Design and Development of Bat-Inspired Unmanned Aerial System for Mapping and Navigation

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This project develops a sonar-based Unmanned Aerial System (UAS) inspired by bat echolocation. The UAS uses a quadcopter design with a bat-like front, where a speaker emits ultrasonic frequencies, and paired microphones capture the echoes to map its surroundings and avoid obstacles. Custom 3D-printed components, designed in SOLIDWORKS and fabricated with a Stratasys F170 FDM printer, form the ESC housings, battery box, sliding door, and bat head. Finite Element Analysis (FEA) verified the structural integrity of these parts. Following the integration of the necessary electronics, a two-minute hover test confirmed stable performance and effective maneuverability.

I. Introduction

Efficient navigation of urban environments is a primary challenge for Unmanned Aerial Systems (UAS). Existing approaches typically rely on expensive sensors and cameras, which drive up the cost and complexity. Leaning on the echolocation of bats, this project proposes a sonar-based UAS that utilizes ultrasonic waves and reflections to navigate and create a map of its surroundings.

The system uses a quadcopter design, featuring a robust structure made around two stacked carbon fiber plates and four supporting booms. Its bat-inspired front compartment houses an ultrasonic speaker intended for ultrasonic pulse emission, mimicking a bat's mouth, while a pair of microphones is used to capture the returning ultrasonic echoes. The full sonar mapping functionality remains to be integrated and tested.

Custom components, including ESC housings, a modular battery box, and a sliding door mechanism, were designed in SOLIDWORKS and 3D printed with a Stratasys F170 Fused Deposition Modeling (FDM) 3D printer. Finite Element Analysis (FEA) was used to verify the structural integrity of the parts. Initial flight tests, conducted using flight electronics that were flight-critical, verified the system's stability and maneuverability of the system, laying the foundation for integration of the sonar mapping system.

II. Literature Review

A. Bat Information

The *Plecotus austriacus* (Grey Long-Eared Bat or GLEB) depicted in *Figure 1* belongs to genus Plecotus. Razgour et al. [1] reports that GLEB are native to mainland Europe with traces in the United Kingdom and Sweden, and GLEB weigh between 7 to 12 grams. Back from the Brink [2] states that 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. They describe GLEB head muzzles as being broader,longer, and dog-like, and GLEB ears are often longer.[1]

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

B. Frequency Range

Back from the Brink [2] states that the average call duration of a GLEB is 3 milliseconds (ms), and the inter pulse interval is 105.0 ms. They report that 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*.

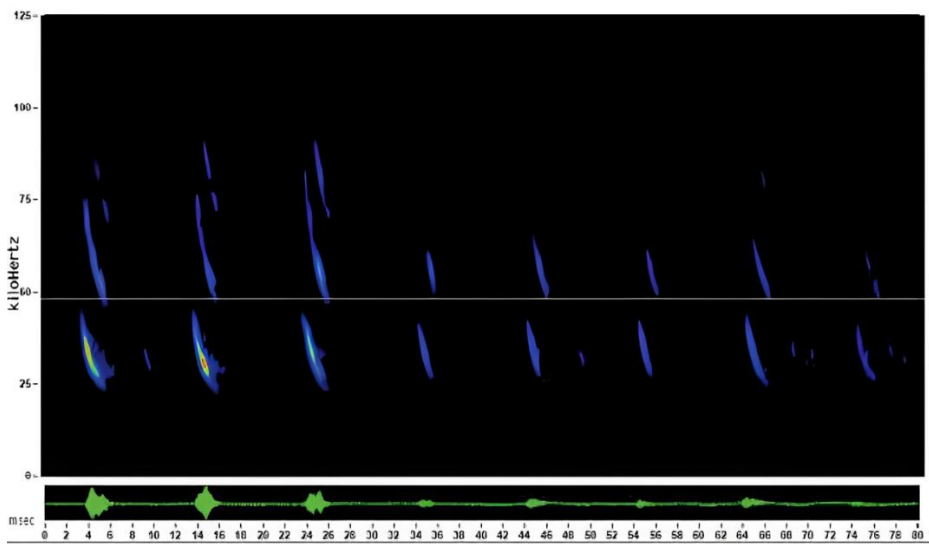

Figure 2: Grey Long-Eared Bat (Plecotus austriacus) echolocation calls. Frequency measured along the ordinate in kHz, and time measured along the abscissa in milliseconds (ms). *[2]*

C. Examples of Bat-Inspired Designs in Literature

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].

