the top could be easily lifted off to access the electronics within. However, due to 3D printer bed size constraints, the fuselage had to be printed in 4 parts instead: top left, top right, bottom left, and bottom right. Additionally, a hatch was added in the top of the fuselage for easy access to the battery.

A major challenge was determining how to design the fuselage such that these various parts could be easily attached together and taken apart as needed without interfering too heavily with the aerodynamics of the design. It was decided that the four pieces would interface with each other via lips and grooves with bolts for ease of assembly. Instead, the fuselage was designed such that the two bottom pieces and the two top pieces were to be assembled first. This stage of the assembly was simple because there was easy access to both sides of the bolt: the side with the head (on the outside of the fuselage), and the side with the nut on the inside of the fuselage. Designing the fuselage such that the top half and bottom half could be bolted together, and the arm braces could be bolted to the sides of the fuselage presented more of a challenge because the nuts were inside the fuselage, so it was not possible to simply hold the nuts in place while screwing in the bolts. This meant there needed to be design features to hold the nuts in place. Threaded inserts are commonly used in situations like this, but threaded bolts of an appropriate

size were not readily available. Instead, inside the fuselage, around every relevant bolt hole, a small cylindrical area was extruded to increase the wall thickness, and then a hexagonal hole was cut into it. The nuts would be heat-inserted into these hexagonal holes to hold them in place (see Fuselage Manufacturing). All these interfaces can be most easily seen in Figure 8. A downside of this approach is that there are 24 bolt heads on the external surface of the prototype, which likely have a small negative impact on the aerodynamics. This will be remedied in future design iterations.

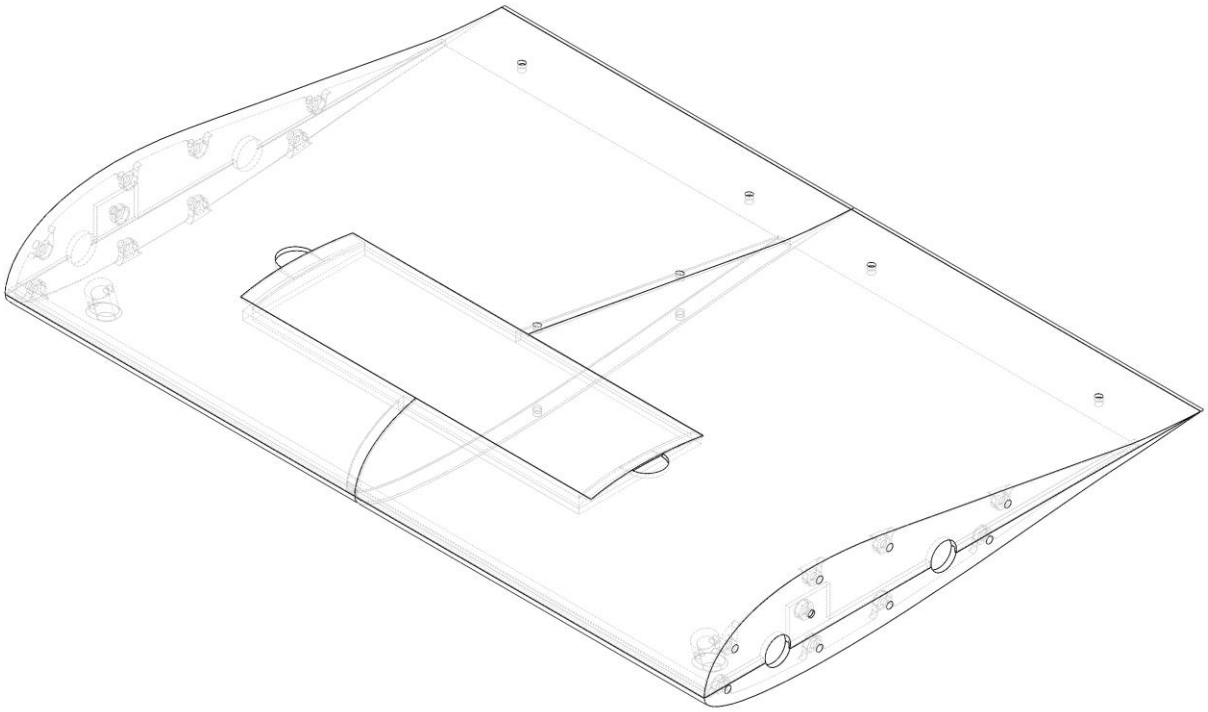

Figure 8: Prototype Fuselage, Hidden Lines Visible

The fuselage also features 4 holes on the sides to pass wiring into the arms, and two recesses on the bottom for the front landing legs to be inserted,

2.3. Fuselage Manufacturing and Assembly

The fuselage was printed from PLA and PETG on Prusa i3 Mk. 3D printers. Each part was printed sitting on its side because this resulted in the smoothest, highest quality surface finish (Figure 9).

