Intelligent Ground Vehicle Competition

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Instructor

Ashish Tamhane, Ph.D.

Course

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Advisors

Krishnanand Kaipa, Ph.D., Lee Belfore, Ph.D., Orlando Ayala, Ph.D.

Project Members

Jared DiMillio, Reece Jordan, Angelous Jimenez, Gabriel Rodgers, Christopher Schappi, Jacob Hightower

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ACRONYMS

IGV – Intelligent Ground Vehicle

IGVC – Intelligent Ground Vehicle Competition

ECE – Electrical and Computer Engineering

ODU – Old Dominion University

GPS – Geographic Positioning System

3D – Three Dimensional

MPH - Miles per Hour

FEA – Finite Element Analysis

PETG-HF - Polyethylene Terephthalate Glycol High Flow

G-Forces – Gravitational Forces

MAE – Mechanical and Aerospace Engineering

DC – Direct Current

BLDC – Brushless Direct Current

ABS – Antilock Braking System

AI – Artificial Intelligence

IDE – Integrated Development Environment

PWM – Pulse Width Modulation

USN – United States Navy

ASME – American Society of Mechanical Engineers

IEC – International Electrotechnical Commission

ISO - International Organization for Standardization

ASTM - American Society for Testing and Materials

IEEE - Institute of Electrical and Electronics Engineers

NEPA - National Environmental Policy Act

NEC - National Electric Code

ABSTRACT

This report documents the progress in developing a novel IGV slated for competition in IGVC 2025 at Oakland University. The team's primary goal is to deliver a remote-controlled vehicle by August 2024 that is capable of integrating a state-of-the-art autonomous driving suite. This goal will be met by enhancing an existing frame, redesigning an inherited wishbone suspension system, creating a newly designed deck plate, and developing a hard-wired analog control system. Careful considerations regarding material choice, design geometry, and system architecture were made with respect to factors such as manufacturability, serviceability, cost, and strength. The result of the team's efforts throughout this semester culminated in an improved wishbone, wheel hub, and motion control systems that are ready for prototyping and implementation onto the IGV. Planned for the spring and fall of 2025 is verification testing of all components to confirm proper functionality in the anticipated operating environments. To aid in the Intelligence of the IGV, the ground vehicle will be retrofitted with lidar sensors and computational hardware in cooperation with the ECE department to enable its autonomous operation and development of training data.

INTRODUCTION

Intelligent ground vehicles, or autonomously operating vehicles, are becoming increasingly prevalent within many industries, some of which include automotive, food delivery, manufacturing, and military-industrial complexes [1]. Applications like lane detection in driverless taxis, autonomous delivery robots, and military transport vehicles all fall under the IGV classification [1]. In the case of ODU's IGV, autonomous mobility will be executed by an onboard autonomy suite that enables the vehicle to navigate a course without human input. The autonomy suite will be designed around a type of autonomous navigation known as behavioral cloning which utilizes training data collected from human-navigated trials and creates navigational guidelines based on observed patterns. This method of autonomous training enables the human operator to define reactions to observed phenomena and implement algorithmic learning to efficiently learn how to navigate a predetermined environment [2]. Previous implementations of autonomous driving at ODU have explored a method known as fuzzy control, which consists of an algorithm that sends out virtual tentacles to determine the system's distance from obstacles and maneuver around them [3]. Both methods mentioned above can be assisted by GPS positioning and lidar sensors to determine if the autonomous system is on the appropriate course [4].

To encourage the development of novel designs for autonomous navigation systems, the IGVC was created in 1993 for engineering students to develop intelligent vehicles to compete in a nationwide competition [5]. The primary objective of this competition is to develop a system capable of navigating autonomously through a standardized course. Critical design considerations that impact an autonomous platform are the range, size, distance, overall weight, payload weight, and expected terrain it will experience [1]. In the past, ODU has participated in the IGVC, where an electric mobility chair was adapted to satisfy the aforementioned criteria. Since ODU's IGVC debut, a new platform designed from the ground up has been in development and inherited by our team. This existing platform will be adapted to fulfill the needs of the competition while defining its speed, motor size, and bed size. As a result, the purpose of this project is to continue the development of an efficient IGV platform from the ground up that can be adjusted continuously for future competitions. This will enhance the team's ability to create a more robust vehicle with higher reliability, greater payload capacity, and a wider range of tasks that can be accomplished.

METHODS

Project Management

Within the world of project management, two main methodologies drive how products are manufactured and developed: lean manufacturing and agile. Lean manufacturing can be described as traditional manufacturing that focuses on reducing waste and standardized procedures. The management of IGV needs to be flexible, quick-reacting, and fluid in communication, because of the multidisciplinary nature of the project and team. Agile can be described as a way to produce products in a more flexible and adaptable manner than traditional lean manufacturing. This is accomplished through weekly check-ins, constant communication, and the determination of requirements from the beginning. Laying out the requirements in a list enables all team members to know what is expected and the tasks that must be accomplished. Since the team has a low budget and needs to reduce waste while producing products quickly, the blended agile and lean management style was adopted. The list of requirements and constant communication mentioned above facilitate this process. To create a work environment catering to the needs of the team, the manager schedules meetings through a group message board to keep all members informed of goals, requirements, changes, and deadlines approaching. The manager also takes a similar approach to communicating with the advisors, holding monthly meetings between the team and advisors up until November. The manager can quickly track all progress and issues that arise with a quick check on parts and assemblies utilizing a cloud-based storage system and then inform the team to move forward with rapid prototyping. To produce prototypes and products quicker and at the same time, reduce waste and cost. The manager utilizes rapid prototyping technologies such as additive manufacturing processes and CAD software.

Wishbone Suspension

The wishbone suspension system for the IGV is made up of 3 primary component types. These are The motor hubs, the wishbones, and the wishbone brackets. The motor hubs are bespoke, machined aluminum parts that encase the hub motor. The wishbones, upper and lower, are assemblies that connect the wheel hub assembly to the frame and create a linear travel for the hub. The wishbone mounts are 3D-printed components that mount the upper and lower wishbones to the chassis. In the case of the upper mount, it also provides a location for the shock to compress into. This overview can be best seen below in Figure 1.

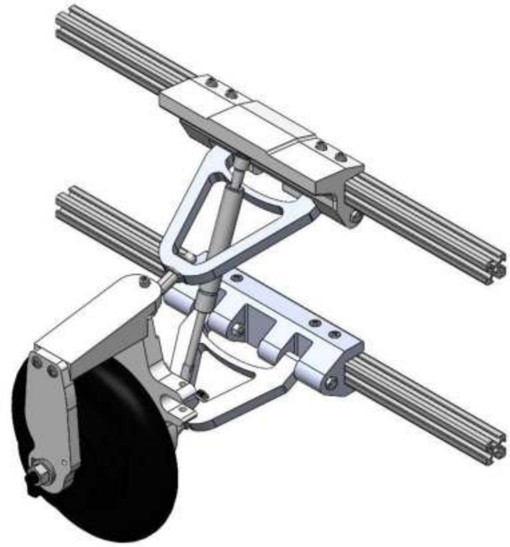

Figure 1. Full Overview of Individual Wishbone Suspension System

The Wishbone suspension system was chosen as the IGV suspension system both as a continuation of the previous teams and as a customer requirement for this vehicle. The double wishbone design also offers a simple and efficient system for transferring the motion of the wheels linearly while maintaining stability. The simplicity makes the suspension system cheaper to manufacture and maintain, both of which were major considerations for this project.

Motor Hubs

The motor hub components were parts inherited from the previous IGV team. Each component that encases the motor is made of 6061 milled aluminum which creates an easy-to-machine and sturdy point for the motor to seat into. Of the three components, the inner hub is the closest component to the chassis as seen in Figure 1 and Figure 2, and provides mounting points for both wishbones and the motors. There are two iterations of the inner hub, with the main difference being whether the control arm mounting point location is either on the left or right. Otherwise, the design points of the inner hub are identical across both inner hub iterations. The inner hubs became the initial focus of this project because of the numerous issues that occurred during the first inspection and disassembly of the hubs.