II. Bat-inspired UAS Design

The CAD model of the bat drone shown in *Figure 3* was taken directly from SOLIDWORKS. Every 3D printed part which made it into the final design was printed inside a 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*.

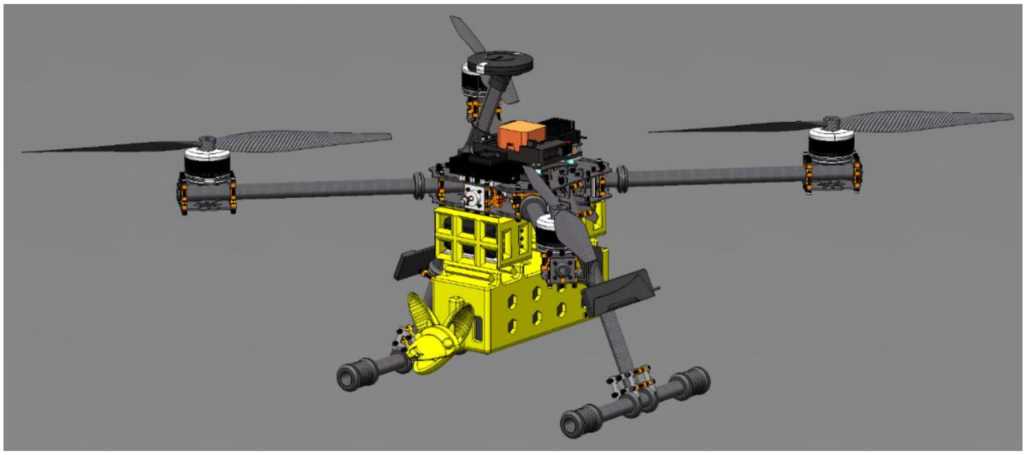

Figure 3: 3D CAD Model of Bat UAS

Figure 4: Photo of Assembled Bat UAS

A. Speaker and Microphone

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 9.5mm in length with a 12.5mm 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 13mm in length and 7.7mm in diameter.

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

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

B. Weight Breakdown

An estimated weight breakdown of the Bat Drone is shown in **Table *1***. It includes the corresponding masses of each subassembly and their contributions in percentages to the drone's overall estimated mass. The overall measured mass of the drone is included for reference.

Table 1: Bat Drone 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

III. Analysis and Results

A. Clearance Analysis between Mated Parts

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 were determined during the prototype phase for the sliding door. Several scaled-down models of the door were printed using a Dremel DigiLab 3D45 3D printer. The prototype doors were 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. The associated dimensions for the prototype can be found in the Appendix. End results showed that a clearance of 0.3mm between the prototype door and the insert were 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 0.3mm was used in the final design for the door and the other mated 3D printed parts located throughout the drone.

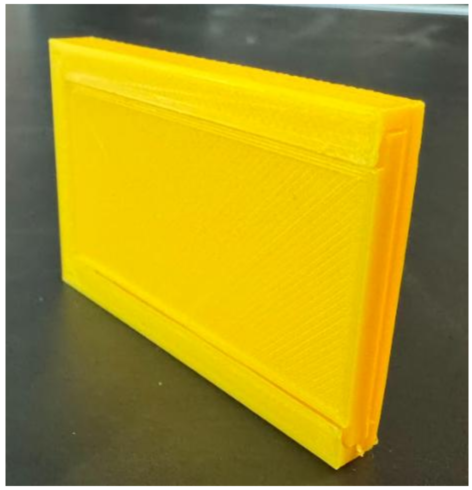

Figure 7: Printed Prototype Door Assembly (Closed)

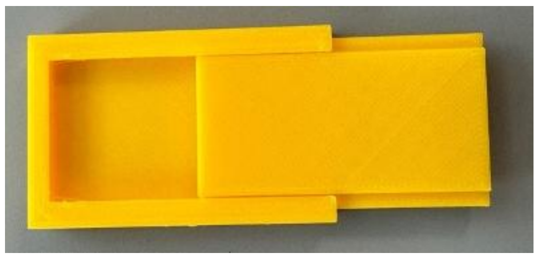

Figure 8: Printed Prototype Door Assembly (Open)

