2023 NDIA MICHIGAN CHAPTER
GROUND VEHICLE SYSTEMS ENGINEERING and TECHNOLOGY SYMPOSIUM
Autonomy, Artificial Intelligence, & Robotics Technical Session
August 15-17, 2023 – Novi, Michigan

EXPENDABLE LOW-PROFILE MODULAR UGVS for COMBAT VEHICLE UNDERBODY OPERATION

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ABSTRACT

Presented are two designs for compact, low-profile UGVs with high cross-country mobility, intended for underbody operations with heavy manned vehicles. These UGVs are designed to remotely detect and assess combat damage incurred during combat operations, and analyze wear, leaks, and cracks, without the need for a human technician to be exposed to enemy fire, allowing crews to rapidly assess the conditions of their vehicles. Since robots required for underbody inspection would necessarily maintain a low, compact profile, they could also perform effective last-mile resupply in a contested environment, their small size allowing them to hide behind terrain and battlefield debris much more effectively than a heavy logistics robot. Naturally, a robotic vehicle that is capable of rapid underbody inspection of friendly vehicles or last-mile resupply could also be easily adapted as a combat platform to be used against enemy vehicles.

Citation: A. Washington, et al., “Expendable Low-Profile Robot for Vehicle Underbody Operation”, in *Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium* (GVSETS), NDIA, Novi, MI, Aug. 15-17, 2023.

1. INTRODUCTION

Recent advances in robotic system capabilities have allowed the US Army to develop numerous robotic systems, from autonomous trucks [1] [2], to a variety of combat robots [3] [4] [5] [6], to fleets of small robots used for bomb disposal [7] [8], search and rescue, and payload integration research [9]. At this point, however, there is one category of robotic system that has not received much attention: compact, low-profile robots with high cross-country mobility intended for underbody operations with heavy manned vehicles. Such underbody robotic vehicles would be able to remotely detect and assess combat damage incurred during an operation, and analyze wear, leaks, and cracks, without the need for a human technician to be exposed to enemy fire in a combat situation. This would allow crews to rapidly assess if their vehicles are capable of continuing an operation, or if they must be pulled back before incurring irreparable damage. Since robots required for underbody inspection would necessarily maintain a low, compact profile, they could also perform effective last-mile resupply in a contested environment, their small size allowing them to hide behind terrain and battlefield debris much more effectively than a heavy logistics robot.

Naturally, a robotic vehicle that is capable of rapid underbody inspection of friendly vehicles or last-mile resupply could also be easily adapted as a combat platform to be used against enemy vehicles. Anti-tank robots carrying underbody blast landmines have been used since World War 2 [10], and continue to be a threat on the modern battlefield [11] [12]. While the US Army is not currently developing such systems directly, a low-cost, expendable anti-tank robot could prove to be useful against near-peer opponents in the future.

With this mission set under consideration, the authors have defined a set of preliminary requirements to guide the development of robotic prototypes. Since the robots are designed to be expendable, they must be as low cost as practical, which sets limitations on complex design. To keep the design mechanically simple and easy to build, the authors settled on development of skid steer robots with robust frames and direct motor-driven wheels. The robots must be compact enough to fit under Army trucks and other tactical vehicles, so a maximum profile envelope of 90 x 90 x 60 cm was selected. To satisfy the requirement for robust cross-country performance, a requirement of surmounting a 15 cm obstacle was selected. Since the robots had to perform both underbody inspection without losing their ground maneuvering capability, it was decided to integrate two cameras: one facing forward for maneuvers and one facing upward to conduct inspections. Finally, the robots were designed to a minimum payload capacity of 15 kg, to ensure they can carry an adequate payload for soldier resupply, or carry a singular anti-tank munition.

Figure 1: Goliath Self-Propelled Anti-Tank Landmine

2. RIGID CHASSIS UGV

The first underbody operation UGV design presented was based around a singular, custom-built, rigid chassis. The rigid chassis allowed the team to focus on optimizing a single baseline configuration for the UGV, which could be adapted to additional payloads by means of modular bracketry. The body, wheels, payload adapters, and electronics enclosures for this UGV were all designed for 3D printed prototyping, with subsequent intent for more rigid components produced by conventional manufacturing.

Figure 2: Rigid Chassis UGV

2.1. Chassis Design

The chassis was designed with the understanding that a large payload weighing more than the rover itself would be sitting atop the rover. With this in mind, the rover's chassis was designed to keep all weight as low as possible in order to lower the vehicle's center of gravity. The chassis was made out of heavier-than-required components to meet this requirement. The chassis was separated into a top plate and a bottom frame that allowed the easy mounting of components, while still keeping the majority of the rover weight as low as possible.

As seen in **Figure 4**, the chassis prototype was manufactured using 20-gauge bare sheet steel. Using the CAD drawing as a reference, the plate was cut manually with a plasma cutter. The plate was then strengthened with ½" solid steel square stock welded to the underside of the plate. Ideally if this design were to go into mass production, the chassis plate would be manufactured with 20-gauge bare sheet steel that is industrially stamped.

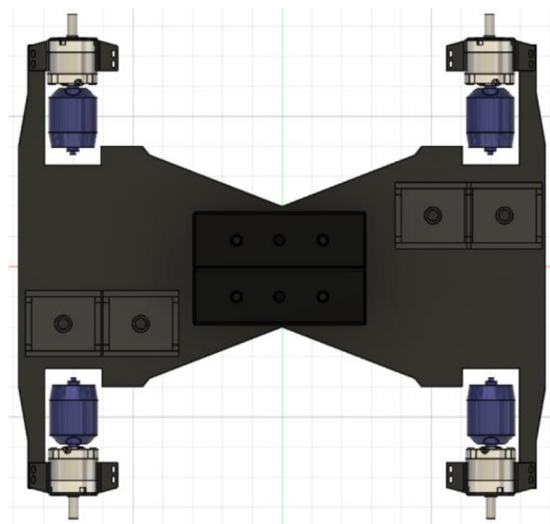

Figure 3: Chassis Design

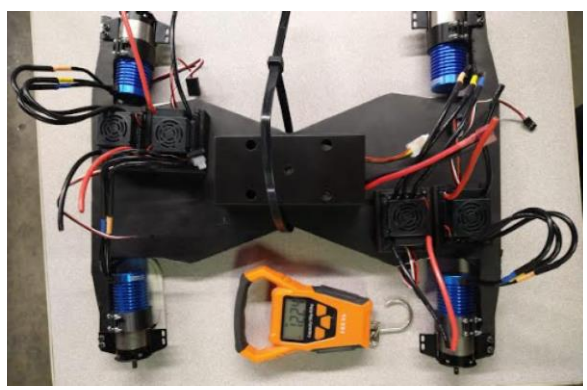

Figure 4: Chassis Prototype

2.2. Body Design

The custom body was designed to fit around the steel chassis described above. It was recurred that the body fit over the chassis, while still remaining within the overall desired dimensions of 2'x2'x1'. In addition the body needed to enclose the components to shield them from the environment, house the cameras, as well as be strong enough to support up to a 30 lb payload. With these constraints a body was designed that featured a separate payload support. This allowed for more flexibility within the body design as it no longer needed to be as strong, and rather functioned as shielding components from environments as well as a mounting location for the cameras.