Figure 2. Inner Hub Isometric View

Early into the project, an attempt was made to disassemble the hubs to categorize and characterize the components the current team inherited. This attempt introduced a major fitment and alignment issue that caused the fixed, hardened steel shaft from the hub motors to marr the inner hub through-hole. This made removal of the motor from the hub difficult and resulted in small aluminum shavings appearing near the rotation point indicating abnormal wear. The motor's wire harness was also at greater risk of being damaged during removal from the un-filleted edges and small wire channel. The lack of proper locking mechanisms also caused the motors to torque significantly when accelerated or during a direction change. This over-torquing action also places the wire harness at greater risk of being damaged under normal use. Another issue with the inherited design was the mounting solution for the upper wishbone to the inner hub. Originally, the upper wishbone needed to be offset from the underside face of the top hub component because of severe interference with the bolts. This was believed to create a lever arm the further away the ball joint was from the face which would put undue stress on the outer edge of the upper wishbones. This meant that both the bolts and the inner hub face in that region needed to be reduced in some way.

During the first half of this project, the current IGV team introduced a few solutions that fix the issues with the inherited design. A recessed hole was created that fit the protruding section of the case where the wire harness terminates which can be seen in Figure [figure number here]. This allowed a raised section of the housing and shaft to sit properly on a pre-existing shelf inside the inner hub. The existing wire channel was drilled fully through the inner hub allowing the wire harness a path of egress with little interference with the motor shaft. The inner edges of the hub were also rounded slightly to remove potential for sharp edges cutting into the wire harness or the hands of people assembling the hub. The most important adjustment made was to combat the upper wishbone interfering with the bolts. A 0.13" deep section was milled away from the area at the top of the inner hub. This removed the interference from the upper wishbone ball joint when it is secured against the top hub component. Half head height bolts were also purchased to set the heads flush with the new face. As seen with the final product in Figure [place figure number here], this change was crucial for maintaining mobility with the upper wishbone ball joint. A final minor change made with the inner hub was increasing the area around the inner locking nut that will draw the casing and inner hub closer together and limit shaft axial movement. Both of these changes can be seen in Figure 3.

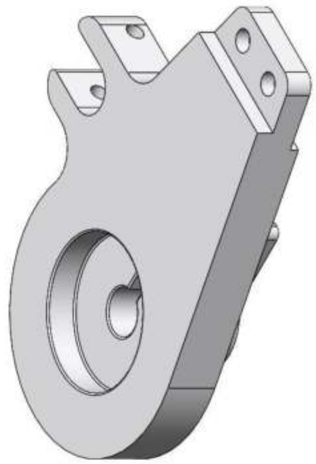

Figure 3. Chassis Facing Isometric View of Inner Hub

To check these modifications, prototypes were created to test the tolerances and combat any fitment issues that could have arisen from the transfer between the SolidWorks model and the final result. A simple PLA 3D printed part helped with sizing up and checking the part against the other parts of the assembly. Checking the bolt sizes and tolerances to allow for the half-head height bolts to sit flush with the new face and be easy to remove was another reason a prototype was made. Fortunately, this prototype worked exactly as expected for each modification made. This pushed the time table up for the final machining of the inner hubs and ensured that no future team would need to revisit this part.

After the inner hubs were machined, cleaned, and checked a final time for consistency, the final assembly of the full wheel hub was conducted. The assembly process was done at this stage for two reasons: to ensure fitment and to give a proper mounting solution for the motors as the electrical system was being developed and finalized. To maintain a safer environment, using the hubs to secure the motors that could then be set upside down on the workstation allowed for motor testing without full vehicle assembly. At this stage, the hubs were functioning properly and kept the shaft almost in place. However, an issue arose where the motors worked after a few tries and then would not function again. A few reasons for this were considered and one resolution method was to research further into how real world applications of this motor were secured. One consistency in the research was the use of a lock washer that has an angled flange that would resist the torquing motion from the wheels. From the way the original hub was designed, the aluminum would have flat faces inside the shaft holes on both the inner hub and out hub components. This would line up with the flat spots on the motor shaft, resisting the torque. However, since the hardened steel shaft has a higher hardness value than the aluminum, a concern about the aluminum being too weak to resist this was raised. A decision was made to mill out a small cubic slot, 0.45” x 0.3” x 0.2”, that would fit the angled flange of the lock washer to help resist the torque. This lock washer also has the flat portions that line up with the shaft which is how the washer keeps its position. Once this quick fix was machined into the outer hub seen in Figure 4, the motors were tested again and the solution worked as intended.

Figure 4: Outer Hub Component with Flange Seat Cut Out

Wishbone

Completed Methods

The primary focus of the last few months has been the finalization of the upper and lower wishbone designs. There have been a few redesigns over this period to ease manufacturing time and cost. The IGV team is currently on version four, which is shaping up to be the final version for both the top and bottom wishbones.

The wishbone components of the whole suspension system are necessary for the translation and creation of linear motion from bumps and shocks as the vehicle moves. The location of the rotation points for each wishbone in relation to the wheel hubs is what creates a suspension profile. The lengths of the upper and lower wishbones along with the position of the pivot points in the brackets need to be taken into account to generate a linear movement. The wishbones also work as a connection between the frame and wheel hub as seen in Figure 2. This means that the connection point between the wishbones and the hubs needs to pivot to account for the linear movement. The original design included press-fit, thin ball joint connections that a bolt passed through into the hub. This design was quickly discarded because previous prototypes displayed a weakness of material strength in the thickness around the press-fit ball joint. These prototypes also influenced the material choice. From seeing the material failure of the previous prototypes, which utilized a nylon carbon fiber 3D print filament, a change to a sturdier 6061 aluminum was deemed necessary.

The second iteration for both upper and lower wishbones considered the new material choice. Since aluminum has a higher ultimate tensile strength and larger Young's modulus than the carbon fiber filament, this allows the wishbone design to include thinner edges, walls, and overall thickness, reducing the necessary material to achieve high strength. To further distribute the stresses theorized from the weight of the chassis and loading from the speed requirement of 5 mph, Version 3 for the upper and Version 3 of the lower wishbones utilizes more rounded edges, large fillets, greater surrounding material around bolt holes, and larger tolerances which are seen in Figure 5. These together would ideally make strong contact points for the washers and reduce any potential for shearing loads from the bolts in any direction. Realistically, these designs would have been more effective for a higher top speed for the robot and the machine shop mentioned that as well.

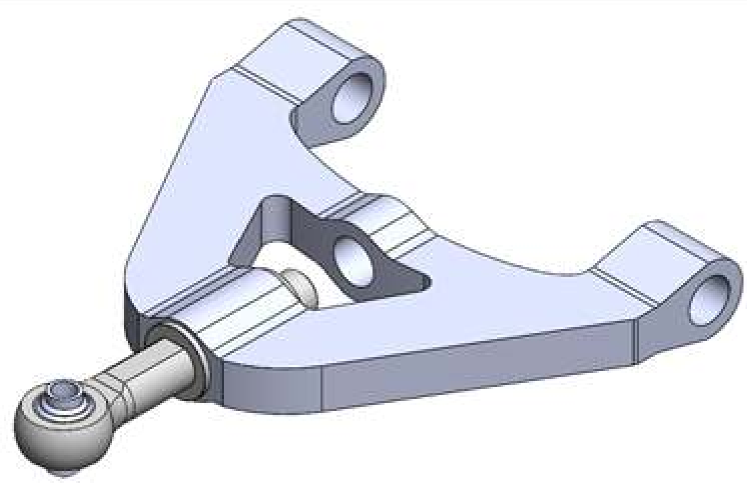

Figure 5. Lower Wishbone V2

As a result of the feedback provided by the machine shop, redesigns over the summer months including slimming down further most of the surrounding material around the bolt through holes. Besides the lack of necessity in driving this robot faster than 5 mph, the material cost would have required a block of 6061 aluminum to be roughly 6” x 7” x 0.75” for each upper and lower wishbone multiplied by 10 for 4 sets and an extra set. The cost alone for the blocks would consume most of the $1,000 the IGV project was allocated. The hypothetical machine cost and the real machining time were also major considerations in the pivot to a thinner design.

The thinner design for the upper and lower wishbones followed a similar design process which standardized the thickness to 0.5”, the bolt holes to fit ¼”-20 bolt of any length for the pivot point at the frame mounts, and the 5/16”-18 bolt hole for the off-the-shelf brass ball joint connection as seen in Figures 6 & 7.