B. FEA Analysis

An FEA analysis was performed on two iterations of the ESC and battery box assembly to examine its structural strength and points of weakness. The first iteration of the model contained 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 was 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 0.825kg was applied to the inner bottom wall of the battery box representing the weight of a HRB 6S 6000mAh Lipo Battery. The yield strength of ABS was set to 6,445.985 psi, this is the average yield strength of ABS at a 43% infill percentage, the percent at which the assembly was to be printed at. The mesh results of the first iteration model included 252,595 triangular nodes and 146,581 elements. The mesh results of the second iteration model included 251,736 triangular nodes and 45,626 elements. The results of the von Mises stress for both models concluded a yield strength of 4.4e+07 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 3.4e+05N/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 2.8e+05N/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.

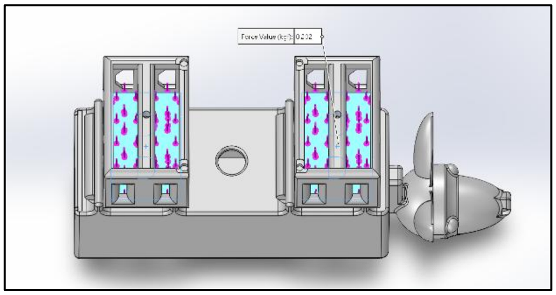

Figure 9: Distributed Load on ESC Boxes of First Iteration Model

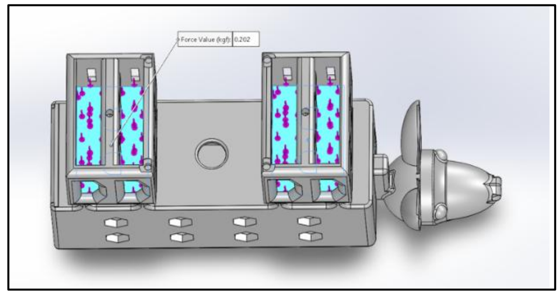

Figure 10: Distributed Load on ESC Boxes of Second Iteration Model

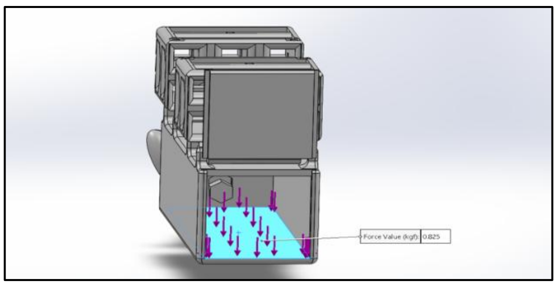

Figure 11: Distributed Load on Battery Box of First Iteration Model

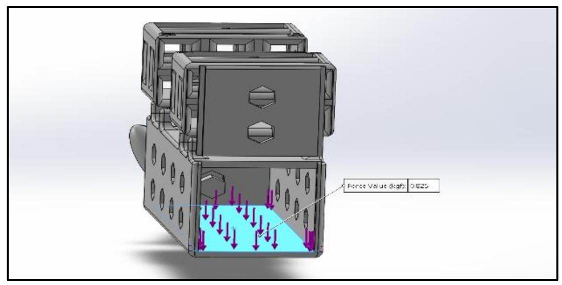

Figure 12: Distributed Load on Battery Box of Second Iteration

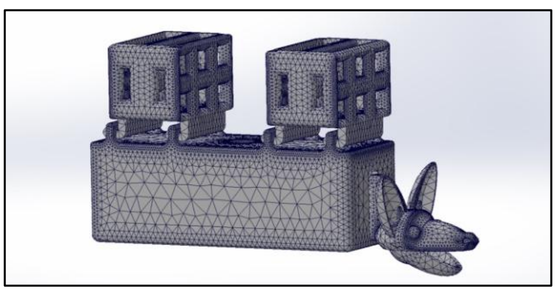

Figure 13: Mesh Results of First Iteration Model

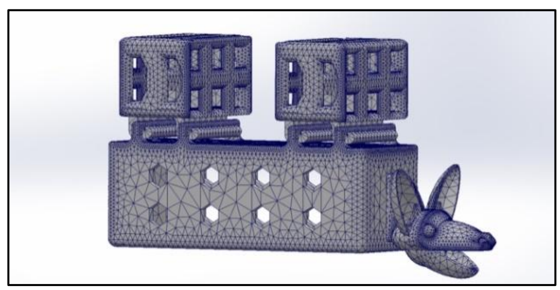