The body of the rover had two major revisions. The initial body design was fairly similar to the final design seen in **Figure 5** colored in light gray, with the main difference being the camera housing locations. Initially in the first design the forward facing camera was centered at the front of the rover and the upwards facing camera was centered at the back of the rover. This design was altered to feature both the upwards and forwards facing camera at the front of the rover. This resulted in the forward camera housing to be shifted to the left of the rover and the upwards camera to the right. Ultimately this design change allows for the user to more easily be able to identify their exact camera location, as they are parallel on the same axes. This also allows for the user to maneuver the vehicle closer to objects on one side, as the front facing camera is offset to the left and thus provides a better view of the left wheel clearance. The prototype of the rover was 3D printed with PLA filament. Due to the size of the part and limited printing size of accessible printers, the body was sliced into four separate parts. These separate parts were then bonded together with a plastic epoxy. Ideally, the body of the rover would be manufactured into one piece by plastic injection molding.

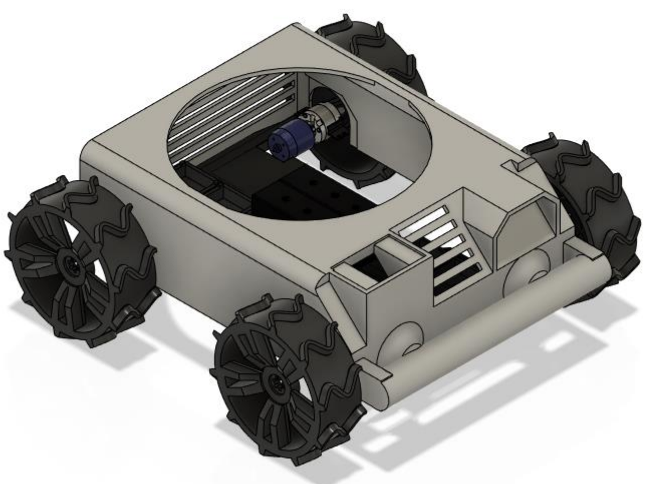

Figure 5: Body Design

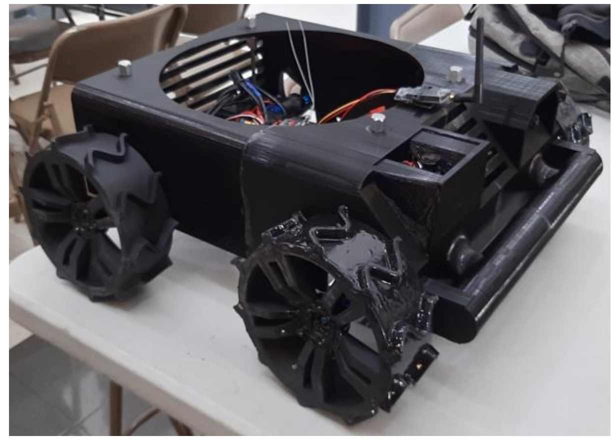

Figure 6: Body Prototype

Internal component brackets that were designed and prototyped were fairly simple and did not change much. Each bracket was modeled to custom fit the component that needed to be secured within the body of the rover. The brackets featured a small clip in each corner to secure the component. The bracket was then secured to the chassis with a nut and bolt through the hole on the base of the bracket. The prototype that was created for testing was 3D printed with PLA filament. Ideally these brackets would still be made of plastic but rather be manufactured with a plastic injection molding process rather than 3D printing.

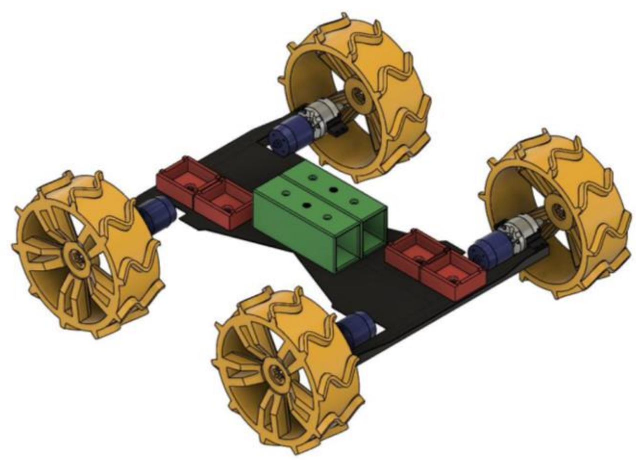

Figure 7: Internal Configuration

When designing the payload support adapter, shown in **Figure 8** in isolation and in **Figure 2** as installed on the UGV, it was desired to have a versatile space that would be used for the transportation of various materials and resources. Also due to the nature of the small footprint of the rover, it was also very important to maximize the usable space on the rover for the payload, while ensuring no fatal compromise would be made to the other components' mounting space was made. Thus a payload support was designed that features a multilevel storage area to maximize the use of space. A simple turn-key lid was designed to encapsulate various sized objects. The design was created to secure any sized at any reasonable diameter, instead of having multiple supports that encapsulates individual objects. This design saves the user time which was one of the purposes in creating the payload support. It was assumed when designing the payload support that it would be printed 100% solid PLA. Due to time constraints, the support wasn't printed. The support also had a thick base which was designed to keep the rover's center of gravity low. Using a heavy base allowed the rover to maintain a low center of gravity which allows the user to encounter steeper hills with the unlikelihood of a rollover.

