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Design and fabrication of Bioinspired UAS by Junior Engineering Students

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Abstract

This study involves a high school student, a sophomore, and a junior-level engineering student in the design, development, fabrication, and integration of a bioinspired Unmanned Aerial System (UAS) that mimics the shape and features of a bat. The UAS, still under development, employs echolocation to map its surroundings, which it then uses to navigate and avoid obstacles during flight. The students are responsible for designing the UAS, developing a mission profile, and conducting vehicle sizing. They select off-the-shelf components, create parametric models using Computer-Aided Design (CAD) software, perform analyses based on these models, update the design, and utilize various fabrication methods, including 3D printing, to build and assemble the vehicle. Electronic components are then integrated into the system. The students involved in the project are at different stages of their academic careers. The high school student gains new skills in computer modeling, testing, integration, and flight, while the college junior students gain early experience with engineering tools and techniques. They also learn the iterative nature of the design process and acquire hands-on experience with research methods, fabrication, and system integration. The paper also explores the students' perspectives on the value of engaging in research early in their academic journeys.

This project aims to develop a sonar-based UAS that uses sound to create a map of its surroundings, enabling the aircraft to navigate and avoid obstacles. The quadrotor design features a central frame made of two stacked carbon fiber plates, with four booms extending from the corners. The front compartment is designed to resemble the head of a long-eared bat, with a speaker placed inside the mouth to emit ultrasonic frequencies, which are then detected by microphones in the ears. The aircraft incorporates custom 3D-printed components, fabricated using a Stratasys F170 Fused Deposition Modeling (FDM) 3D printer, including Electronic-Speed-Controller (ESC) housings, battery box, a sliding door, and the bat head. Each part is designed using SOLIDWORKS. The team aims to meet the mission's requirements by focusing on modularity, accommodating electronics, minimizing weight, and ensuring proper clearances and aerodynamic efficiency. To ensure the structural integrity of the aircraft, the students perform Finite Element Analysis (FEA) and conduct flight tests.

Introduction

This project aims to develop an unmanned aerial system (UAS) that mimics the echolocation behavior of a bat. High school and undergraduate students are involved in the entire design, fabrication and flight process. The UAS will navigate an urban environment using only ultrasonic speakers and microphones, a more cost-effective alternative to the expensive cameras typically used in UASs. The vehicle features a 3D-printed bat head, modularly attached, containing an ultrasonic speaker in the mouth and two microphones in the ears to capture reflections from the sound waves emitted. As part of the design, casings for the electronic speed controllers (ESCs), which regulate the motor speeds, as well as the bat head, are designed and fabricated.

Throughout the development process, several challenges are encountered. Minimizing dead weight and drag while maintaining structural integrity is critical. To address this, components are consolidated into a central area rather than being spread across the UAS, and fillets are incorporated to increase strength. Additionally, holes are added to selected parts to reduce dead weight. Modularity was a key objective, with friction-fit and hook/slot systems used throughout the design.

The ESC casings, which house the controllers for each of the four motors, are 3D-modeled and fabricated to reduce weight, enable cooling, and enhance aerodynamics and flight time. These casings are mounted to the UAS battery casing, and cooling holes are included for airflow. Rather than using four separate ESC casings, two larger casings, each holding two ESCs, are designed to reduce drag. A hook-and-slot system is implemented to allow easy detachment of the battery casing from the ESC casings. During the assembly in CAD, potential conflicts with protruding bearings and bolt heads are identified, and adjustments made by creating provisions on top of the casings to avoid interference. Once finalized, the battery and ESC casings are 3D-printed in two batches using ABS and QSR support material using the Stratasys F-170 printer.

The 3D-printed bat head is designed using SolidWorks to closely resemble the dimensions of a long-eared bat. Various affordable miniature ultrasonic speakers and microphones are reviewed and selected for integration with a microcontroller. The head is designed to hold these components in place using circular slots, and internal tunnels are created to allow the wiring to pass through the back of the head. The ears of the bat are designed to friction-fit into the head using slots and protrusions, while the head itself is attached to the battery casing via a hook-and-slot system. Once the vehicle design is finalized, the wiring for the microphones and speakers is done to meet the project's objectives. Following the design finalization, the bat head and ears are 3D-printed using ABS and QSR support material, and all printed parts undergo a sodium hydroxide bath to remove the QSR support material. The remaining electronics and 3D-printed parts are assembled and wired into the UAS to enable autonomous flight. The flight computer is programmed to navigate the environment using the ultrasonic speaker output and microphone input. Finally, test flights are conducted, and the UAS is refined based on performance feedback.