Figure 14: Mesh Results of Second Iteration Model

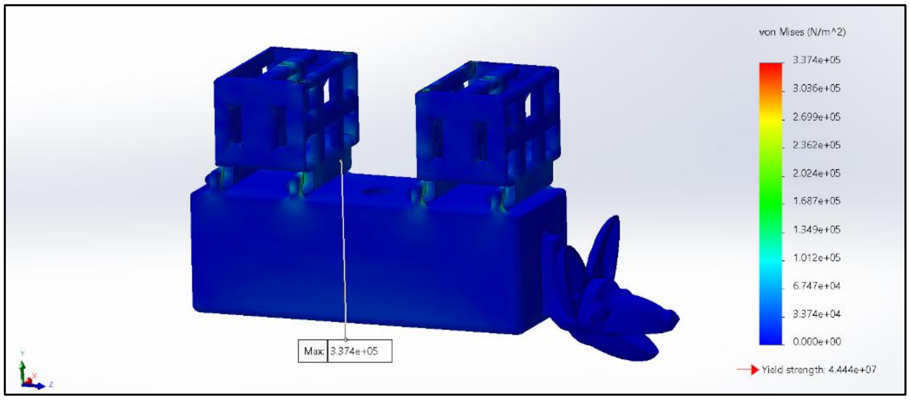

Figure 15: Results of Von Mises Stress of First Iteration Model

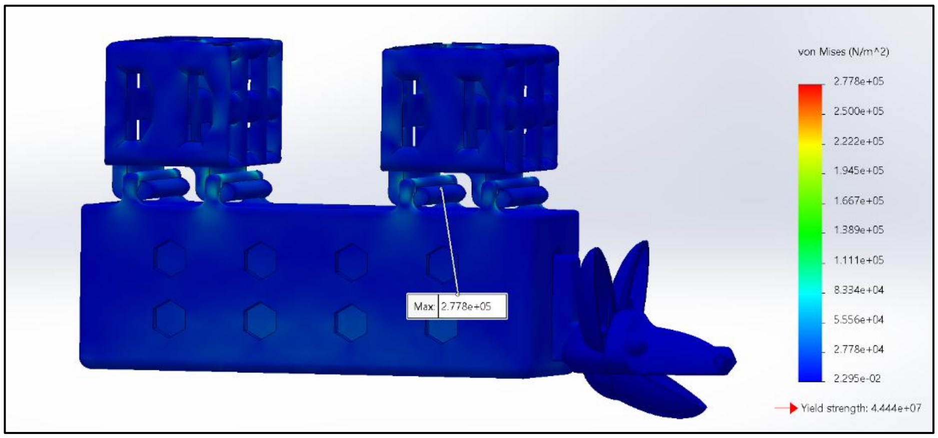

Figure 16: Results of Von Mises Stress of Second Iteration Model

IV. Flight Test

During an outdoor flight test with a remote control, shown in *Figure 17*, the UAS was evaluated for its basic flight performance. During a one-minute test, the vehicle maintained steady while hovering at approximately five feet, executed controlled turns, and executed basic directional maneuvers without experiencing any abnormal behaviors or performance issues. This flight test confirms that the flight-critical electronics and control systems are operating consistently in real-world conditions, and this provides a strong foundation for the eventual integration of the entire sonar mapping system.

Figure 17: 5-foot Hover Test

V. Conclusion

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 that 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.

References

[1] O. Razgour, D. Whitby, E. Dahlberg, K. Barlow, J. Hanmer, K. Haysom, H. McFarlane, L. Wicks, C. Williams and G. Jones, "Conserving grey long-eared bats (Plecotus austriacus) in our landscape: a conservation management plan," University of Southampton, Southampton, 2013.

[2] Back from the Brink, "Guide to identifying longeared bats in Britain," Back from the Brink, London, 2020.

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[4] I. Eliakim, Z. Cohen, G. Kosa and Y. Yovel, "A fully autonomous terrestrial bat-like acoustic robot," *PLoS Computational Biology,* vol. 14, no. 9, September 2018.