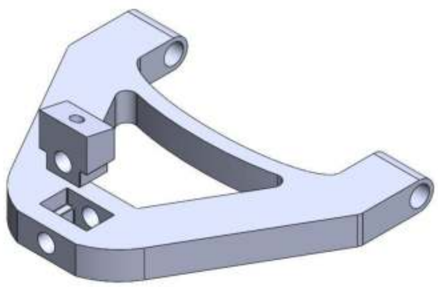

Figure 6. Lower Wishbone and Shock Block

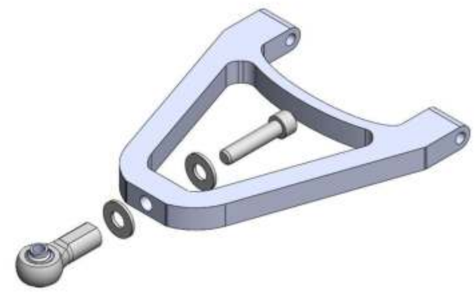

Figure 7. Upper Wishbone Design V3/V4

Standardizing the bolt sizes and material dimensions ensures the costs are minimized when assembling multiple sets of suspension systems. At this point in the design process, the upper and lower wishbones deviate sharply because the lower wishbone also needs to account for the shock mounting solution. The shock is the most important factor in returning the hub to a nominal position after moving upward. Version 2 of the lower wishbone did not include a shock mounting solution. Version 3 does, however. In version 3, the lower wishbone foregoes the rounded designs for a flatter variant while also including a design for the shock mount, dubbed the shock block. This shock block would slot inside a hole cut out from the lower wishbone. The hole would include steps to restrict the movement downward and distribute the forces of the shock into the wishbone. The key part to locking the shock block in place and keeping it aligned was the 5/16”-18 bolt would slot through the wishbone and the shock block together. This bolt would also take the shearing forces as the wishbone moved up and down. With this solution, the shock block could be cut out from inside the void of either the upper or lower wishbones to better use the scrap material. The robot will not be traveling more than 5 mph and the shearing forces acting on the bolt are assumed minimal in this iteration. Figure 6 shows the shock block exploded out from the slot in the lower wishbone. Figure 8 illustrates the full Version 3 lower wishbone assembly with the shockblock already inserted into its place.

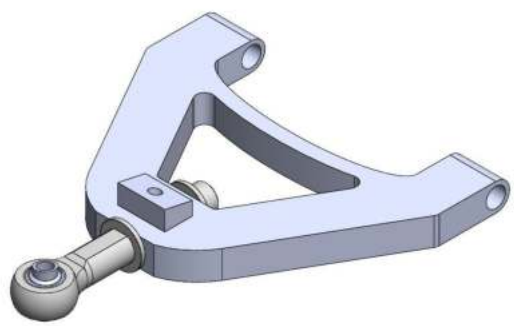

Figure 8. Full Unexploded Lower Wishbone Assembly V3

Following this iteration, the machine shop responded with a simpler and more efficient solution: instead of creating a shearing point, the shock block could be a geometry that is welded on top of the wishbone instead of slotting through. This suggestion would halve the machine's time while allowing for a simpler and stronger design. The solution as designed, would be a triangular geometry that is 0.5” thick like the 6061 Aluminum sheet metal with the length being no longer than 0.85” and a height as high as necessary to account for the shock ball joint shack length. 0.71” was found to be an adequate height. This new shockblock design is extremely simple in that most of the geometry can be cut with a waterjet alongside the wishbone shapes, requiring little post-processing besides tapping and drilling the M6-1.0 hole for the ball joint shank. The shock block will then be welded onto the wishbone aligned parallel with the bolt.

Figure 8 shows an exploded view of the current Version 4 lower wishbone assembly where the final shock block design and its weld location can be seen.

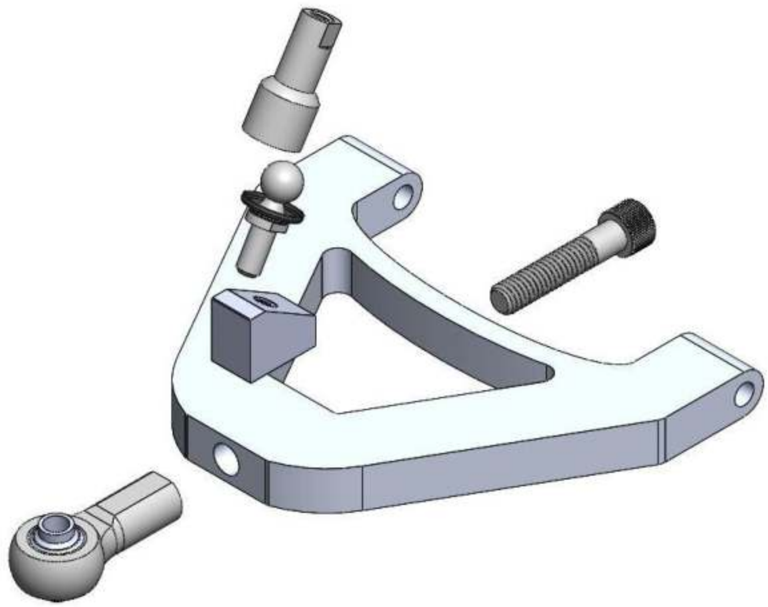

Figure 9. Exploded View of Lower Wishbone Assembly V4

Wishbone Mounting Brackets

With both the motor hubs and wishbone designs finalized, two unique brackets were developed to provide an anchoring point to the IGV. These brackets needed to meet the following criteria: (i) constrain the translational motion of the upper and lower wishbones in a manner that maintains the alignment of their center lines and permits actuation of the suspension, (ii) provide an anchoring point for the gas strut damper, and (iii) support the anticipated mechanical load cases. In order to optimally fulfill the criteria above, two variations of mounting brackets were designed to mount to the top and bottom of the 80/20 aluminum chassis. Both variations consist of a C-clamp interface with the 80/20 chassis in order to provide two mounting surfaces that will symmetrically distribute the forces across the bracket.

The chosen method of fabrication for these brackets is FDM. This choice was made due to the low-cost nature of FDM filaments and their short fabrication timeline. Furthermore, the utilization of 3D-printed parts allowed the IGV team to take advantage of the "free" complexity a designer can introduce into the component. When preparing a FDM print, it is important to know what your operating environment is and how your material will react. In the case of the IGVC, the vehicle must be able to operate consistently from 17℉ to 150℉ in both sunny and rainy conditions. For these reasons, PETG was selected as the ideal material due to its resistance to water, ultraviolet light, temperature fluctuations, and strength when compared to other commonly utilized filaments such as PLA without the carcinogens that other UV-resistant materials such as ASA produce during the printing process.

After material selection, a careful consideration must be made for the characteristics of the print process. Four primary factors influence the printing process, layer height, loops/layer quantity, infill pattern/percentage, and support structures. For the bracket designs shown in Figure 10, the print settings depicted in Table 1 were used.

Figure 10. Mounting Bracket Designs

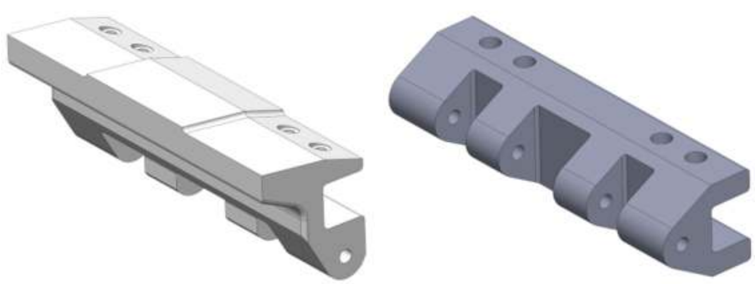

Table 1. Slicer Print Settings

Layer Height	Wall Loops	Top Shell Layers	Infill Pattern	Support Angle
0.2mm	6	5	40% infill - Gyroid Pattern	45 degrees

Each print specification was selected due to its advantageous impact in one of two categories, print time or component strength. A layer height of 0.2mm was selected for the most advantageous balance of print time vs layer adhesion. Similarly, supports were enabled for any overhang angle over 45 degrees to provide the most material-efficient population of support structures. A gyroid infill pattern was utilized for its nearly quasi-isotropic properties when compared to rectilinear arrangements. Furthermore, an infill percentage of 50% is ideal as this represents the tipping point in material cost to strength gain. However, to expedite the print time and conserve material due to logistical delays on FDM filament reception, a value of 40% was used as a compromise. Lastly, 6 outer loops and 5 top shell layers were used to distribute the clamping force of our bolts and dissipate any loading imparted by the gas strut damper.

The primary sources of loading experienced by the mounting brackets are the normal force against the IGV’s wheels, the moments applied by the wishbones actuation, and the weight of the IGV’s chassis, deckplate, and electronics.