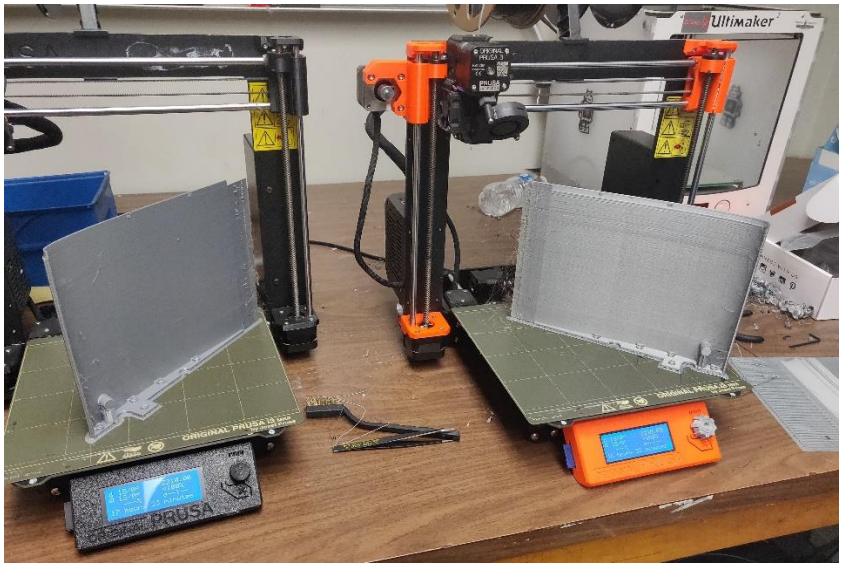

Figure 9: The Top Halves of the Fuselage Just After Printing Completed

The then parts received a small amount of sanding and filing to remove large blemishes, and the nuts were heat-inserted into the hexagonal recesses.

The top two pieces and bottom two pieces fit together nicely (Figure 10) however, the top and bottom halves and arm brackets were less cooperative, primarily due to some unexpected warping during the printing process. This left a gap at the front of the fuselage that was covered in tape to maintain smooth airflow over the fuselage. This will be remedied in future composite prototypes.

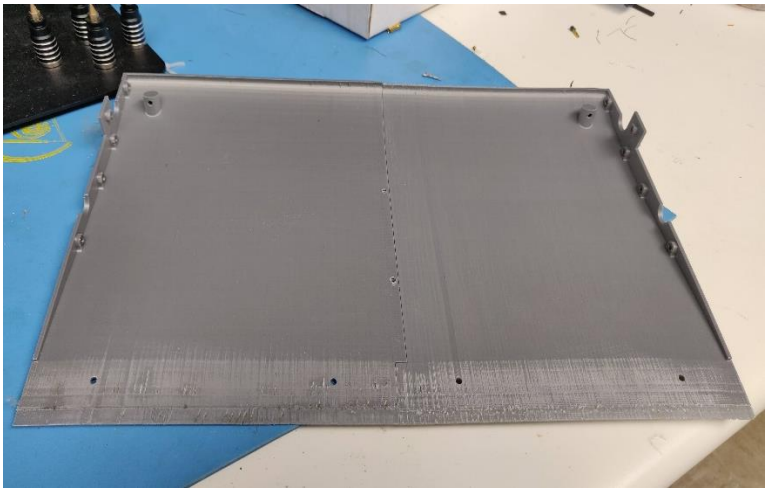

Figure 10: Bottom Half of Fuselage Showing Reasonably Good Fit

The two 3D printed landing legs were inserted into the bottom of the fuselage and the arms, motor mounts, and electronics were all installed without major issues.