Literature Review

In this project, research students engage in literature reviews, synthesizing, and documenting their findings. This process not only builds their self-confidence but also encourages them to explore studies beyond the scope of traditional college curricula. Research has shown that students who actively participate in hands-on engineering projects acquire knowledge and skills that surpass those gained through conventional classroom instruction. Kokotsaki et al. [7] argue that student-centered, active learning fosters autonomy, inquiry, goal-setting, collaboration, and improved communication. Such projects accommodate a diverse range of learning styles, promote critical thinking, and encourage reflection. Mills et al. [8, 9] assert that current engineering programs fall short in providing students with adequate design experience, which leads to gaps in communication and teamwork skills. As a result, engineering programs must raise awareness of social, environmental, economic, and legal issues—topics more effectively addressed through project-based learning than traditional classroom settings. Almulla conducted a quantitative study examining the relationship between project-based learning, collaborative learning, and subject-specific learning, demonstrating a positive impact on student engagement [11]. They emphasize the importance of involving university students in research early in their academic journey. Miller et al. [12] explore the benefits of engaging undergraduate students in research, addressing the challenges and opportunities, particularly for underrepresented and minority students. This project provides an invaluable opportunity for research students to enhance their collaboration, communication, and critical thinking skills.

Bioinspired vehicles have been designed and produced for a while [4, 5]. The Plecotus austriacus (Grey Long-Eared Bat or GLEB) depicted in Figure 1 belongs to genus Plecotus. Razgour et al. report that GLEB are native to mainland Europe with traces in the United Kingdom and Sweden and weighs between 7 to 12 grams [1]. The average forearm length for a GLEB is 39.5 millimeters (mm) for males and 41.2 mm for females, and the average tragus width is generally more than 5.5 mm [1, 2]. GLEB fur colors are generally greyer in appearance with white on its underside. GLEB head muzzles are broader, longer, and dog-like, and GLEB ears are often longer. GLEB often roosts on buildings, crevices, or timbers, and they emerge 45-55 minutes after sunset.

Figure 1: Plecotus austriacus (Grey Long-Eared Bat) [3]

The average call duration of a GLEB is 3 milliseconds (ms), and the inter pulse interval is 105.0 ms. The average peak frequency of GLEB call is 32.6 kilohertz (kHz), the average start frequency is 43.4 kHz, and the average end frequency is 23.6 kHz. The frequency recordings of the GLEB echolocation calls are provided in Figure 2. Eliakim et. al created a bat-like terrestrial robot called a “Robat” that relies on echolocation to autonomously navigate and map an environment based on sound [4]. Similarly, several other robots and other machines have been created that use acoustics as their primary sensor for measurements and making decisions.