Figure 11. Top Mounting Bracket FEA

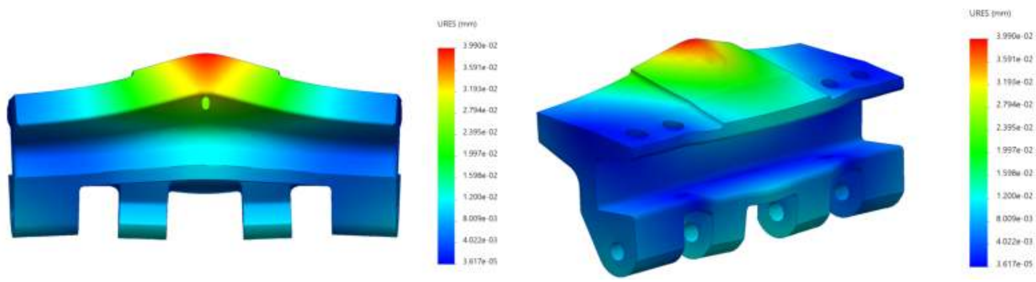

Figure 11 depicts the displacement resulting from the anticipated loading conditions the IGV will encounter during its maximum, competition-mandated, 5mph forward movment

Deck Plate Methods

Completed Methods

The deck plate of the IGV is responsible for supporting the load associated with the IGVC payload and electronics. The measurement process, design iterations, and analysis conducted on the deck plate were done using SolidWorks software, which aided in determining material requirements. The current ground vehicle (inherited by a previous team) consisted of an earlier deck plate that required the utilization of more resilient material (measurements taken of the plate consisted of a 36” x 24” x 0.125” thick, adding 1” x 1” square cutouts at the four corners where the deck plate is localized in the chassis laying on all four sides as shown below in Figure 13. On all four sides, 0.25” slot screw clearances were added to ensure equal integrity across the deck plate. With this information, the design's first version was formulated using SolidWorks (Dassault Systemes Corp., Waltham, MA).

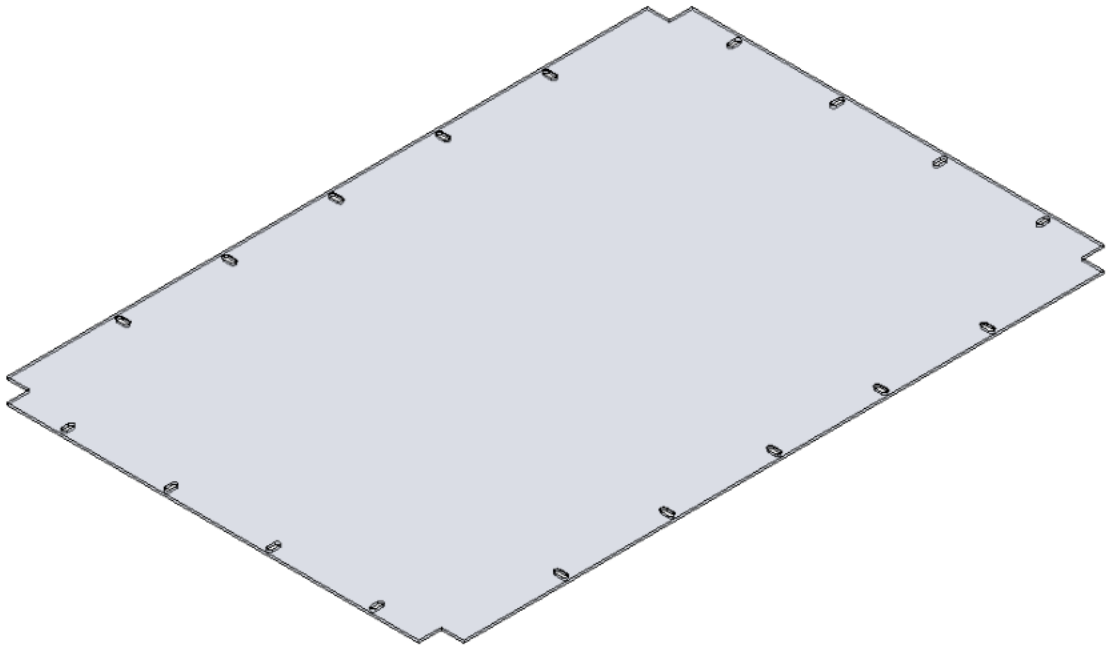

Figure 13: First Iteration of the Deck Plate

With version 1 of the design being completed, the following process entailed the selection of a suitable material that best aided the deck plate construction for the ground vehicle—choosing a material involved notation of all aspects the deck plate needed to go through for this project: vibrations, G-forces, weight (combined weight of 35 lbs), speed (0 to 5 mph), and deflection (less than 0.25"). Based on these parameters, aluminum was chosen for the deck plate. The most suitable variety of aluminum that meets all requirements is aluminum 5052-H32. This material is usually the desirable option for ground vehicle application, as it is lightweight, has an excellent strength-to-weight ratio, making it favorable for maintaining stability and safety, and has good impact resistance, which helps absorb shocks and vibrations without compromising the integrity of the deck plate and electronic components, as well as excellent heat dissipation as the thermal conductivity prevents overheating and ensures optimal performance of the ground vehicle. The use of slots, an application to the screw clearances, provides substantial freedom when it comes to guaranteeing adaptability and the serviceability of the plate as they are opened up.

After these steps were completed, the following steps entailed placing a considerable amount of weight on the deck plate to test how sound the deck plate was. A 16” x 8” x 8” cinder block weighing 20 lbs was placed on the deck plate. The load is located at the vehicle's rear, providing a greater down-force on the rear tires to increase traction. Furthermore, the location of the cinderblock enables the electronics suite to be integrated at the front of the vehicle, which will be the principal application that will make this vehicle function intelligently.

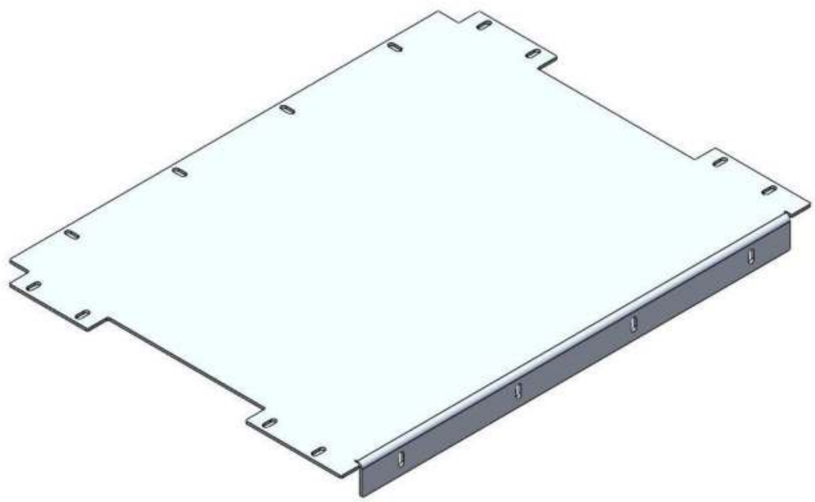

Figure 13. Deck Plate Section

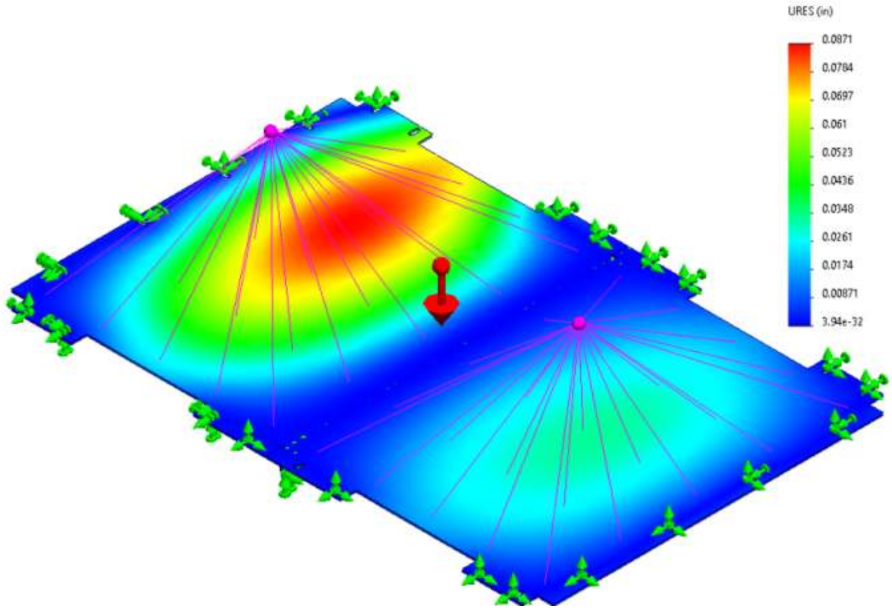

Figure 14. Displacement FEA on Split-Plate Design

During the end of the summer, we decided to modify the deck plate design by splitting it into two symmetrical pieces with a 90-degree bend connecting them, two cut-outs were added on both sides of the deck plate, allowing the mounting brackets to sit flush with the chassis and be easily removable. These adjustments improved the modularity of the ground vehicle, making it easier to service and adapt, as seen in Figure 8. The bend was only possible as the 5052 variant we chose allows this bend to happen, as other variants wouldn't be able to do it with cracking. This change increased the overall stiffness and integrity of the plate, better supporting the load associated with the payload and electronics of the IGV. As shown in Figure 14, we performed (FEA) on the redesigned deck plate. The analysis included a 100-pound distributed load on one side, a 40-pound load on the other, and a two-times gravity inertial loading to achieve a Factor of Safety of two. The results showed a maximum displacement of 0.0871” near the 100-pound load, which is well under the acceptable standards of a deck plate. The analysis confirms the design’s structural integrity and ability to handle operational loads while maintaining stiffness and modularity, with the potential for optimization in high-stress areas.