[5] Mouser Electronics, "(Pro-Wave Electronics) 400EP125-NBWN," Mouser Electronics, [Online]. Available: https://www.mouser.com/ProductDetail/Pro-Wave-Electronics/400EP125-NBWN?qs=3Rah4i%252BhyCFPJyW2W27Tsg%3D%3D. [Accessed 16 November 2024].

[6] Sonorous Objects, "SO.2 Ultrasonic Omni Lapel Lav Microphone," Sonorous Objects, 22 December 2021. [Online]. Available: https://drive.google.com/file/d/187CkyWX1MLp4XFQOv_oFFPmgm01IF9rC/view. [Accessed 16 November 2024].

Appendix

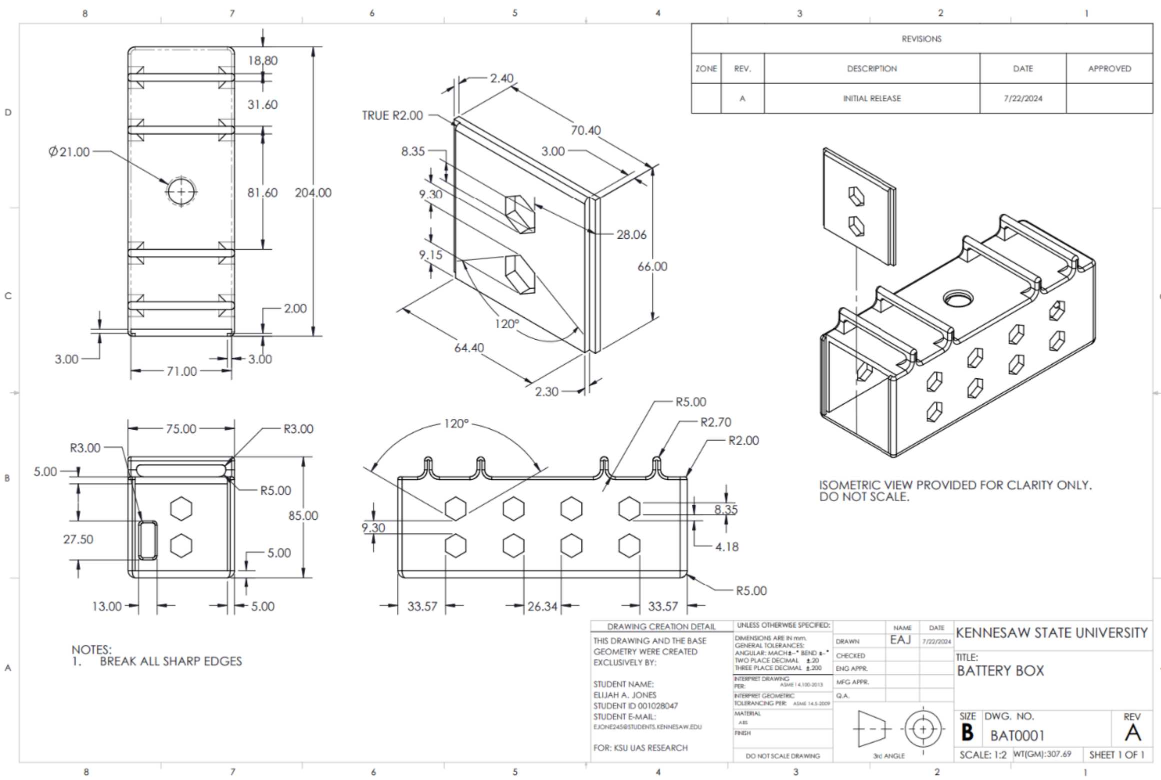

Figure 18: Technical Drawing for Battery Box Assembly