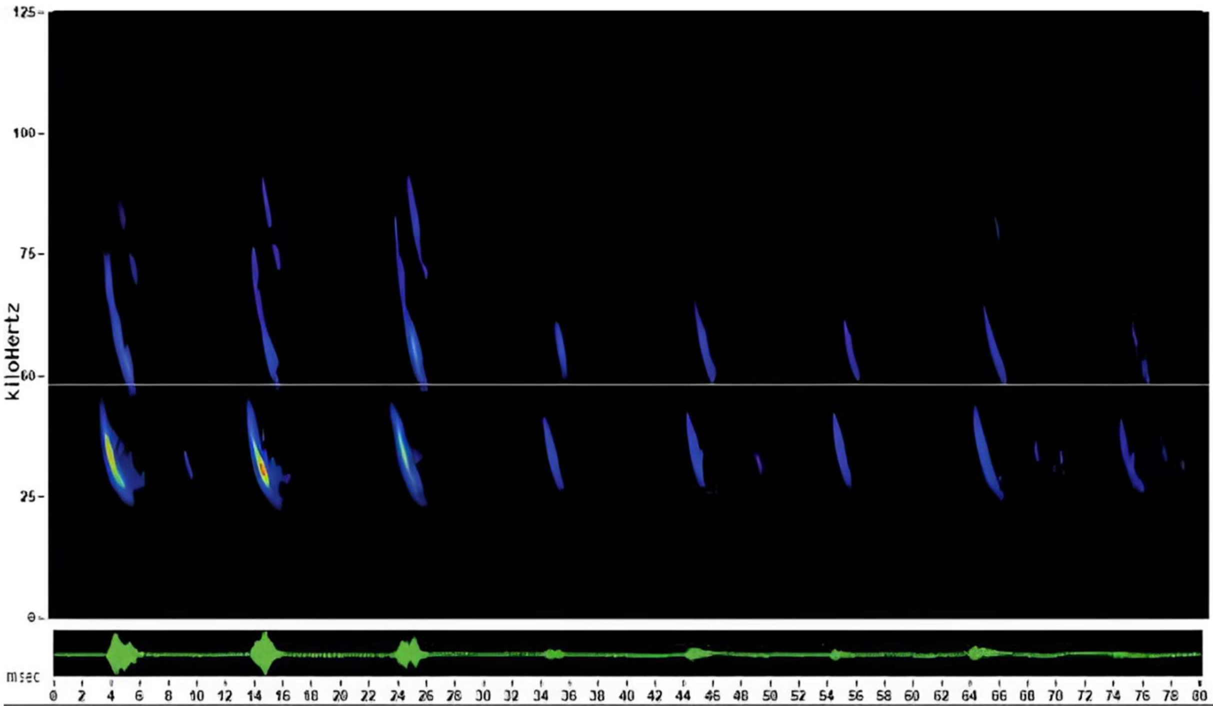

Figure 2: Grey Long-Eared Bat (Plecotus austriacus) echolocation calls. Frequency measured along the ordinate in kHz, and time measured along the abscissa in milliseconds (ms). [2]

Methodology

Engaging undergraduate students in research offers numerous benefits to students. In this study, we investigate the experience of undergraduate students who take part in the design and development of a bioinspired UAS. The research students involved in this study include one college level junior, one sophomore and a high school student. Their tasks include but are not limited to:

1. Conduct literature review
2. Create CAD models by reverse engineering the shape and size of a long ear bat
3. Perform computer simulations including Finite Element Analysis (FEA)
4. Fabricate components using 3D printing and other techniques
5. Perform weight and balance calculations
6. Perform trade studies (motor, battery, prop, flight computer etc. selection)
7. Integrate system and test fly the aircraft
8. Draw inferences and write report

By involving undergraduate research students in this study, their interest and engagement in the subject seems to increase as indicated by their comments listed in the student reflections section. Their perspectives on performing literature review, going through the aircraft design process, research training, conducting experiments, collecting, and compiling data, and performing comparative analyses is discussed. Their responses are indicative of the positive impact of engaging undergraduate students in research on their desires to pursue STEM career paths.

Design, Fabrication and Integration

The goal of this research project is to replace complex and expensive sensors including optical, thermal or infrared sensors on UASs by simple, effective and inexpensive acoustic sensors. This research will help determine the feasibility and application of such sensors in various UAS working environments including congested airspaces, ground obstacles, and for indoor navigation.

Bat inspired UAS are designed and fabricated in this project. The design and fabrication are completed by the high school and junior undergraduate students. The CAD model of the bat UAS is shown in Figure *3*. All the modeling is done using SolidWorks. Students are involved in the design, analysis, iteration, fabrication and testing phases. The fuselage is made of carbon fiber. All the electronics including the flight computer, Electronic Speed Controllers (ESCs), receiver, GPS, accelerometer, gyroscope, motors, and propellers are sized for the aircraft and acquired off the shelf. The aircraft is designed to fly for 15 minutes and can carry up to 5 pounds of payload. Students also performed weight and balance calculations. Students designed the ESC and battery boxes. Finite Element Analysis (FEA) is performed to ensure that the boxes are strong enough to sustain the static and flight loads.

Every 3D printed part which made it into the final design is printed using Stratasys F170 Fused Deposition Modeling (FDM) 3D printer using ABS plastic filament with a 43% infill, a 45% infill angle, and a 0.06-inch body thickness. A photo of the assembled aircraft is displayed in Figure *4*.