2.4. Comparison with Holybro S500

2.4.1. Introduction and Methods

Flight testing of the prototype was conducted to prove that the airfoil-shaped fuselage concept had significant enough advantages in aerodynamic performance to notably improve power efficiency. The results from this testing were compared with results from a Holybro S500, which uses the same electronics and weighs a similar amount to the prototype. Flight testing was conducted at Virginia Tech's Kentland Farms. Both drones were tested on the same day and around the same time under similar weather conditions. Data collection was attempted for flight speeds of 3, 5, 7.5, 10, 12.5, and 15 m/s, however, due to data collection errors and fear about crashing the prototype, data was actually collected for the speeds shown in Table 1 and Table 2.

The drones took off from the ground, accelerated to the desired speed and altitude, and flew some distance before either accelerating to the next desired speed or decelerating and landing. The Holybro S500 flew 100 m above ground level and the prototype flew 5 m above ground level. The repercussions of this discrepancy are discussed in more detail in the Analysis and Discussion section. The Holybro S500 flew 150 m each sortie, while the prototype flew 70-100 m. It is not believed that there are any major repercussions as a result of this discrepancy.

2.4.2. Results

The data collected from the prototype is in Table 1, and the data gathered from the S500 is in Table 2. These data are the average values taken from the raw data while the drones were flying at the desired speeds.

Table 1: Speed, Current, and Voltage Flight Test Data from the USL Prototype

USL Prototype		
Speed (m/s)	Current (A)	Voltage (V)
3.0	14.25	15.50
7.5	12.00	15.50
10.0	10.60	15.35
12.5	11.50	14.86

Table 2: Speed, Current, and Voltage Flight Test Data from the Holybro S500

Holybro S500		
Speed (m/s)	Current (A)	Voltage (V)
5.0	13.75	15.50
10.0	14.00	15.35
12.5	16.50	15.12
15.0	22.00	14.75

2.4.3. Analysis and Discussion

The formula,

$$P = I * V \qquad (1)$$

where P is power in watts, I is current in amps, and V is voltage in volts, was used to calculate the power for each drone at each speed (Table 3 & Table 4).

Table 3: Speed, Current, Voltage, and Power for the USL Prototype

USL Prototype			
Speed (m/s)	Current (A)	Voltage (V)	Power (W)
3.0	14.25	15.50	220.875
7.5	12.00	15.50	186.000
10.0	10.60	15.35	162.710
12.5	11.50	14.86	170.890

Table 4: Speed, Current, Voltage, and Power for the Holybro S500

Holybro S500			
Speed (m/s)	Current (A)	Voltage (V)	Power (W)
5.0	13.75	15.50	213.125
10.0	14.00	15.35	214.900
12.5	16.50	15.12	249.480
15.0	22.00	14.75	324.500

Power vs velocity for the two drones is plotted in Figure 11 below.