Electronics Integration and Control Systems Methods

Completed Methods

Developed in tandem with the mechanical platform of the IGV, the electrical control system fulfills the requirements of motion: speed control, directional control, and their corresponding safety features. The control system's design began as a continuation of a previous MAE group's attempt at making a self-contained motion system, where they purchased 6 x 350-watt brushless direct current motors, which were shown to have ample speed and torque to meet customer requirements of 5 mph at approximately 100 lbs of vehicle weight. Supporting the IGV is an inherited wishbone suspension and motor capture system that utilizes 4 of the 6 brushless DC motors. Considering the wishbone's heritage and the suspension team's decision to iterate upon its design, the determination was made to develop a control system focused on manipulating a traditional four-wheeled rover through the BLDC motors on hand. From this determination arose a few engineering questions: how are the motors powered, what microcontroller is the best option to power the motors, how can we reliably control the motors, what considerations are needed to operate the vehicle safely, and what control scheme should be developed to satisfy customer requirements?

The motors are powered through a three-channel input connected directly to the center of the hub; also connected to the center of the hub is a hall-effect sensor embedded within the motor that serves as the feedback system discussed later in the paper. The three motor channels are connected to a motor controller, which alternates power for each channel in a variable square wave to produce a turning motion. This process is made simple using a BLDC motor controller with a hall-effect sensor reader, the DC 6-60V 400W BLDC Three Phase DC Brushless Motor Controller PWM Hall Motor. This controller was chosen for its low cost, high availability, and its ability to integrate with motors. Unable to generate their commands, these motor controllers require signal manipulation to provide motion. This is done through the use of the motor controller's native PWM signal, which is designed to receive a voltage from 0 to 5 volts to cause a respective increase in power output. To answer the question of reliable control, we decided to go with a hardwired connection to lay the foundation for future teams to inherit a working system and begin to establish a more autonomous approach. The hardwired system connects the motor control signal pins to different voltages determined by integrated electronic components. For example, the left and right motors are actuated separately via a left and right controller joystick that completes the circuit between the respective motor controller’s positive signal and their PWM receiver.

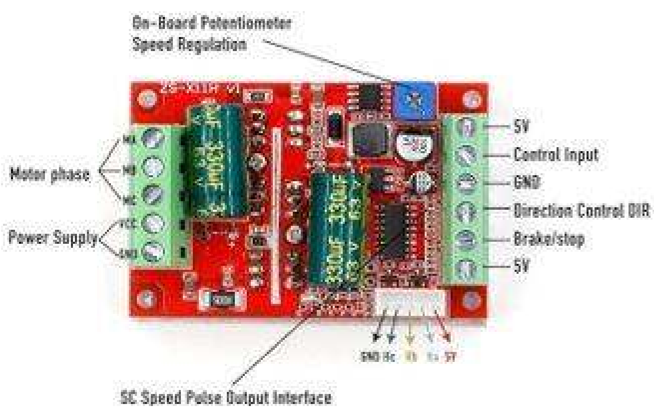

Figure 15: Schematic of DC 6-60V 400W BLDC Three Phase DC Brushless Motor Controller PWM Hall Motor

To address the concern of electrical system safety, research had to be conducted regarding the handling of battery-controlled systems, highly capable motors, and motor controllers without built-in over-current protection. When designing a motion control system for the IGVC, overcurrent protection is a critical safety measure. Without safeguards, excessive current draw can overload motor controllers, damage batteries, or even cause fires. To mitigate these risks special care was taken to ensure all powered components were grounded to the negative terminal of the battery to avoid induction and charge build-up on the chassis and other electrical components. An emergency stop is also integrated into the system to act as a quick way to cut power from the battery. There were considerations when choosing the wire gauge to connect to the battery and the higher voltage pins of the motor controllers.

Size	Temperature Rating of Copper Conductor		
AWG	60°C	75°C	90°C
	Types: TW, UF	Types: RHW, THHW, THW, THWN, XHHW, USE, ZW	Types: TBS SA, SIS, FEP, FEPB, MI, RHH, THHN, THHW, XHH, XHHW
	Current Rating, A(RMS)		
18	-	-	14
16	-	-	18
14	15	20	25
12	20	25	30
10	30	35	40
8	40	50	55
6	55	65	75
4	70	85	95
3	85	100	115
2	95	115	130
1	110	130	145
0	125	150	170
00	145	175	195
000	165	200	225
0000	195	230	260

Table 2. Current rating by wire gauge chart standard

Referencing Table 2 we see the current limits for standard American wire gauge sizes or AWG. Originally the higher current portion of the power system was wired using 18 AWG wire, which would melt if exposed to the 20 Amp load from the system's battery. This was switched 12 AWG, as determined by the chart standards, to ensure a safe transfer of current.

At first, this control system design was mocked up on a tabletop test setting to verify basic functionality and safety during development. The table top had the same controller as the one used offering individual control over direction, speed, and braking for left and right motor pairs. In this tabletop validation process, we were able to troubleshoot and verify basic functionality as they have been wired up. A low power setting was used in these tests, running at 24 volts and 1.5 amps.

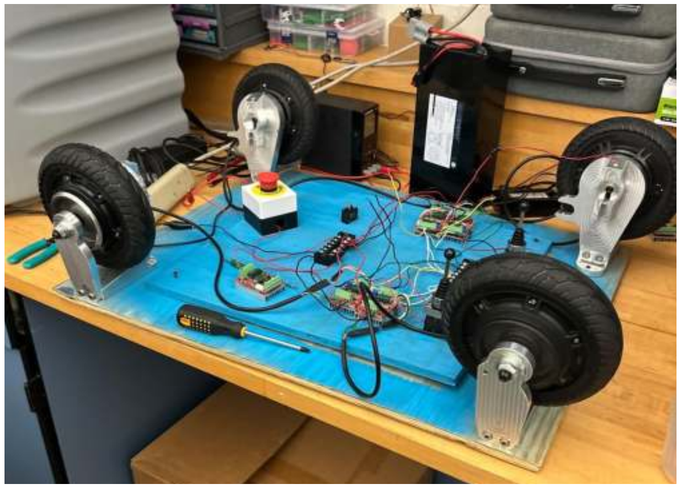

Figure 16. Tabletop testing setup

After the completion of the chassis and suspension manufacturing process, the tabletop test platform was directly integrated into the deck plate of the chassis, with the motors and motor hubs mounted to the wishbones as designed. Since the tabletop testing period was so extensive, the full integration was seamless.

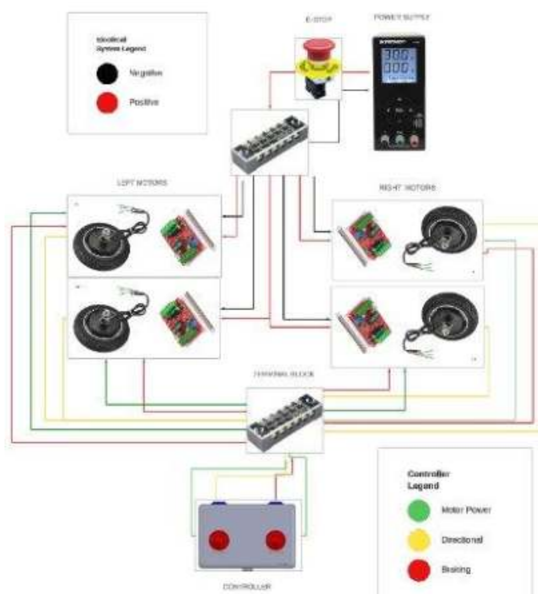

Figure 17. Analogue Electrical Schematic

The final step of transferring between the tabletop testing was to develop a wired controller that worked as a toggle between on and off, as shown in Figure 16. This gave simplicity and functionality as the team tested the capabilities of the vehicle. The analog electronics in the remote: buttons and joysticks, act as the logic for control over the bot by manipulating the circuits open and shut.