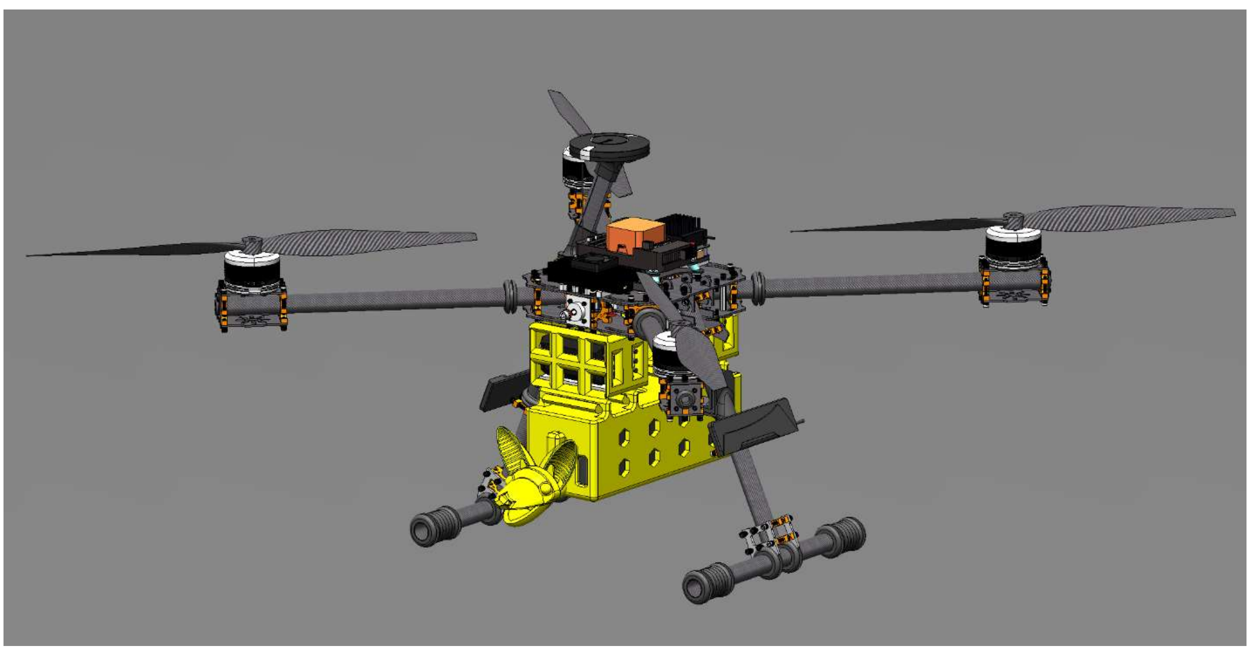

Figure 3: 3D CAD Model of Bat UAS

Figure 4: Photo of Assembled Bat UAS

Speaker and Microphone

Speaker and microphone trade study is an example of the studies performed by the students. A Pro-Wave Electronics (400EP125-NBWN) Speaker shown in Figure *5* projects sound used for echolocation from the bat head's mouth. The speaker can produce sounds up to 40KHz with a Sound Pressure Level (SPL) of 100dB, and its dimensions are 9.5 mm in length with a 12.5 mm diameter [5]. An individual Sonorous Objects SO.2 Ultrasonic Omnidirectional Lapel Lav Microphone from Figure *6* is placed inside each ear to receive the sounds projected by the speaker to map out and navigate terrain. Each microphone uses an omnidirectional polar pattern, allowing them to equally pick up sound from all directions [6]. Their frequency response ranges from 20KHz to 70KHz with a self-noise of 20dBA, a dynamics range of 95dB, and a maximum input SPL of 155dB while also maintaining a small form factor of 13 mm in length and 7.7 mm in diameter.

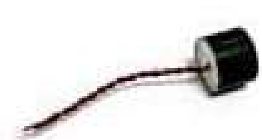

Figure 5: Pro-Wave Electronics (400EP125-NBWN) Speaker *[5]*

Figure 6: Sonorous Objects SO.2 Ultrasonic Omnidirectional Lapel Lav Microphone *[6]*

Weight Breakdown

The weight and balance analysis is performed by the sophomore student. An estimated weight breakdown of the Bat UAS is shown in **Error! Reference source not found.**. It includes the corresponding masses of each subassembly and their contributions in percentages to the UAS's overall estimated mass. The overall measured mass of the UAS is included for reference.

Table 1: Bat UAS Weight Breakdown

Assemblies	% of Overall Mass	Estimated Mass (g)
Electronics	45.61%	1912.64
Frame	16.99%	712.51
Propulsion	23.74%	995.48
3D-Printed Parts	13.65%	572.53
Assemblies to Overall Estimated Mass	100.00%	4193.16
		Measured Mass (g)
Overall Measured Mass		3761

Analysis and Results

A tolerance of 3D printed parts trade study is performed by the sophomore students. To ensure that the printed parts would fit together in physical space, the distance between the adjacent surfaces of the mated parts, or the "clearance", is first determined. General clearances between mated parts such as the bat head mounting bracket and battery box as well as the battery box handles and ESCs are determined during the prototype phase for the sliding door. Several scaled-down models of the door are printed using a Dremel DigiLab 3D45 3D printer. The prototype doors are made in various sizes to determine the amount of clearance needed between the sliding door and its battery box insert in the final design. An assembled prototype shown in Figure *7* and Figure *8* mimics the door used for the battery box, and the figures depict the intended functionality of the prototype door sliding in and out of its insert. End results show that a clearance of 0.3 mm between the prototype door and the insert is most optimal in terms of sliding the door securely into the slot without it being too large to fit or small enough to wiggle. Following this analysis, a general clearance of 0.3 mm is used in the final design for the door and the other mated 3D printed parts located throughout the UAS. This trade study helps build confidence in the student to perform engineering analyses and make decisions based on their findings.