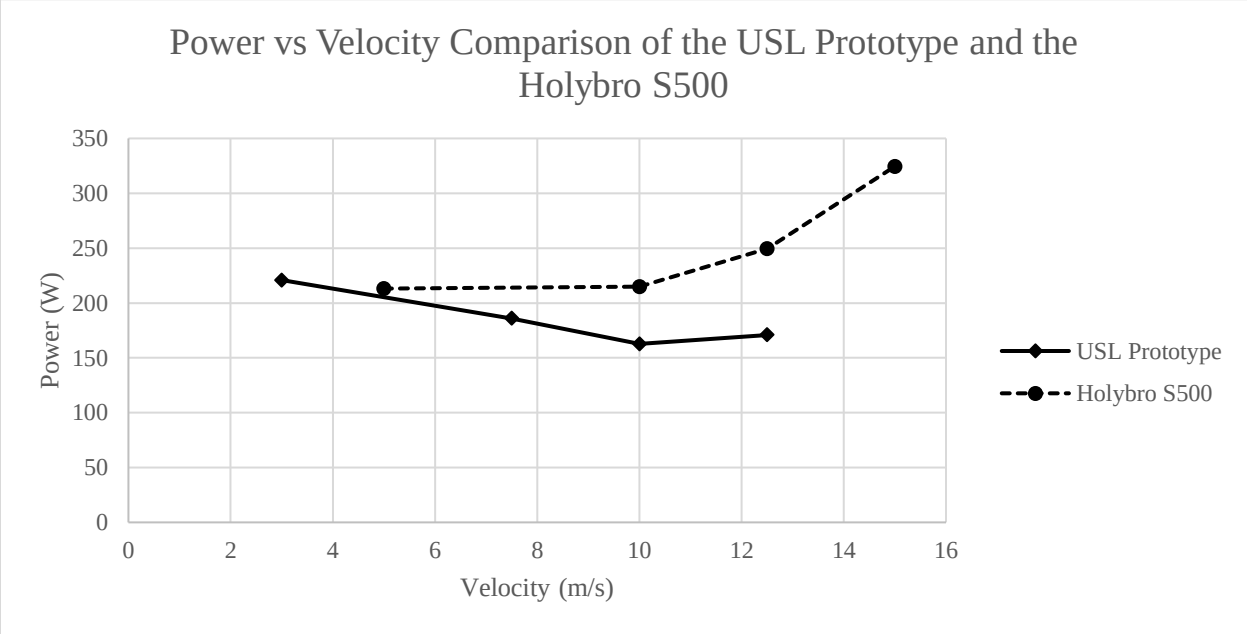

Figure 11: Power vs Velocity Comparison of the USL Prototype and the Holybro S500

The prototype uses less power as its speed increases, except for a small jump in power from 10 to 12.5 m/s. The S500, on the other hand, consistently requires more power as its speed increases. Additionally, the prototype uses less power than the Holybro S500 at all tested speeds, and the difference becomes more pronounced as the speed increases. To see just how different the power values are, the percent difference was calculated using eq. (2):

$$Percent\ Difference = \frac{|V_1 - V_2|}{\left(\frac{V_1 + V_2}{2}\right)} * 100 \quad (2)$$

Where V_1 is S500 power in watts and V_2 is USL prototype power in watts. The results are in Table 5 below.

Table 5: Percent Difference in Power Usage Between the USL Prototype and the Holybro S500 at 10 m/s and 12.5 m/s

Holybro S500	USL Prototype	Percent Difference
Power (W) at 10 m/s:		
214.90	162.71	27.64%
Power (W) at 12.5 m/s		
249.48	170.89	37.39%

Unfortunately, there are only two speeds at which the team managed to get data for both the S500 and the prototype, however, that's still enough to see that the prototype is significantly more energy efficient than the S500.

There are three notable limitations to this experiment. The first is that the prototype and the Holybro S500 do not weigh exactly the same; the prototype is around 35 g heavier. However, heavier vehicles generally require more power to remain aloft, which makes the fact that the prototype required less power even more impressive. The second is that the prototype and the Holybro S500 were not tested at the same altitude. The S500 was tested at 100 m above ground level, whereas the prototype was tested at 5 m above ground level because the pilot in command did not want to risk crashing the prototype. Drones generally require more power at higher altitudes because the air is thinner [24]. However, the prototype was high enough off the ground that it almost certainly was not flying in ground effect [25]. In this regard, the prototype got an unfair advantage over the S500. The final major limitation is that the prototype was not tested at its design cruise speed of 15 m/s because, again, the pilot in command did not want to risk crashing the drone.

The prototype handled well throughout testing. There were no notable stability or control issues, which is particularly exciting because stability and control issues are a known challenge for BWB aircraft.

2.4.4. Conclusion

The results of this experiment were very promising. Despite the limitations, it seems that the airfoil-shaped fuselage does indeed significantly improve energy efficiency, and stability and control are not major concerns. Because of the results of this experiment, the team at the USL will absolutely be moving forward with this BWB quadcopter concept. This may be a key, enabling development in our mission to serve our particular customer base.

2.5. Future Work

There is an immense amount of exciting work remaining for this project due to the incredible complexity of designing, building, testing, manufacturing, and marketing a new product. This section of the report focuses only on the immediate future work that is a direct continuation of the work described in this report.

2.5.1. Configuration Testing and Downselection

Now that it has been established that the airfoil-shaped fuselage significantly enhances power efficiency, design optimization can begin. The first thing that will be investigated is arm length and configuration. The team at the USL will flight test different arm mounting angles and arm lengths, as well as pusher prop configurations. The primary measure of merit that will be used to select the best arm configuration will be power minimization. This testing is particularly important because of the difficulty associated with modeling propeller-wing aerodynamic interactions. Going straight to flight testing allows us to side-step this issue, at least until much later in the design optimization process.

This testing has been directly enabled by how the prototype was designed. There is no need to print an entire new frame for each configuration; the only things that needs to be re-printed are the 4 arm brackets, which take only about an hour to print each. This significantly increases the speed at which the USL can complete this testing.