Figure 18. Analog remote controller

RESULTS

Electronic Integration

Resulting from the electrical design process, the IGV has a pendant remote-driven motion control system capable of all-wheel-drive motor speed control, translational motion, turning, zero-turning, braking, and emergency power cut-off. The IGVC 2024 team ran trial runs using the lower current power supply at 84 watts, validating the motion control's functionality when integrated with the chassis. While these tests met project requirements, the lower amperage was not enough for smooth control over the system. In this test, the vehicle displayed high levels of vibration and a lack of turning capability.

In the higher power, 480-watt battery tests, the vehicle was capable of smoother translation, and gained the ability to turn, by providing power to one side or the other. The team has taken the vehicle to an outdoor setting to test its ability to crawl over obstacles and for a full power speed test. The outdoor testing validated that the power system would be sufficient to navigate a rugged environment and showed a top speed nearing 15 mph.

The vehicle has the ability to zero-turn or turn in place about the center of the vehicle, but due to limited space on the controller and the somewhat violent nature of these turns, we have disabled that ability on the current controller. To regain the zero turn function, the left and right motors simply need to run in different directions. This could be easily accomplished by either incorporating another switch onto the controller or retrofitting the Arduino to Raspberry Pi controls as initially intended. Due to competition limits, the vehicle is limited to 5 miles per hour, so the power to the motors would likely need to be stepped up to perform the turns.

Hubs and Wishbone Machining

After several design reviews and conversations with the machine shop, we settled on making the wishbones out of 6061 aluminum alloy. As per the machine shop's suggestion, 6061 aluminum was chosen for its ease of machining, which was part of the core philosophy in designing the wishbones. The in-house machine shop spent 9 hours machining the wishbones and hub modifications, with post-processing and simple drilling taking most of the time. All parts were received within roughly two business weeks from the initial handoff.

Assembly

Assembly happened in stages, with all motors and hubs assembled before installation onto the vehicle. The wishbone brackets, top and lower wishbone, and structs were assembled onto the vehicle as full assemblies. Once everything was checked for proper alignment, the motos were added to complete assembly. After installing all parts, the electrical components were installed in a sled format for ease of bench testing and removability. The assembly of the vehicle proceeded without any issues or fitment issues.

DISCUSSION

Purpose

The project aims to continue developing an efficient and reliable intelligent vehicle platform from the ground up that can be adjusted continuously to compete and win in an autonomous robotic competition requiring a robust platform controlled by an articulate AI-commanded drive system.

Limitations of the project

The main limitations for the IGV are budget approval and time constraints for the final product and testing. With a budget of around $2,000, the constraints for supplies to enhance our given frame were significantly impacted. With hub motors on a lower cost perspective and the lack of maintenance, electrical issues were bound to occur. Issues arose with the motors when integrating the simple joy stick controls, motor power at first would not equally distribute and directional mistakes occurred as well. Our budget constraints only affected the result following the modifications done to the frame. Without the limited budget the modifications done to the initial vehicle passed down to the team would have been much more. Within the four-month time crunch, our main assembling supplies arrived at the laboratory around October, two months from the customer deadline. Along with the supplies, the final iterations of the plastics printed were finished the day before the Thanksgiving holiday leaving a sizable constraint to our assembling schedule. This constraint is still significantly more challenging than industry standards.

FUTURE WORK

Suspension

For the suspension system, a couple of future changes need to be made to ensure the vehicle is stable and effective. One change is to utilize the existing tie-rod mounting points on the inner hubs and create a mounting point on the chassis that reduces the play in the hubs for better performance in normal operation and zero-turn situations. The current gas struts utilized as shocks should also be changed out to a spring-driven shock to increase damping frequency and rebounding nature.

Electrical

Future work for the electrical portion of the IGVC project includes a few notable actions. One action is porting over the existing analog system into a microcontroller-driven system. Also, we recommend changing the single-core wires with multistrand wires to make the wiring cleaner and more presentable. Another large portion of the future work would be integrating the existing ECE team's autonomy suite into the new bot and switching the mounting platform from plywood to a more permanent, safer solution. Lastly, we recommend adding proper cable management and routing to keep the motor cables from being pulled and experiencing abrasion. The suggested microcontroller architecture would include a Raspberry Pi imputing to an Arduino MEGA, which outputs to the motor controller low-voltage terminal block already integrating

Deck Plate

In the future, the deck plate will need to be modified to accept the updated electronic mounting hardware. Some vibration-dampening rubber mat/feet should also be added underneath the electronic mounting suite to safeguard it from vibrational issues. Possible vibration analysis can also be conducted on the deck plate to further diagnose and add quantitative results to the reduction.

Wishbone Mounting Bracket

Suggested future work for the wishbone mounting bracket is to utilize the provided g-code to reprint all four sets of brackets with PETG and conduct destructive testing to confirm FEA predictions. Additionally, analysis should be conducted on the effects of cyclical fatigue on the longevity of the brackets as well as their response to vibrations - particularly their modal response.

CONCLUSION

The IGV team has finished building its all-wheel-drive electric vehicle, which has exceeded all requirements set out by stakeholders. The work done by the IGV team includes machining the wheel hubs and finalizing the wishbone system. The IGV team is currently in an administrative block preparing a handoff package to stakeholders for the next IGV MAE team. With the conclusion of the project, the IGV team has successfully built an analog-controlled all-wheel drive vehicle capable of zero-turn capability and exceeding 15 mph. Thanks to the wonderful candy product created by gentlemen Mike and Ike, the team morale directly increased with a massive boost in productivity. With 14lbs of Mike and Ike’s delectable candy consumed, over the duration of the semester, this allowed the team to finish the vehicle to a functional state.

STANDARDS USED

Mechanical and Structural Design Standards

ISO 2768-1:1989 - General Tolerances for Linear and Angular Dimensions

This standard is essential for ensuring that parts such as the wishbone suspension and motor hub assemblies maintain proper dimensional accuracy and tolerances in manufacturing, which is crucial for ensuring the integrity and fit of mechanical parts. Tested and ensured the wishbone suspension and motor hubs were solidly cleared through SolidWorks, so there was no issue when machining.

ASTM B221M - Standard Specification for Aluminum and Aluminum-Alloy Extruded Bars, Rods, Wire, Profiles, and Tubes

Outlines the procedures for testing the mechanical properties of those materials, ensuring their strength and suitability for load-bearing components like the wishbone or hub.

ASME Y14 - Drawing Standard Series

Used with all SolidWorks sketches and model drawings, overviewing essentials such as dimensioning and tolerancing, as well as product definitions.

Material and Hardware Standards

ASTM B209-14 - *Standard Specification for Aluminum and Aluminum-Alloy Plate*

Ensures the aluminum plate meets specific mechanical properties and quality standards, which are essential for maintaining structural integrity and reducing vibration effects. Ensured the deck plate could withstand forces up to 4x gravity.

ASTM D638-14 - *Standard Test Method for Tensile Properties of Plastics*

3D-printed components: this standard applies to the testing and validating of polymer parts, such as those made with nylon or other materials used in the hub or suspension system.

ISO 13850:2015 - *Brake Standard*

Standard specifies functional requirements and design principles for the emergency stop function on machinery, independent of the type of energy used.

IEC 60706 - *Maintainability of Equipment*

Standard of examining the maintenance of equipment and the necessary activities it takes to uphold such equipment.

Testing and Prototyping Standards

ASTM E1559-09 - *Standard Guide for Sampling Strategies for Additive Manufacturing (AM) of Materials*

Using 3D printing for rapid prototyping, this standard provides guidelines for ensuring that the materials and parts produced through additive manufacturing meet the required tolerances, strength, and durability.

ASTM F2792-12a - *Standard Terminology for Additive Manufacturing Technologies*

This standard defines terms and methods used in 3D printing, helping to ensure clear communication and consistency when discussing design parameters and testing methods for 3D-printed components.

ISO 9001 - *Quality Management Systems- Requirements*

This international quality management standard ensures that manufacturers maintain a high level of quality throughout their processes.

IEC 60034 - *Rotating Electrical Machines Part 1: Rating and Performances*

The International Electrotechnical Commission's standard for rotating electrical machines provides guidelines for testing and measuring motor performance; applicable to rotating motors.