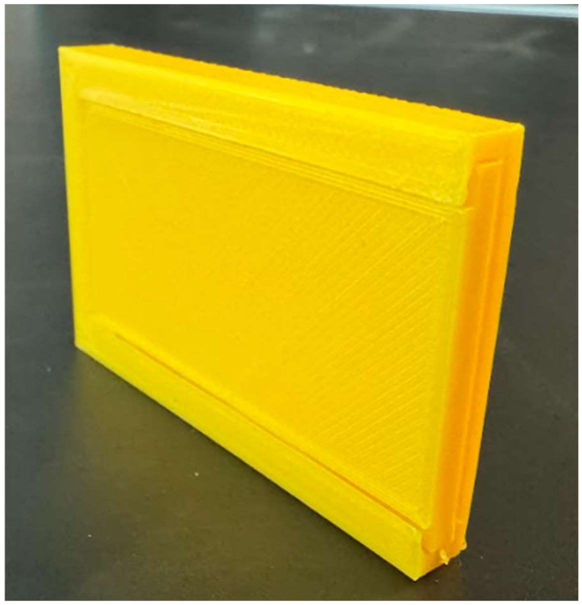

Figure 7: Printed Prototype Door Assembly (Closed)

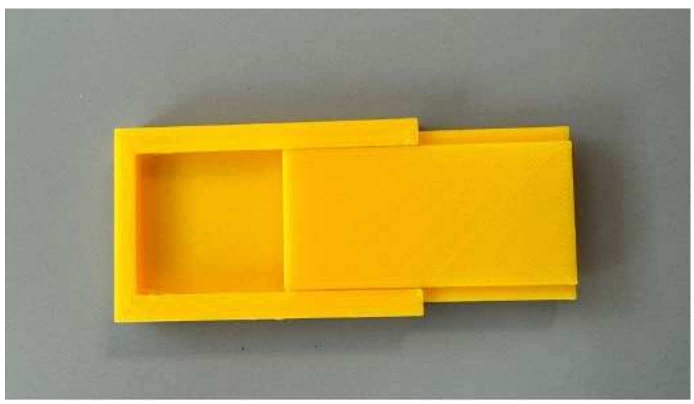

Figure 8: Printed Prototype Door Assembly (Open)

FEA Analysis

One junior student is in-charge of the FEA analysis. An FEA analysis is performed on two iterations of the ESC and battery box assembly to examine their structural strength and points of weakness. The first iteration of the model contains no holes around the battery box, while the second iteration includes hexagon shaped holes around the battery box allowing for cooling of the battery and reducing weight added to the aircraft. A distributed load of 0.202 kg (Kilogram) is applied to the inner bottom wall of both ESC boxes representing the weight of two KDE-UAS55HVC ESCs in each box. Another distributed load of 0.825 kg is applied to the inner bottom wall of the battery box representing the weight of a HRB 6S 6000 mAh Lipo Battery. The yield strength of ABS is 6,445.985 psi (pounds per square inch), this is the average yield strength of ABS at a 40% infill percentage, the percent at which the assembly is printed. The mesh results of the first iteration model include 252,595 triangular nodes and 146,581 elements. The mesh results of the second iteration model includes 251,736 triangular nodes and 45,626 elements. The results of the von Mises stress for both models concluded a yield strength of 4.4 x 10^7 N/m^2. Both iterations of the model experienced the greatest stress around the hooks of the ESC boxes and handles of the battery box. The first iteration model produced a maximum stress of 3.4 x 10^5 N/m^2 which is 4.3 x 10^7 N/m^2 less than the yield strength. The second iteration model produced a maximum stress of 2.8 x 10^5 N/m^2 which is 4.3 x 10^7 N/m^2 less than the yield strength. Both analyses showed the maximum stress being less than the yield strength, suggesting the assemblies are strong enough to handle the applied loads to be placed in each respective box.