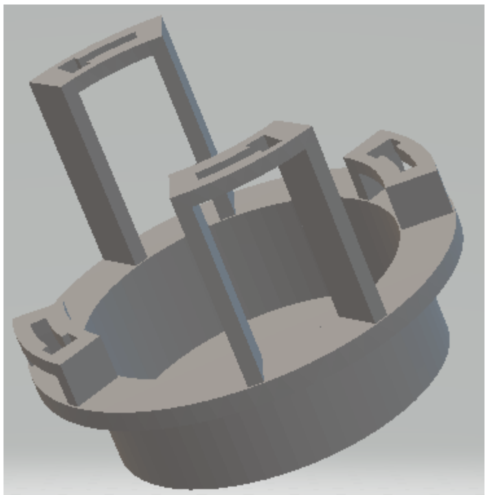

Figure 8: Payload Support Adapter

2.3. Drivetrain Design

Due primarily to cost as well as time constraints it was desired to select a more simple and cheap drivetrain that was still effective at meeting our requirements. This led to a selection that did not have a single point of failure, did not require complex steering, and was not required to have a suspension system. Ultimately the decision was made for a four motor direct drive system that would be controlled by differential steering. The combination of these methods proved to be the most effective at meeting the requirements and constraints. Four planetary gearboxes were used to mount the motors inline with the driving axes. This allowed us to not only lose a wheel, motor, and or gearbox in the rover without hindering the rover's ability to complete its mission but also allowed us to steer the rover using a simple twin-stick setup.

2.4. Wheel Design

The design of the wheel was based around the maximum strength of the wheel which was to be calculated using the payload weight and the chassis rover weight. The wheels needed to be able to carry a heavy load when static and kinetic, so each of the wheel characteristics from the width of the outer ring to the number of spokes were carefully decided. The wheel calculations were made assuming that it would be printed 100% solid PLA but due to time constraints, it wasn't fully filled. This caused the wheel prototype to be weaker than expected. After five different wheel design iterations, shown in **Figure 9**, the final wheel was created, shown in **Figure 10**.

To fit within the size constraint for the prototype, wheel width had to be under 50mm, to avoid interference with the body plate. When designing the wheel, the first two dimensions we used for our base design were the diameter and width. By setting the width to 50mm from the beginning, it was ensured the wheel would fit on the UGV. A standard wheel hub was designed, with a simple bolt pattern, to interface with the selected motor shaft adapter. This was all designed and planned by using the outer diameter of the thread for the screw holes and purchasing the corresponding screws.

The grousers on the wheels were designed for a height of 5.4mm, to provide adequate traction on soft soil, while remaining short enough to be sturdy when printed in PLA. To provide continuous traction while minimizing slippage, the wheel was designed with 10 grousers. A sinusoidal profile was selected for the grousers to improve driving performance on side slopes.

The wheel of the rover went through four design iterations as the best option was desired for rough terrain. The final design of the wheel, shown in **Figure 10**, was built with thick, rigid double spokes, a hub patterned to fit with the motor shaft adapter, large sinusoidal grousers, and a thick, cylindrical rim. For the UGV prototype the wheels were 3D printed with PLA filament. Once printing was completed the wheels were then coated in a thin layer of rubber to increase the traction on smooth surfaces. If this were to go into mass production, it would be desired that the wheels are manufactured with a plastic injection molding process and bound with a urethane coating.

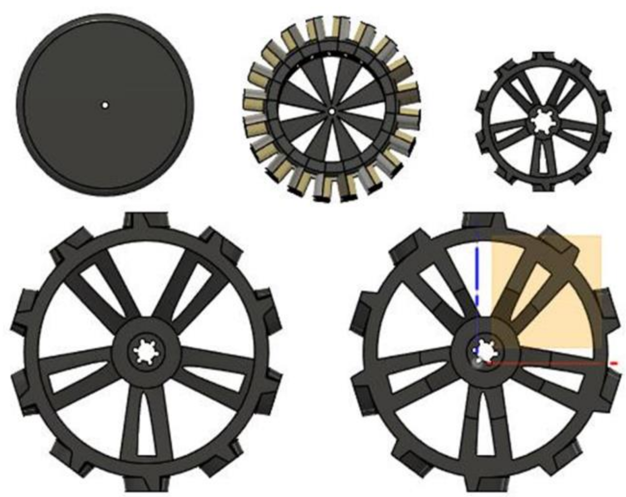

Figure 9: Wheel Design Iterations

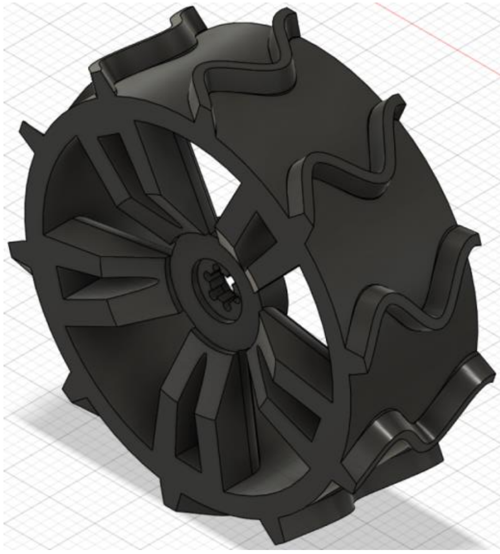

Figure 10: Final Wheel Design

2.5. Power Architecture

The power supply was initially designed so the rover would be able to be powered by a single battery safely. The battery was selected by calculating the necessary voltage and current required by the motors, ESCs, and receiver in a circuit. The circuit was modeled with the ESCs being connected to the battery in parallel, splitting the current evenly among the ESCs but keeping voltage at maximum availability for the motors. Once this was done, a battery was selected on the basis of being able to run the components at 60% capacity to allow for potential voltage/current spikes. By using a single battery it would keep the overall weight down, as well as limit the volume inside the rover taken by the battery. As the project prog power all the electronics successfully, the connector and wiring used in the batteries construction was not sufficient to facilitate the load demanded. Thus a two battery system was adopted. When switching to the two battery system, it was determined that each battery will power an axle as opposed to having a battery power either side of the rover, similarly to the differential steering. Ultimately this leads to a better design as there is enough power supplied for all components and if one battery is rendered inoperable, the rover would still prove functional.

The motor and ESC are connected in parallel, and the ESC only draws the necessary current for the motor. Ideally, when designing the system, no corner would draw more than 60A. To power the system a battery of either 2S and 3S classification was determined to be sufficient. 2S batteries are 7.4V, whereas 3S batteries are 11.1V. The decision was made to proceed with a 3S battery to maximize available power. Given the initial design of the rover involving a one battery system with the motors connected in parallel, the circuit draw was calculated as 240A.

In order to prevent damage to the components or the battery, it was determined that any battery selected should be able to provide this amperage at 60% of its maximum output in the event of demand spikes from the motors, ESCs, or receiver.