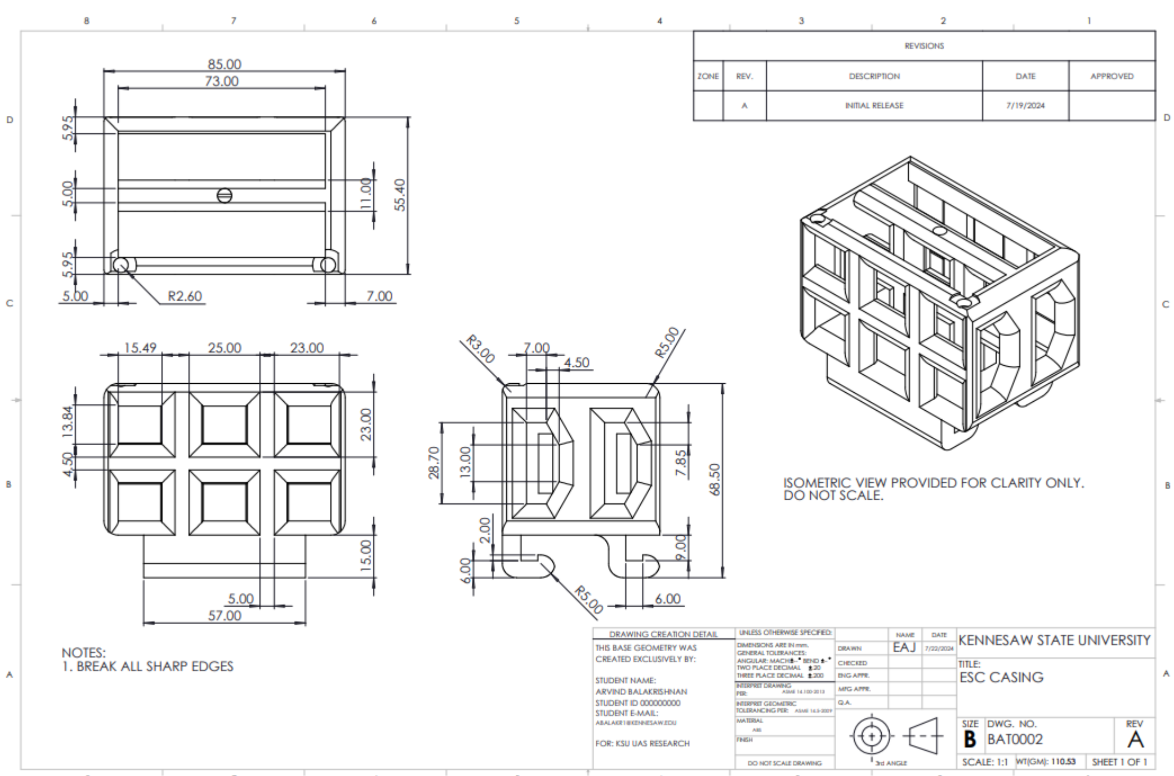

Figure 19: Technical Drawing for Electronic Speed Controller (ESC) Casing

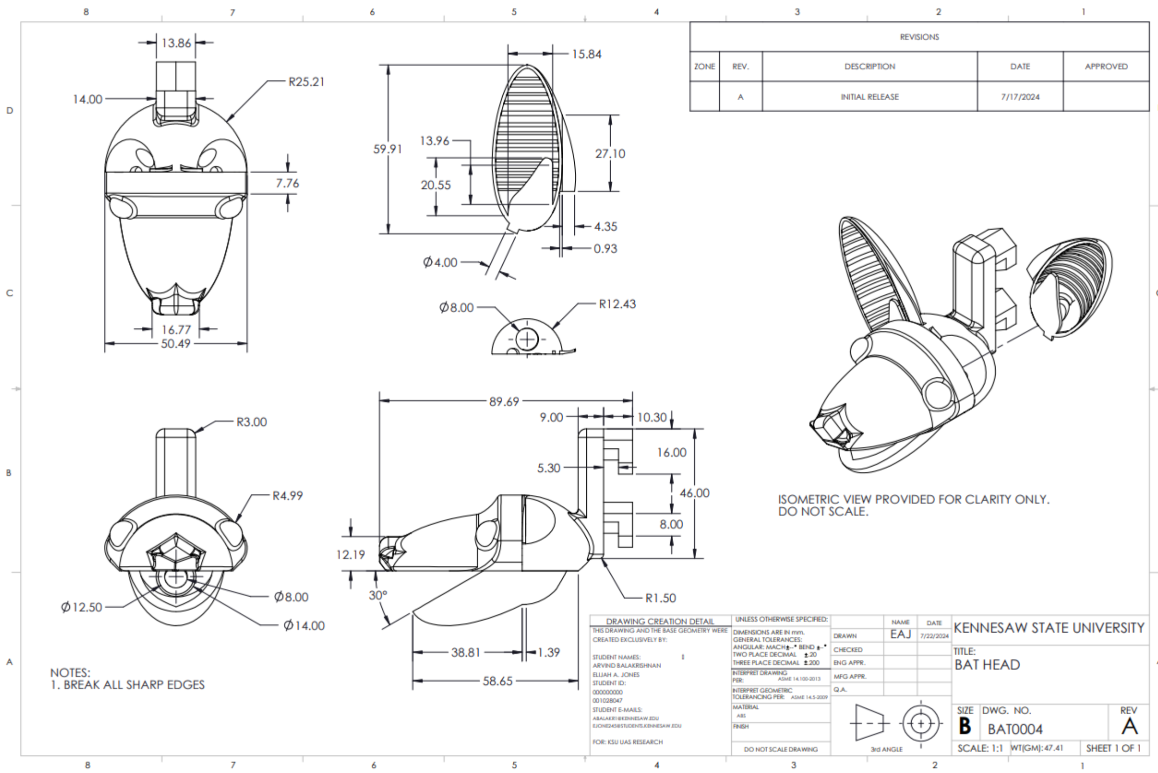

Figure 20: Technical Drawing for Bat Head Assembly

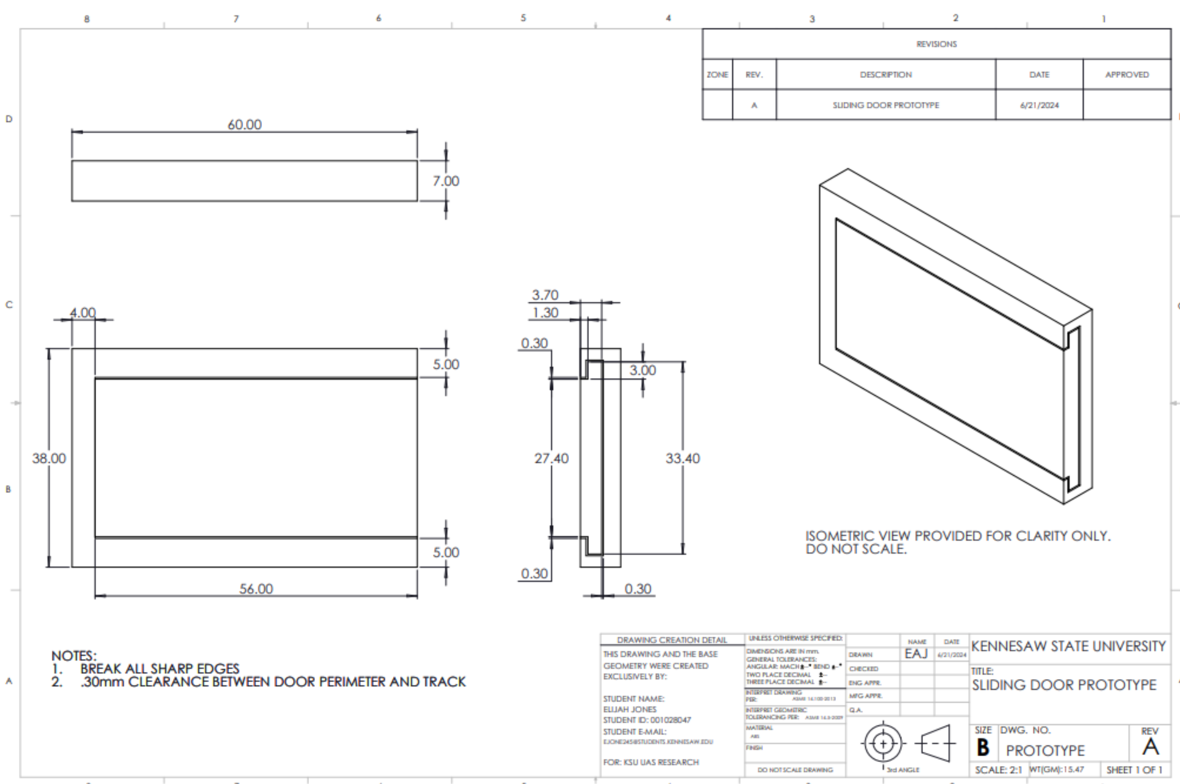

Figure 21: Technical Drawing of Prototype Sliding Door Assembly