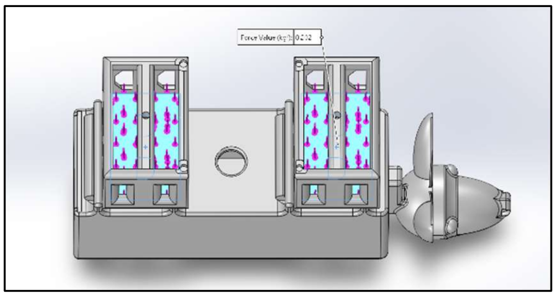

Figure 10: Distributed Load on ESC Boxes of First Iteration Model

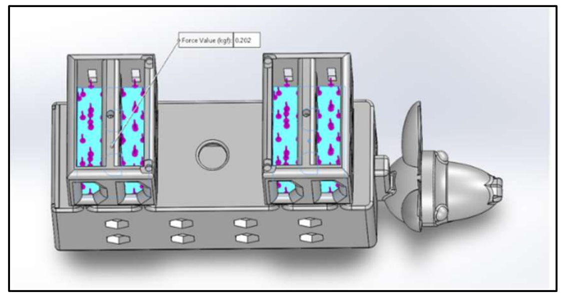

Figure 9: Distributed Load on ESC Boxes of Second Iteration Model

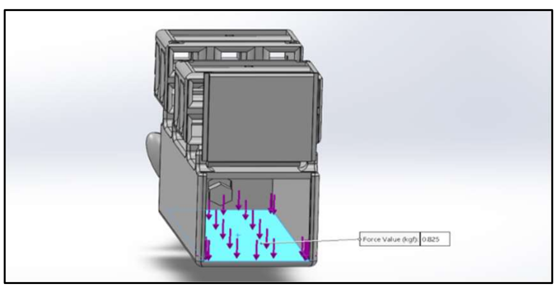

Figure 12: Distributed Load on Battery Box of First Iteration Model

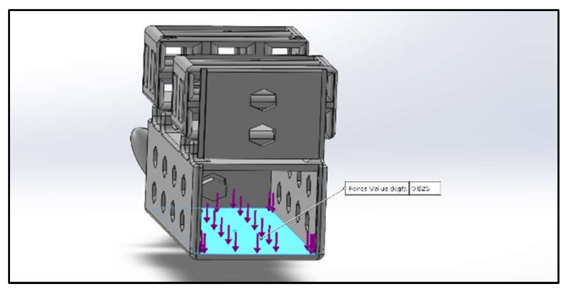

Figure 11: Distributed Load on Battery Box of Second Iteration

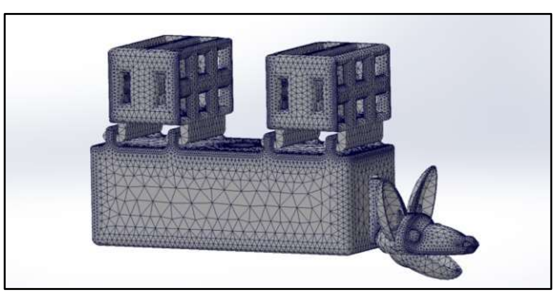

Figure 14: Mesh Results of First Iteration Model

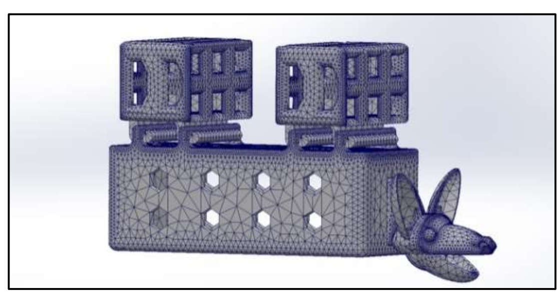

Figure 13: Mesh Results of Second Iteration Model

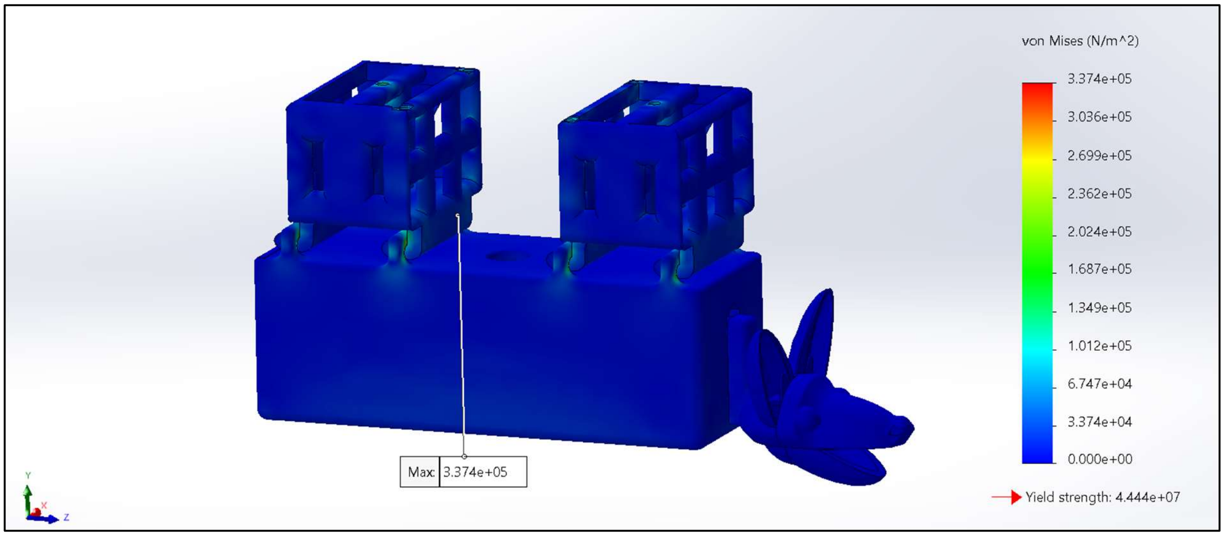

Figure 15: Results of Von Mises Stress of First Iteration Model

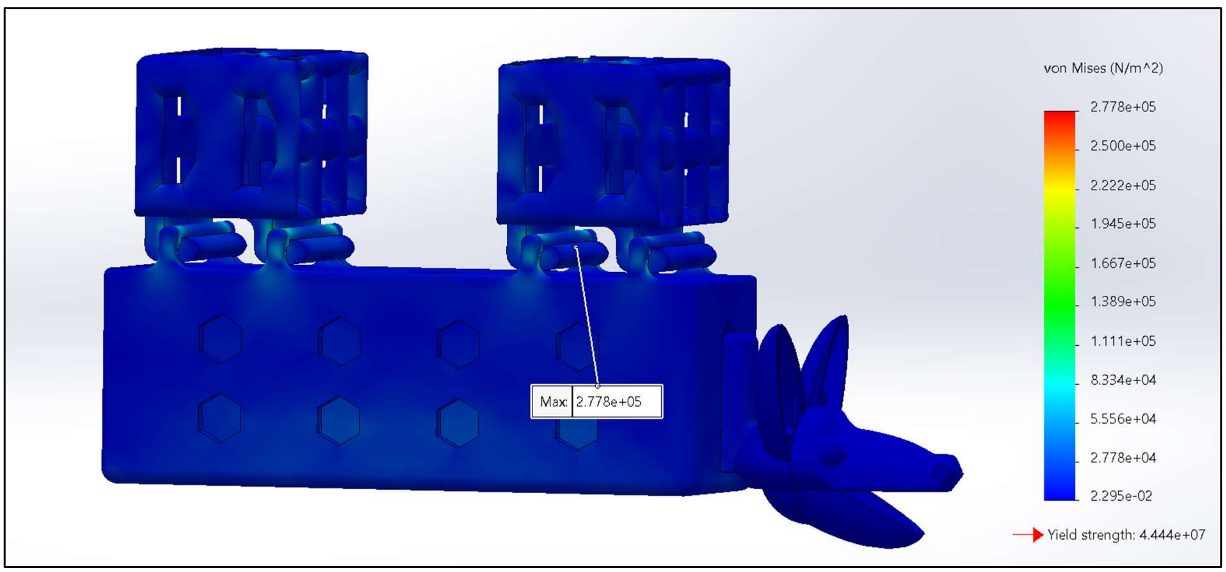

Figure 16: Results of Von Mises Stress of Second Iteration Model

Figures 9 and 11 show the distributed load on ESC boxes in the first iteration. After the holes are added to the battery box, the same distributed load is shown in Figures 10 and 12 from a different angle. The mesh for the first iteration is shown in Figure 13 and the mesh for the second iteration is shown in Figure 14. Similarly, the Von Mises stresses and the maximum locations of stresses for the first and second iterations are shown in Figures 15 and 16 respectively. This analysis helps the students understand a) saving weight is an important part of aircraft design because it could help improve the flight performance and b) how weight can be reduced on an aircraft without compromising the structural strength.

Student Reflections

In this section, student reflections are included. Students are asked the following questions specifically in the context of working on this UAS design and fabrication project. Their answers reinforce the importance of involving students in research studies. Questions and student answers are presented below.

1. **What motivated you to participate in this research project?**

The sophomore student mentioned

"The opportunity to apply my SOLIDWORKS CAD modeling skills and gain experience in 3D printing. Additionally, being introduced to things outside my area of focus such as soldering electrical components."

The junior student said

"I wanted to get involved in the research project because I saw it as a good opportunity to apply what I've been learning in class and gain hands on experience. I also felt it would allow me to learn new skills that are not typically covered in the classroom."