2.6. Control

The initial plan was to have the signals from the controller be distributed to multiple channels on the receiver end, but this was not feasible. It was decided that the wiring harness for the rover would be used as the main control of signal distribution. Each ESC was connected to multiple channels to help and reduce confusion for the user, but this proved to be problematic when signal inputs were ignored or lost on the receiving side. Due to this, an alternate control scheme was constructed and used that limited connections to the bare minimum as well as provided a relatively simple control scheme for the user. The new wiring harness was able to send a signal from a single channel to multiple motors. This limited potential issues with the signal transmission.

2.7. Structural Load and Vibration Analysis

For the rigid chassis UGV simple beam bending calculations, our scenario used a 10 kg point load centered on the longest beam (425mm) in the middle of the rover. Each of the 4 motor mounts was contained and all simulations used mild steel with a yield strength of 207 MPa. Our goal was a design with a minimum safety factor to fail of 3.0.

Our actual simulated safety factor came in at 2.639 and was short of our 3.0 goal, this failure occurred at the motor mounting brackets and showed the vehicle would fail by benign the connection between he motor and the frame, this would beach the rover and not allow it to move. The correction for the rover was a second arm extending from the rovers main rail counting to the inside mounting holes off the motor mounts. A v2 would see the hastily added supports shown in figure integrated into the frame design.

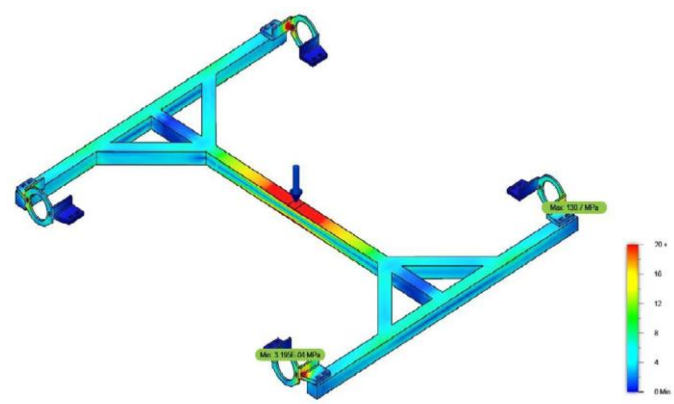

Figure 11: Static Load Simulation

Modal vibration analysis was used to find the resonant frequencies of the vehicle. At resonance frequencies, the vehicle can react strongly to a small amount of externally applied force and energy. This can cause damage or entirely destroy the vehicle. To prevent damage, the vehicle's lowest natural frequency should be greater than the dominant vibration frequencies experienced while driving over rough terrain. Based on data available for cross-country performance testing of small robots, a minimum modal frequency of 60hz is used as the key design criterion.

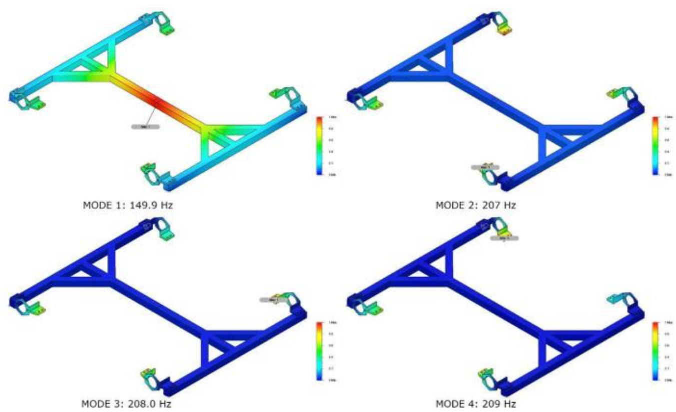

Figure 12: Lowest Frequency Vibration Modes

2.8. Cost Analysis

Our goal was to push the cost of the rover to its bare minimum. When developing the chassis we used a 20 gauge sheet plasma cut to shape, which was welded to ½" solid steel stock. Our ideal design for the chassis would be a stamped 20 gauge sheet plate similar to how automobile unibodies are produced. The brackets that were made to hold the drive train to the chassis, electrical component mounting, and body were made out of 3d printed plastic. This helped speed up our design process with rapid prototyping. We would want to injection mold all the component bracketry and body out of a single plastic mold that would be fastened to the chassis with clips. The wheels were printed with PLA plastic. Liquid rubber sealant was used to coat the wheel for traction on smooth surfaces. In the future, the wheels would be plastic injection molded and urethane coating would be bonded to the plastic. The total cost for the prototype came to $1,159.70, which given the price of similar products in the industry is extremely low. The total cost is satisfactory given the requirements and desires for as low a cost as possible. Injection molding rather than printing, a stamped chassis and the elimination of steel fastening hardware will push the production cost of the unit to a fraction of our prototype's cost.

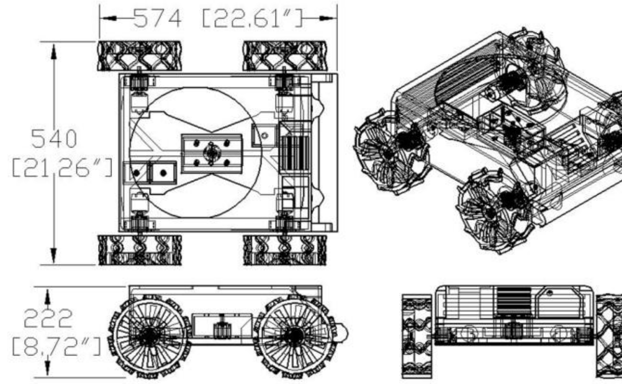

Figure 13: Rigid UGV Schematics

2.9. Testing

The speed was measured by driving the rover over a specific length and recording the time it takes for the rover to travel the distance. During previous testing a few wheels had been damaged at the hub. These had been repaired but were not up to the ideal strengths required, thus creating issues. After many attempts the top speed was significantly less than expected, hitting its peak at 6.5 MPH before the wheels failed. In the future with more time to print new wheels at 100% infill, it is expected the speed would be much higher.

The range of the video transmitter and receiver were tested by placing the two radio modules at increasing distances from one another in a relatively open field until the video signal was no longer being transmitted to the receiver. It was found that at roughly 275 m the signal between the receiver and transmitter was considerably weak and no longer provided an adequate image.