2.5.2. Composite Prototype Manufacturing

Once a configuration has been selected, it will be time to produce another full prototype; a composite prototype with arms that blend into the wing. This prototype will be of great significance because it will bear a much stronger resemblance to the product we actually intend to bring to market. It will weigh significantly less, be stronger, have better aerodynamic properties, and be made from fewer parts. Designing and manufacturing this prototype will give the USL team the opportunity to explore composite design and manufacturing best practices that will remain invaluable for the remainder of the project, and work out potential challenges like how to best attach composite parts together while still keeping the design simple to assemble and disassemble. This prototype will also be used to conduct more flight testing to analyze how much blending the arms into the wing improves power consumption. This may also be the point when the team starts digging much deeper into developing standardize payload attachment fittings.

2.6. Conclusion

The USL's BWB quadcopter design shows great promise for public safety and law enforcement applications.

Before delving too deep into the design, the team established an excellent understanding of the problem in order to ensure that what we were designing would be the best solution to our customers' problems. The laws and drone bans that caused the problem were explored and it was established that this trend of banning Chinese technology will likely continue well into the future. Market research and surveys were conducted to determine what was lacking in the current solutions and what the customer base truly needed to solve their problems. This made the USL come to the conclusion that incorporating BWB structures into the product could help make our design truly fit what the customer needed with regards to range and endurance. Thus, a literature review was conducted to investigate the pros and cons of BWB structures. This literature review showed that the realm of small UAVs is seemingly perfectly poised to take advantage of the pros of BWB structures while avoiding most, if not all, of the cons, however, this area of research is largely untapped at this time. Thus, we came to the conclusion that we would have to do our own experiment as a proof of concept.

Thus, a prototype quadcopter with an airfoil-shaped fuselage was designed, manufactured, and tested. The decision was also made to design it such that it will be highly useful for configuration downselection in future studies. Designing and manufacturing this drone was a challenge, but ultimately successful enough for a proof of concept. It was flight tested and compared with a Holybro S500 and found to be significantly more energy efficient. This was precisely what the team hoped to see, and thus, we will continue working on optimizing and maturing this design. The next steps include arm configuration testing and downselection followed by building a composite prototype. The team at VT's USL has high hopes for making this an actual product that will be profitable and beneficial to society by catering to public safety and law enforcement customers.

References

[1] C. Farivar, "Florida's Ban of Chinese Drones Leaves Firefighters and Mosquito Control Workers Scrambling," Forbes, 21 April 2023. [Online]. Available: https://www.forbes.com/sites/cyrusfarivar/2023/04/21/floridas-ban-of-chinese-drones-leaves-firefighters-and-mosquito-control-workers-scrambling/?sh=93759c73e778. [Accessed 1 May 2023].

[2] C. Che, "All the drone companies in China — a guide to the 22 top players in the Chinese UAV industry," The China Project, 18 June 2021. [Online]. Available: https://thechinaproject.com/2021/06/18/all-the-drone-companies-in-china-a-guide-to-the-22-top-players-in-the-chinese-uav-industry/#:~:text=More%20than%2080%25%20of%20commercial,used%20mostly%20by%20the%20military.. [Accessed 1 May 2023].

[3] C. Anstey, "America's Anti-China Restrictions Are Going Local," Bloomberg, 11 March 2023. [Online]. Available: https://www.bloomberg.com/news/newsletters/2023-03-11/america-s-anti-china-restrictions-are-going-local-new-economy-saturday. [Accessed 1 May 2023].

[4] A. Prisca, "The Top 20 Best Drone Companies Right Now," Luxatic, 3 Janurary 2023. [Online]. Available: https://luxatic.com/best-drone-companies/#:~:text=DJI%20is%20easily%20the%20top,the%20newer%20videographers%20and%20pilots.. [Accessed 1 May 2023].

[5] G. Mortimer, "US Army calls for units to discontinue use of DJI equipment," sUAS News, 4 August 2017. [Online]. Available: https://www.suasnews.com/2017/08/us-army-calls-units-discontinue-use-dji-equipment/. [Accessed 1 May 2023].

[6] E. Guo, J. Aloe and K. Hao, "The US crackdown on Chinese economic espionage is a mess. We have the data to show it.," MIT Technology Review, 2 December 2021. [Online].