IEEE 112-2017 - *Standard Test Procedure for Polyphase Induction Motors and Generators*

The Institute of Electrical and Electronics Engineers standard outlines procedures for testing electric motors and generators.

Electrical Standards

ASTM B258-18 - Standard Specification for Standard Wire Gauge for Electrical Conductors

This standard outlines the American Wire Gauge (AWG) system, specifying the diameter, cross-sectional area, and resistance of electrical wires, ensuring compatibility and safety in electrical systems.

NFPA 70 (NEC) - Current Ratings for Electrical Wire Gauges

Part of the National Electrical Code (NEC), this guideline provides allowable ampacity values for various wire gauges based on insulation type, temperature ratings, and environmental factors to ensure safe electrical operation.

IEEE 1184-06 - Standard Practices for Safe Operation with Batteries

This standard details safety procedures for handling and operating batteries, focusing on current limits, discharge rates, and preventing thermal runaway in electrical circuits.

IEEE 80-2013 - Standard for Safety in Grounding of Electrical Equipment

This standard specifies proper grounding techniques to mitigate electrical hazards, ensuring that stray currents are safely directed to the ground to protect equipment and personnel.

APPENDIX

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(accessed Feb. 14, 2024).

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LIST OF FIGURES

FIGURE 1. FULL OVERVIEW OF INDIVIDUAL WISHBONE SUSPENSION SYSTEM

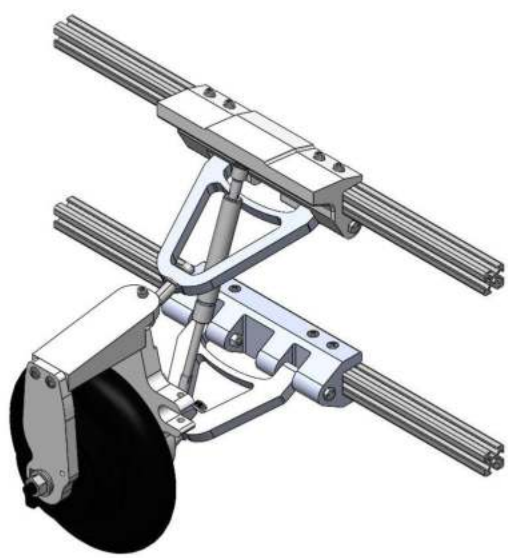

FIGURE 2. INNER HUB ISOMETRIC VIEW

FIGURE 3. CHASSIS FACING ISOMETRIC VIEW OF INNER HUB

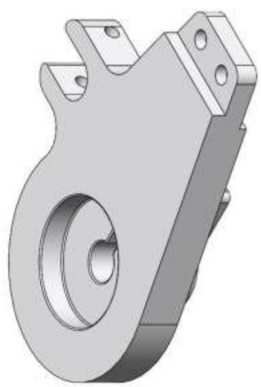

FIGURE 4. OUTER HUB COMPONENT WITH FLANGE SEAT CUT OUT