The connection between the controller and the receiver on the rover was tested by increasing the distance between the controller and the rover, and testing if the rover was still receiving input from the controller. If the rover did receive a signal it was considered a pass. The rover never lost control connection, but the test was concluded at a maximum of 275 m, as the rover is no longer usable at this range due to video loss. This result did still meet expectations being that the desired distance was only 100 m.

3. MODULAR ASSEMBLY UGV

The second underbody operation UGV presented was designed for modular assembly using standard extruded stock. This allows for the same basic design to be easily modified to a different profile, producing longer or wider UGVs, optimized for specific payloads of interest, with negligible effort. Unlike the first UGV design, with customized, 3D printed wheels, body, and electronics housings, the modular assembly UGV was primarily built with low-cost, ruggedized, off-the-shelf components, for robust high-speed cross-country performance.

3.1. Design Constraints

The length and width constraints for this design were defined around the outermost bounding box of the UGV, including the wheels, tires, chain drives, motors, and protruding rigid axles. Based on available data describing the vehicles the UGV would need to operate with, a maximum bounding dimension of 36 inches was selected for both the length and the width of the UGV, to ensure it is compact enough to be deployed from a vehicle with minimal human interaction, and perform underbody inspection with ample clearance from the heavier vehicle's polygon of ground support.

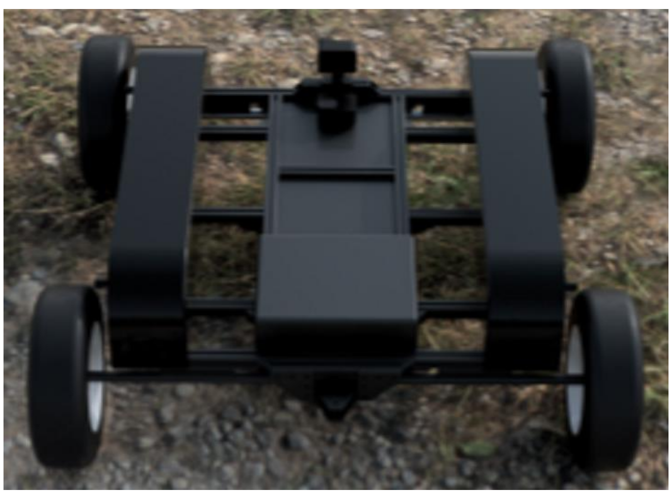

Figure 14: Modular Assembly UGV

The height constraint of ≤ 24 inches defined the maximum total height of the inspection vehicle and its associated bodies and critical payloads. This constraint was developed via research of the average ground clearance height of common military vehicles, mainly tactical logistics trucks, and it was found that anything under 24 inches would suffice.

The payload weight constraint defined the minimum weight that the inspection vehicle shall be able to carry on itself and still perform adequately. The constraint of ≥ 30 lbs was developed based on research of the average weights of possible payload and modular components (ammo crates, robotic arms, food and general supplies, etc.).

The payload area constraint defined the area available to install modular components on the deck of the inspection vehicle. The constraint of ≥ 12 in2 was developed by research in overall size of the possible payload and modular components that may be attached (ammo crates, robotic arms, food and general supplies, etc.).

The battery capacity constraint defined the operational runtime onboard batteries could support to power the vehicle at "wide open throttle." The constraint of ≥ 15 minutes was developed in conjunction with both requirements of a 10 mph top speed and a minimum travel distance of two miles (one mile round trip). At the inspection vehicle's top speed of 10 mph, and a battery life of 15 minutes, the vehicle shall be able to travel 2.5 miles, giving the vehicle a good factor of safety.

A custom modular frame was designed for the base of the vehicle. The custom frame allowed for modular attachments and tank style steering to be implemented. The custom frame was also built to be stronger and lighter than the other frame options.

For the vehicle, a chain drive system was selected. This was selected because the motors were designed from a Razor electric DirtBike MX350 [3]. Also due to it being an off-road vehicle mud and debris is a given and chain drive is less likely to fail [4]. This Machine uses a chain drive. As such the model also uses a chain drive. Using this product as reference the gear ratio was also selected. The tire was attached to a 47 tooth gear, and the motor a 11 tooth gear. 25H chain was used. These components were experimentally found from the disassembly of the motorcycle.

3.2. Power

It is well known that lithium ion batteries have a longer lifespan, better cyclic performance, and faster charging times than lead-acid batteries. Lithium batteries also have constant power throughout the discharge cycle and lead-acid battery power tapers off throughout the discharge cycle. Thus, ideally, lithium ion batteries would have been used in this design, but due to budget constraints lead-acid batteries were used to build the prototype.

The designed vehicle used four lead-acid batteries in total. On each side of the vehicle were two 12V lead-acid batteries connected in series to obtain a total voltage of 24V and an amperage of 9A. The series connection doubled the voltage while maintaining the same amperage.

In order to power a DC motor in the particular application of a RC Vehicle, there are a few components required to complete the circuit. There must be a main battery supply, microcontroller, motor driver and a RC transmitter/receiver. The chosen microcontroller is the Arduino Mega due to the extra ports allowing the capability to run more motor drivers. The Arduino Mega is programmed to take the signal coming from the transmitter/receiver which is then sent to the BTS7960 motor driver. The benefit of having a motor driver vs direct connection gives the ability to control the direction and speed of each DC motor. Below is a simple diagram of just one DC motor to understand the concept of how the circuit works. The signal from the receiver is sent to the arduino as a pulse, which is then converted to a PWM signal for the motor driver using the particular code. The motor driver is powered separately using a 12v battery in this model and the arduino is powered by its own 9v supply. The final wiring diagram will follow the same concept below but with more motor drivers and a higher battery capacity.

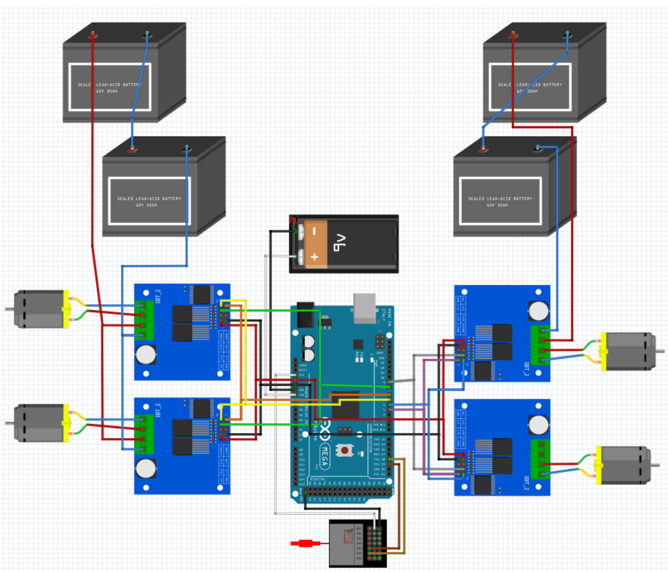

Figure 15: Electronic / Power Architecture

3.3. Structural Load Analysis

For our modular assembly UGV, we initially performed simple beam bending calculations. Two scenarios were used: a 100 lb point load centered on the longest beam (24in), and an evenly distributed 100 lb load on the longest beam. We then compared the bending stress to the fatigue stress of the support beam, to ensure that the beam could support the entire weight of the machine as well as the payload. The stress of the beam was calculated using the characteristics of 20mm 80/20 aluminum beams.