The high school student remarked

"In pursuit of a career as an aerospace engineer, I wanted to have experience in aerospace engineering outside of school. Dr. [] introduced me to this project, and it seemed very interesting to me, and I thought this was a step in the right direction to learn more about aircraft technology."

2. **What have you gained / expect to gain by participating in this research?**

The sophomore student asserted

"I have gained further insight into Design for Manufacturing (DFM) principles. For instance, I learned the design elements that must be considered when additively manufacturing parts for an unmanned aircraft using 3D printing technology."

The junior student remarked

"Through this research, I've gained several valuable skills. I've gained practical skills like soldering, 3D printing, and learned to use new tools in SolidWorks, including how to perform an FEA analysis. Additionally, working with a team has helped me develop stronger collaboration and communication skills."

The high school student explained

"At the beginning of this project, I had very little experience in 3D modeling. After creating several iterations for various components for this project, I felt like I had enough experience with CAD to tackle any problem that comes my way."

3. **What has worked well in the overall research process?**

The sophomore student indicated

"Communication with team members through in-person meetings, cloud-based services such as Microsoft OneDrive, and Outlook email have all proven effective. Also, giving students the opportunity to test fly in order to examine flight performance of the unmanned aerial systems."

The junior student asserted

"The research process has been effective due to its structured approach, with weekly meetings, clear task assignments divided among team members, and documentation. We were also adaptable to any challenges that came up, for example, when the battery box broke, a new one was quickly designed and developed."

The high school student mentioned

"During the research process, I think what worked well is how I constantly had something to work on and wasn't left with nothing to do at any moment in the process. Also, the constant advice Dr. [] gave made all of the components of the project the best they could be."

4. **What are your plans after graduation? How has this research experience influenced your plans to work in a specific field (post graduation education, specific industry, academia etc.)?**

The sophomore student remarked

"I plan to enter the job market in an effort to become a Product Design Engineer. My decision is influenced by my enjoyment working with CAD software throughout this research experience."

The junior student implied

"After graduation, I plan to pursue a master's degree. This research experience has broadened my understanding of the various areas involved in creating a product. I've particularly enjoyed working on the avionics side of the project, which has sparked my interest in the electrical and electronic aspects and given me something to consider as I move forward with my studies."

The high school student suggested

"Before coming to the AERO Lab, I knew I wanted to pursue a career in aerospace engineering. However, I was unsure what specifically I wanted to work on as an aerospace engineer. Working on this project gave me some inspiration for a potential career in UAS development."

5. **How can the process be improved to make this research more meaningful?**

The sophomore student suggested

"A neat and clearly defined outline of the research process from start to finish with tentative due dates for tasks should be provided to students at the start of every project. This would help students manage their schedules, and it would be meaningful in teaching them to more effectively pace their workflow."

The junior student remarked

"Overall, I think the research process has been well-organized and effective. To enhance it further, conducting more field tests and performance analysis would help us gather valuable data and gain experience with new tools to optimize the design and improve the research."

The high school student asserted

"This project could be more meaningful if it had a more practical impact. For example, the project could be modified to be used in search and rescue."

These responses and recommendations are insightful and could help make the experience even more meaningful for the future students. As can be seen from the student responses, the overall experience of working on this research project has motivated students to pursue the STEM careers and even a graduate degree. The author recommends that students at undergraduate and some at high school levels are involved in research projects. This not only benefits the students, but could also help the research team achieve their greater goals.

Conclusions

Two undergraduates and one high school student is involved in a research project to design and develop a UAS. Through iterative design and fabrication, the project developed a cost-effective SONAR based UAS that can mimic bat behavior. A map of the surroundings of aircraft will be generated using ultrasonic signals which is used to navigate through spaces avoiding obstacles. The UAS utilizes a quadcopter design, with two stacked carbon fiber plates form the central frame with each of the four booms extending from its corners. By incorporating speakers and microphones inside the mouth instead of integrating cameras and sensors, it provides a more cost-effective solution for navigation. Finite element analyses were conducted to assess the structural strength and points of weakness of the assembly. These analyses showed the maximum stress is less than the yield strength, suggesting the assemblies are strong enough to handle the applied loads to be placed in each respective compartment. Student reflections indicate that their involvement in the research project helped enhance their interest in engineering and that they learned new skills that they would otherwise not have learned in traditional classroom. Training junior students takes time and effort but the benefits outweigh the cost. Given the benefits to the research lab, faculty and especially the students, the author recommends that most researchers consider involving undergraduate students in their research projects.

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