Available: https://www.technologyreview.com/2021/12/02/1040656/china-initative-us-justice-department/. [Accessed 1 May 2023].

[7] M. McNabb, "U.S. Department of Interior Grounds DJI Drones," dronelife, 1 November 2019. [Online]. Available: https://dronelife.com/2019/11/01/u-s-department-of-interior-grounds-dji-drones/. [Accessed 1 May 2023].

[8] J. Peters, "The US just showed it still believes Chinese-made drones are a security risk," TheVerge, 29 Janurary 2020. [Online]. Available: https://www.theverge.com/2020/1/29/21113533/us-interior-department-chinese-drone-ban-grounding-security-dji. [Accessed 1 May 2023].

[9] BLUE UAS, "UAS Policy Guidance," Defense Innovation Unit, 2020. [Online]. Available: diu.mil/blue-uas-policy. [Accessed 1 May 2023].

[10] Executive Office of the President, "Protecting the United States from Certain Unmanned Aircraft Systems," 1 Janurary 2021. [Online]. Available: https://www.federalregister.gov/documents/2021/01/22/2021-01646/protecting-the-united-states-from-certain-unmanned-aircraft-systems. [Accessed 1 May 2023].

[11] U.S. Department of Defense, "Department Statement on DJI Systems," 23 July 2021. [Online]. Available: https://www.defense.gov/News/Releases/Release/Article/2706082/department-statement-on-dji-systems/. [Accessed 1 May 2023].

[12] G. Bade, "'A sea change': Biden reverses decades of Chinese trade policy," 26 December 2022. [Online]. Available: https://www.politico.com/news/2022/12/26/china-trade-tech-00072232. [Accessed 1 May 2023].

[13] J. Daleo, "Arkansas the Latest State to Implement DJI Drone Ban," 2 May 2023. [Online]. Available: https://www.flyingmag.com/arkansas-the-latest-state-to-implement-dji-drone-ban/. [Accessed 3 May 2023].

[14] D. Gettinger, "Public Safety Drones, 3rd Edition," March 2020. [Online]. Available: https://dronecenter.bard.edu/projects/public-safety-drones-project/public-safety-drones-3rd-edition/. [Accessed 2 May 2023].

[15] Community Oriented Policing Services, "Drones: A Report on the Use of Drones by Public Safety Agencies - and a Wake-Up Call about the Threat of Malicious Drone Attacks," Washington, D.C., 2020.

[16] B. I. Larrimer, Beyond the Tube-and-Wing, Washington, DC: National Aeronautics and Space Administration, 2020.

[17] W. contributors, "Blended wing body," Wikipedia, The Free Encyclopedia, 25 April 2023. [Online]. Available: https://en.wikipedia.org/wiki/Blended_wing_body. [Accessed 25 April 2023].

[18] R. H. Liebeck, "Design of the Blended Wing Body Subsonic Transport," *Journal of Aircraft,* vol. 41, no. 1, pp. 10-25, 2004.

[19] L. Wang, N. Zhang, H. Liu and T. Yue, "Stability characteristics and airworthiness requirements of blended wing body aircraft with podded engines," *Chinese Journal of Aeronautics,* vol. 35, no. 6, pp. 77-86, 2022.

[20] D. A. Day, "Composites and Advanced Materials," National Aeronautics and Space Administration, 2003.

[21] C. L. Nickol, "Silent Aircraft Initiative Concept Risk Assessment," National Aeronautics and Space Administration, Hampton, 2008.

[22] K. Xiao, Y. Meng, X. Dai, H. Zhang and Q. Quan, "A Lifting Wing Fixed on Multirotor UAVs for Long Flight Ranges," in *2021 International Conference on Unmanned Aircraft Systems*, Athens, 2021.

[23] "The Flying Wing," VTOL Technologies, 2019. [Online]. Available: http://www.vtol-technologies.com/flying-wing.html. [Accessed 25 4 2023].

[24] M. Frąckiewicz, "What are the factors that affect a drone’s flight time?," TS2, 21 February 2023. [Online]. Available: https://ts2.space/en/what-are-the-factors-that-affect-a-drones-flight-time/. [Accessed 6 May 2023].

[25] X. Kan, J. Thomas, H. Teng, H. G. Tanner, V. Kumar and K. Karydis, "Analysis of Ground Effect for Small-scale UAVs in Forward Flight," IEEE ROBOTICS AND AUTOMATION LETTERS, 2019.