Further design analysis included load simulations of the vehicle. A 1 ft diameter disk weighing 30 lbs was loaded on the vehicle to simulate the inspection equipment or other modular payloads. The Max Von mises stress on both the steel and aluminum components was sound and then compared to the fatigue strengths to ensure the vehicle could support the minimum requirements. All added components, such as the batteries and motors, were simulated as solid steel. This results in the load effect of these components to be larger than reality indicating that the factor of safety is higher than simulated.

From the load simulation below the max load from a 1 ft round plate and gravity effects would result in a max Von Mises stress on steel components of 24.38 Mpa and 16.02Mpa on aluminum components. This point is located at the connection point of the axle to the frame, and the corner of the frame respectively. Based on yield stress, the minimum factor of safety of the steel components is 14.25. The minimum factor of safety on aluminum parts is 15.04. From fatigue stress, the minimum factor of safety of steel components is 8.61. The minimum factor of safety from fatigue stress on aluminum parts is 5.92. From these calculations the minimum factor of safety of the vehicle is 5.92. This indicates that the vehicle can support a payload of 177.6 lbs. In reality this value is higher. This is due to the batteries and motors being simulated as solid steel as opposed to their actual materials.

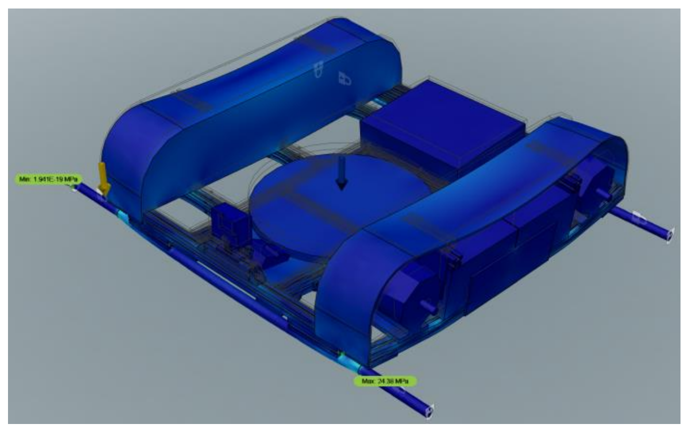

Figure 16: Static Load Simulation

3.4. Vibration Analysis

For testing purposes, four models were used. This was done to better identify a failure if one was to occur. For each model, two cases were tested. Test one is where the vehicle is grounded at the axle to simulate the vehicle driving across the ground. Test two the center of the frame was constrained to simulate the vehicle momentarily leaving the ground. For all tests, a minimum resonant frequency of 60 hz was used. From testing it was concluded that all models passed test one. This indicates that under normal driving conditions modal frequencies are not less than 60hz, and no resonant damage will occur. When conducting the second test however, model 3 and model 4 both failed. This is due to adding the motors and batteries. Because of this, it can be concluded that from the current design, launching the vehicle from obstacles should be avoided because it can possibly cause resonant damage.

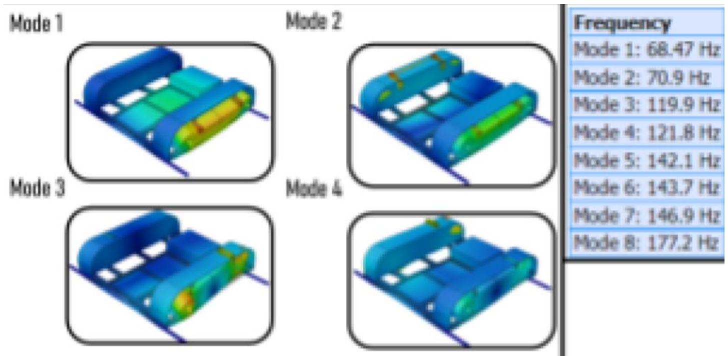

Figure 17: Vibration Modes with Constrained Corners

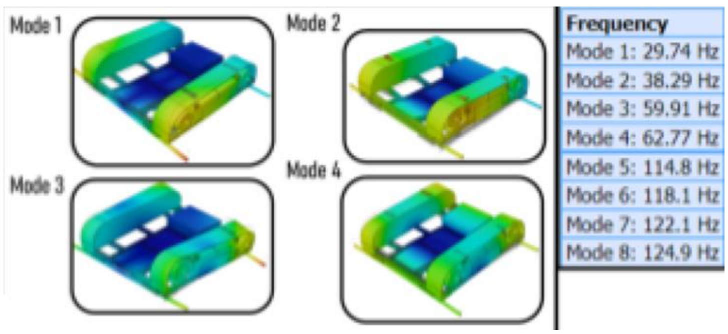

Figure 18: Vibration Modes with Constrained Center

3.5. Stability Analysis

As part of the vehicle's off-road capabilities, it must be able to traverse up, down, and across inclines without tipping over. To determine at what angle a slope can be before the vehicle will tip, stability analysis was calculated. When traversing a hill, the center of mass must not be horizontally outside the vehicle's points of contact. As such the max angle, θ, a vehicle could traverse at any given direction would be when the center of mass is vertically above the contact point on the ground.

To simplify calculations, a polygon of support can be drawn by connecting all points that touch the ground. For the calculations it was assumed that the tires are fully inflated and only the center point of the tire is touching the ground. The angle produced from the vertical axis through the center of mass and the vector from the center of mass and the polygon of support is the max angle the vehicle can descend at a slope in that direction. Pythagorean theorem can be used to determine angles of tipover in any direction.

Because the vehicle is modular, it was assumed that regardless of the components attached, the center of mass would be within a 8'' x 8'' square around the center of the vehicle and would vary in height from 5'' to 15''. At each center of mass height, a stability map is computed at the points indicated in Figure 5. Due to symmetry, stability maps for the back and right can be assumed to be rotated or flipped and equal in magnitude as the front or left.