FIGURE 5. UPPER WISHBONE DESIGN V4

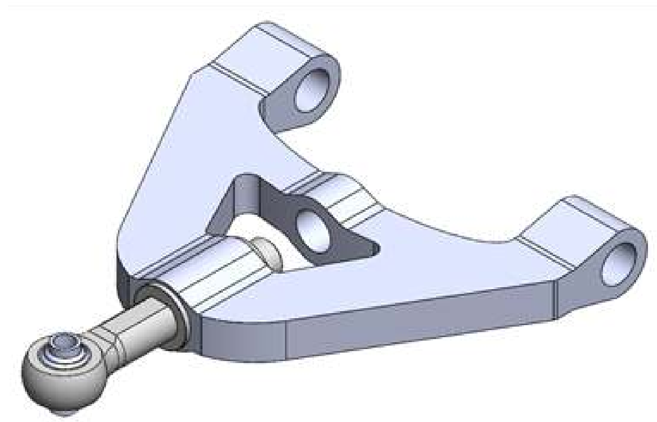

FIGURE 6. LOWER WISHBONE AND SHOCK BLOCK

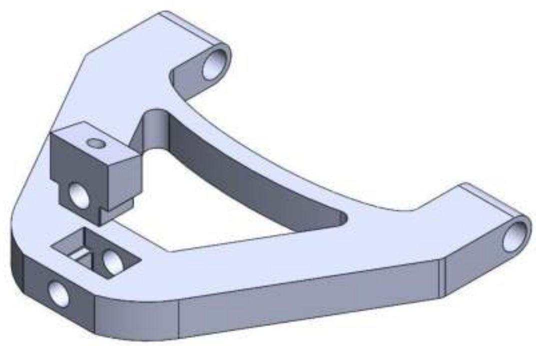

FIGURE 7. UPPER WISHBONE DESIGN V3/V4

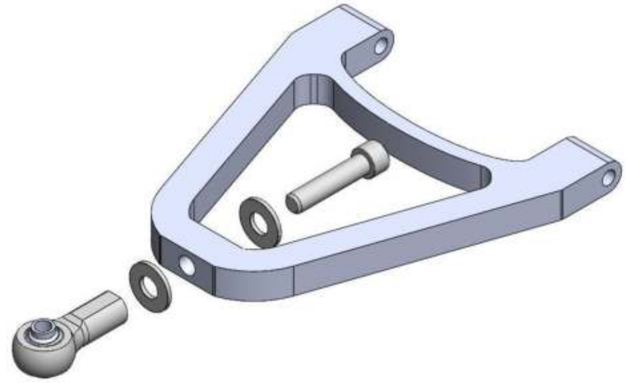

FIGURE 8: FULL UNEXPLODED LOWER WISHBONE ASSEMBLY V3

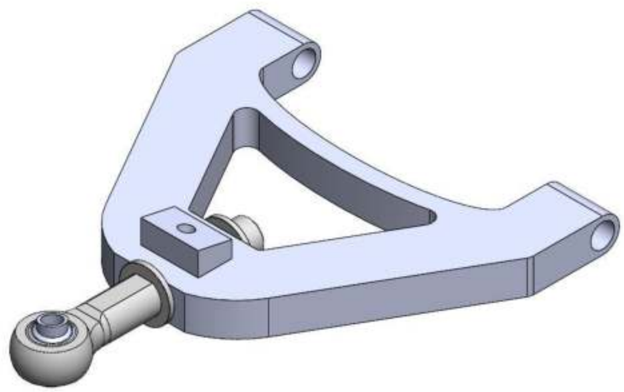

FIGURE 9. EXPLODED VIEW OF LOWER WISHBONE ASSEMBLY V4

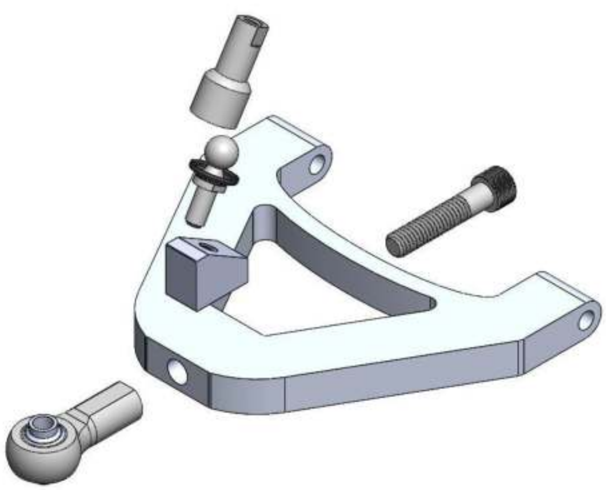

FIGURE 10. MOUNTING BRACKET DESIGNS

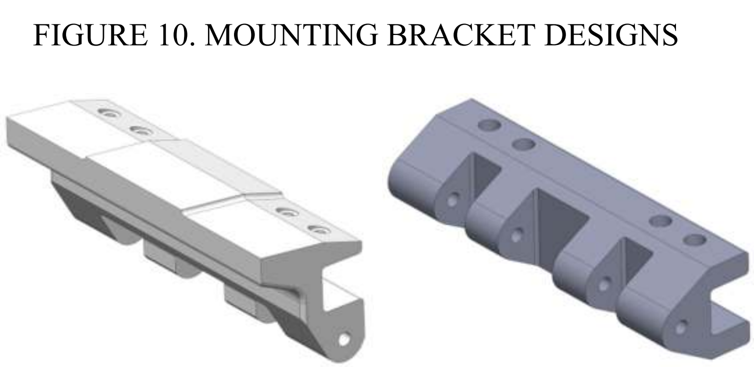

FIGURE 11. TOP MOUNTING BRACKET FEA

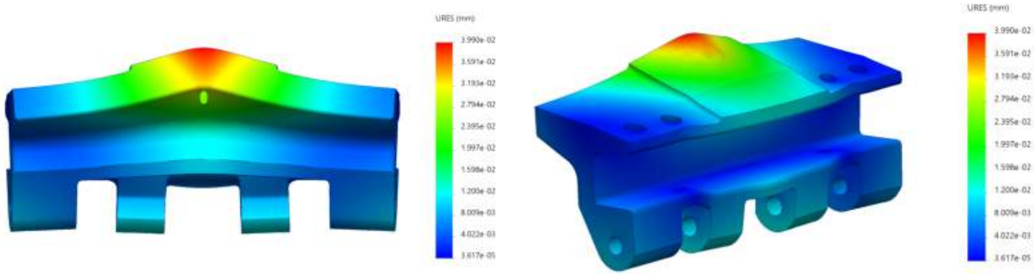

FIGURE 12. FIRST ITERATION OF DECK PLATE

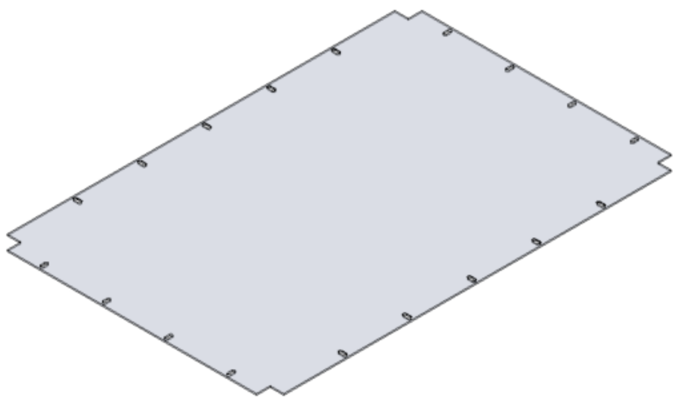

FIGURE 13. DECK PLATE SECTION

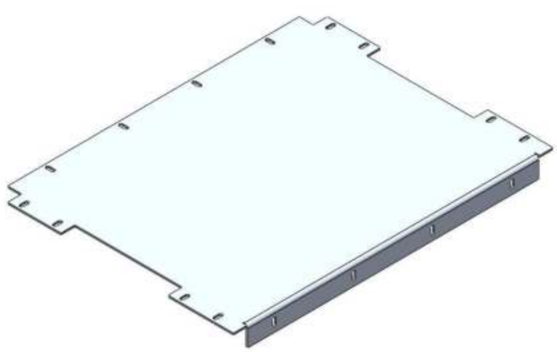

FIGURE 14. DISPLACEMENT FEA ON SPLIT-PLATE DESIGN

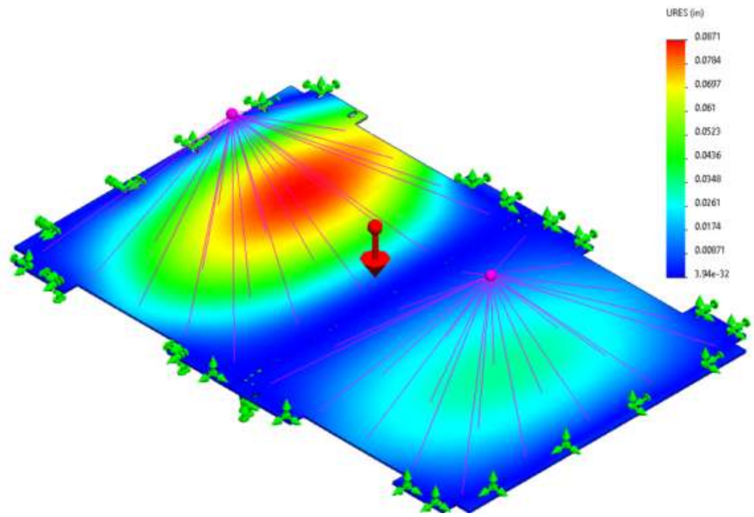

FIGURE 15. SCHEMATIC OF DC 6-60V 400W BLDC THREE PHASE DC BRUSHLESS MOTOR CONTROLLER PWM HALL MOTOR

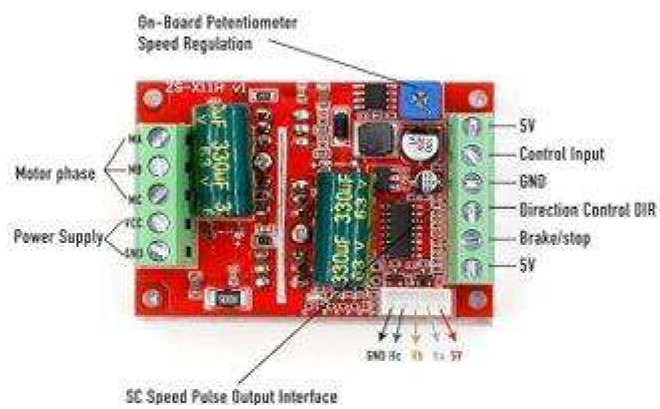

FIGURE 16. TABLETOP TESTING SETUP

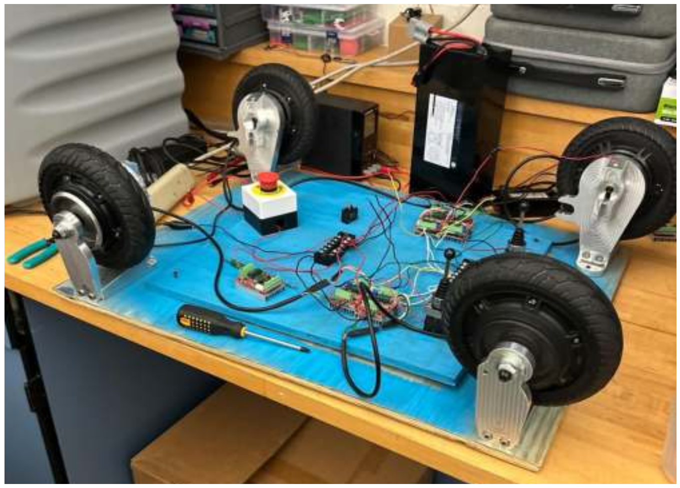

FIGURE 17. ANALOG ELECTRICAL SCHEMATIC

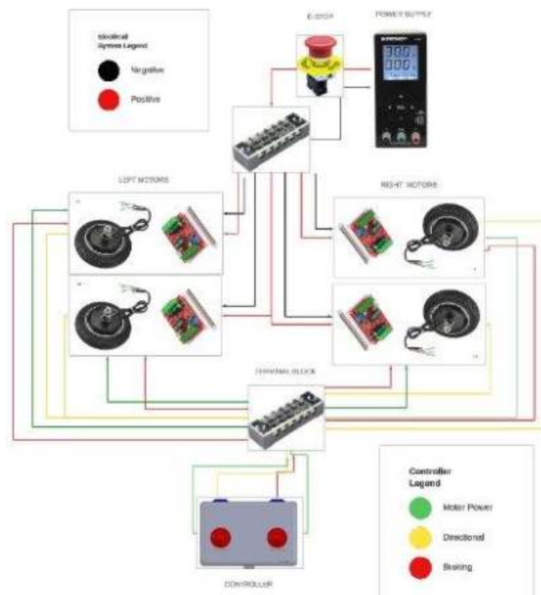

FIGURE 18. ANALOG REMOTE CONTROLLER

LIST OF TABLES

TABLE 1. SLICER PRINT SETTINGS

Layer Height	Wall Loops	Top Shell Layers	Infill Pattern	Support Angle
0.2mm	6	5	40% infill - Gyroid Pattern	45 degrees

TABLE 2. CURRENT RATING BY WIRE GAUGE CHART STANDARD

Size	Temperature Rating of Copper Conductor		
AWG	60°C	75°C	90°C
	Types: TW, UF	Types: RHW, THHW, THW, THWN, XHHW, USE, ZW	Types: TBS SA, SIS, FEP, FEPB, MI, RHH, THHN, THHW, XHH, XHHW
	Current Rating, A(RMS)		
18	–	–	14
16	–	–	18
14	15	20	25
12	20	25	30
10	30	35	40
8	40	50	55
6	55	65	75
4	70	85	95
3	85	100	115
2	95	115	130
1	110	130	145
0	125	150	170
00	145	175	195
000	165	200	225
0000	195	230	260