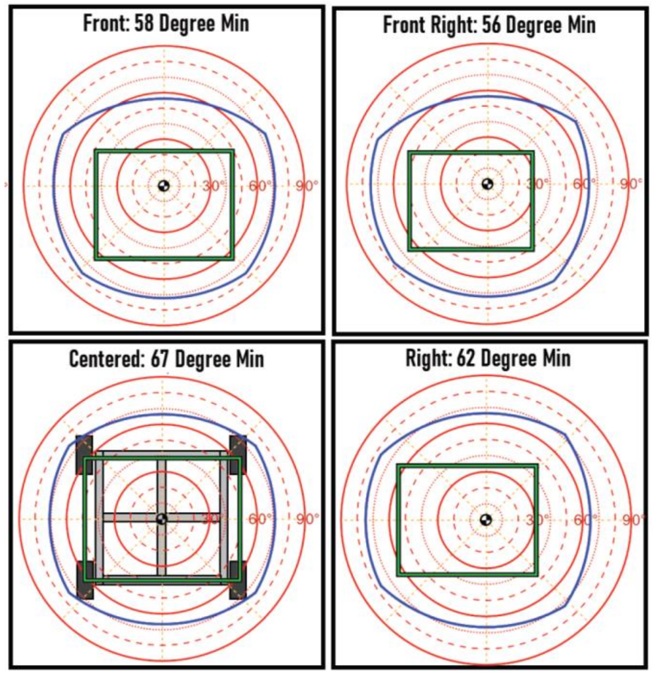

Figure 19: Tipover Stability (5in Center of Mass Height)

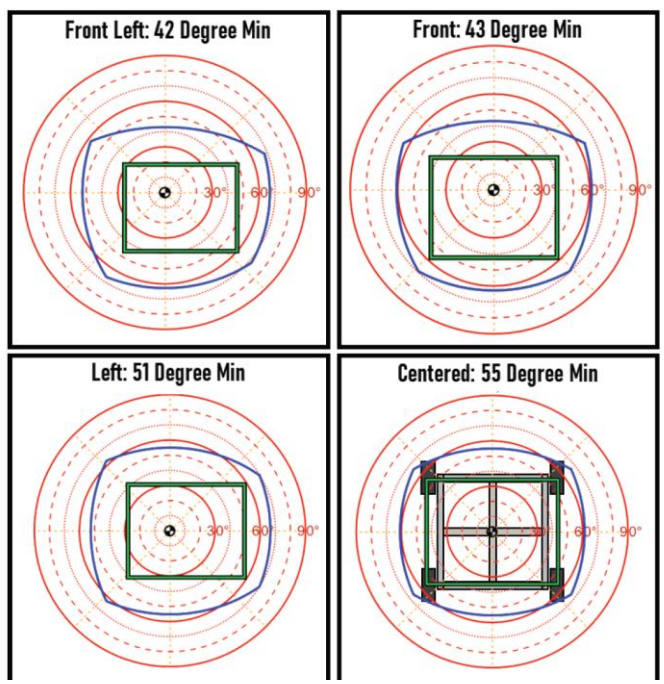

Figure 20: Tipover Stability (8in Center of Mass Height)

From the designed vehicle with an overall dimension of 32'' by 33'' with 10'' diameter tire 3'' wide, the polygon of support of the vehicle was concluded to be a 29''x23'' Rectangle. The Minimum angle of tipover for 5'', 8'', and 12''center of mass heights are calculated below for every point. Additional Calculations were conducted for the center of mass of the model designed. From the model it was found that the center of mass is 7.202'' from the ground, and 11.956'' from the front of the model. The designed model had a minimum tipover angle of 56 degrees. A minimum angle of tipover from the requirements was set at 30 degrees. And no center of mass was a tipover angle less than 31 degrees. All tipover calculation were conduction through a Python program that computes a 360 degree map of tipover angles.

3.6. Prototype

The prototype was assembled from 80/20 extrusion of 2020 series aluminium alloy. Four 24V 350W brushed electric motors were used for propulsion, with 25H heavy duty chain and sprockets used to transfer power to the wheels. Heavy duty 10 inch wheels with pneumatic tires were used for ground propulsion, held on 5/8 inch threaded rod as the axle.

The prototype was powered by a Weize 12V 9AH battery, held on a Traxxas 4-cell battery housing. An Arduino Mega 2560 R3 was used for robot control, with BTS7960 43A motor drivers for motor power. Connection was provided by a RadioLink TS8 receiver, and a GoPro Hero 9 was used to record onboard video while driving. The total cost of the prototype came out to $971.

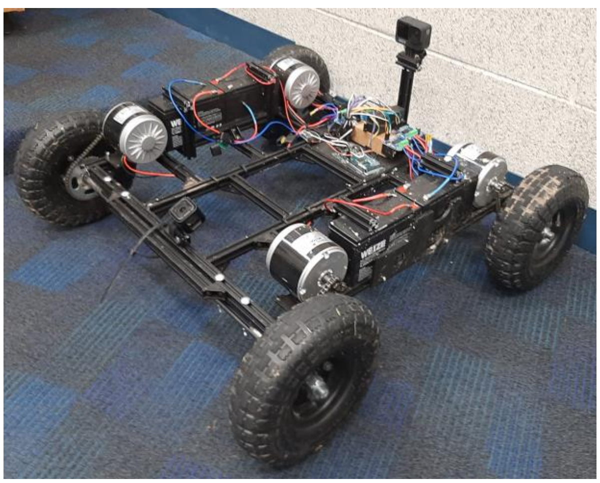

Figure 21: Modular UGV Prototype

3.7. Testing

To determine whether the prototype was able to meet its design requirements, and to see if the models were accurate, a multitude of tests were conducted to see how it performed. These tests included parameters such as stability testing, obstacle surmounting testing, payload testing, and various tests while off-roading.

Vertical obstacle testing was completed to ensure the vehicle was able to traverse over difficult obstacles that it may encounter in the field. With a curb being a relatively vertical obstacle that can get to being taller than the vehicle, it was the perfect obstacle to test the extreme end of an obstacle the vehicle could come across. If the vehicle was incapable of surmounting a curb of these sizes, it would be very ineffective in the field. Testing the prototype for vertical obstacle climb exceeded expectations; the vehicle was able to scale curbs up to 12 inches tall.

Next, the prototype was tested for tipover stability and driving performance while carrying a payload. With a 35 pound weight attached to the vehicle, hill climbs of varying inclines at various angles of attack were attempted. The prototype was tested on 20° and 30° hill slopes at all angles of attack, and was able to drive up / down / along the hill without tipping over or getting stuck. The vehicle even lost a wheel during testing, due to faulty manufacturing of one of the purchased wheels, and was still able to climb the hill with the payload on only 3 wheels. On flat terrain, the vehicle was able to continue operating while carrying 140 pounds of payload.

The importance of testing the vehicle on a large hill is that it simulates going over terrain in the field. If it were to easily tip over while on an incline, or not be able to climb an incline at all, it would quickly get stuck in an uncontrolled environment. Testing the payload capacity is also important, as if the vehicle is to be used to carry ammo and supplies, it must be able to do so without impacting its operation to a point that it is no longer able to deliver these payloads. The vehicle showed in these tests that it is more than capable of performing these tasks.

On both flat terrain and on hill slopes with a 35 pound payload, the robot was able to sustain a maximum speed of 18 mph, surpassing the goals of 15 mph and 10 mph. The vehicle was able to travel over 3.2 km (2 mi) on a single charge, making it much more capable at traveling a large distance than anticipated. The vehicle was able to run continuously for 2 hours before the batteries died. This means the vehicle was able to run for 8 times the amount of time initially desired.

Figure 22: Modular UGV on Field Testing

3.8. Modular Mounting Interface

To increase the modularity of the vehicle, a quick release mounting system was designed to allow for various cargo and attachments to be locked onto the vehicle. This mounting system was designed using switchable magnets installed into a 3D printed mounting base. Electric motors are used to rotate these magnets into either the on or off position, and they will be locked in place with a worm gear box between the motors and the magnets. The magnets will be controlled remotely by the operator of the vehicle, so that unauthorized personnel cannot interfere with the payload on the vehicle.

The outer width of the mounting component is 12" across, which utilizes a standard measurement to increase the number of different payloads the vehicle can accept. For an additional interface with the mounting system, a flat plastic sheet with steel legs was created to allow for cargo to be mounted in any way, such as with tie down straps, bolts, or picatinny rails.

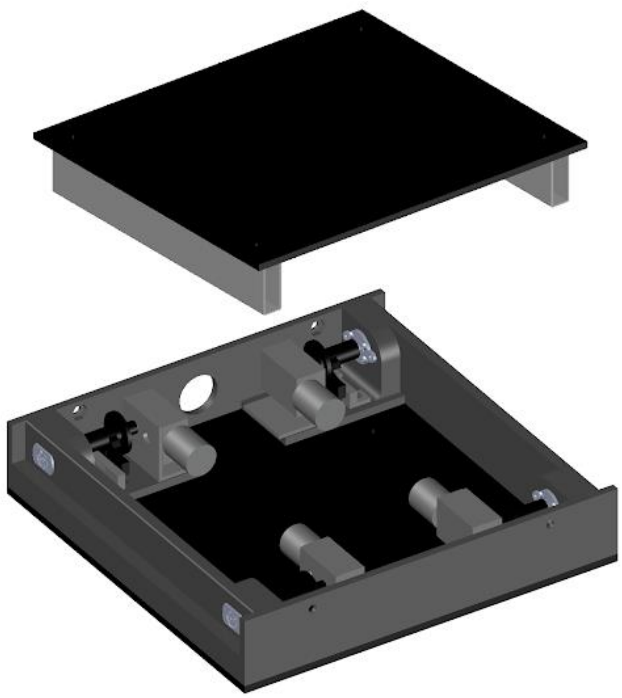

Figure 23: Modular Mounting Interface

Various styles of locking mechanisms were considered for use in this mounting device, including using locking rods or one way latches. While these types of mechanisms provide a more rigid and secure attachment for the payload, they require external moving parts to operate, and the payload must line up with these mechanisms for successful operation. This would introduce a failure point in the field, as any debris could make the mechanism inoperable. The switchable magnet was chosen for the design, as it allowed for the mechanism to be controlled without any external movement. This is beneficial, because it prevents any debris from getting into the mechanism, which would prevent the latch from either engaging or disengaging. This design also allows the design to be more easily waterproofed, soundproofed, as well as completely concealed.

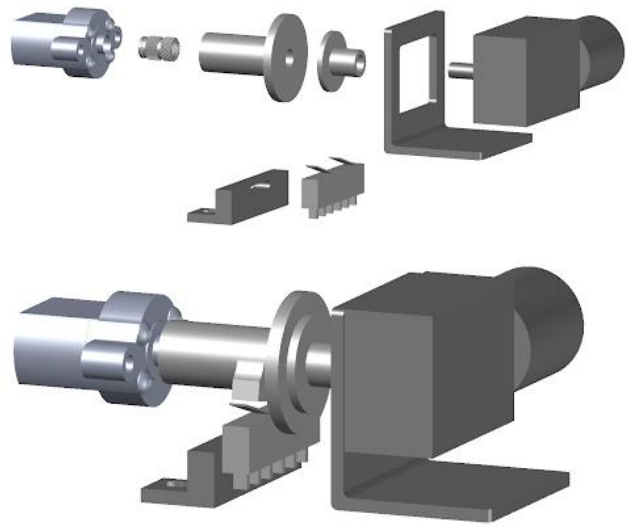

Figure 24: Switchable Magnet Design

Electric motors are used, so the magnets can be controlled by the operator with the same controller used to drive the vehicle. The first design had a motor directly connected to the shaft of each magnet, but this was found to be ineffective, as it was possible for the magnet to flip back to the off position while the motor was shut off. The final design adds a worm gear to each motor, to prevent this unwanted action. Although having one motor per magnet increases the complexity of the design, it increases the durability of the device by introducing a redundancy for the magnets.

Using a locking mechanism that relies on magnets rather than a physical lock may be seen as worrisome, as the only force preventing the payload from being removed is frictional shear force. While this may be a cause for concern in a typical military vehicle, the minimal weight and size of Modular Assembly UGV makes it so that the magnets need to just be strong enough to lift the vehicle itself. This is due to the fact that if the vehicle were in the scenario of an unauthorized removal of the payload, the vehicle itself would be lifted with the payload. This would then lead to either the payload and vehicle being taken anyways, or the vehicle staying attached to the payload, becoming a deterrent from its size and weight. With calculations and real-world testing, it was found that magnets used in this device were adequate in holding the payload by themselves, relying solely on the shear force between the magnets and steel square tubes.

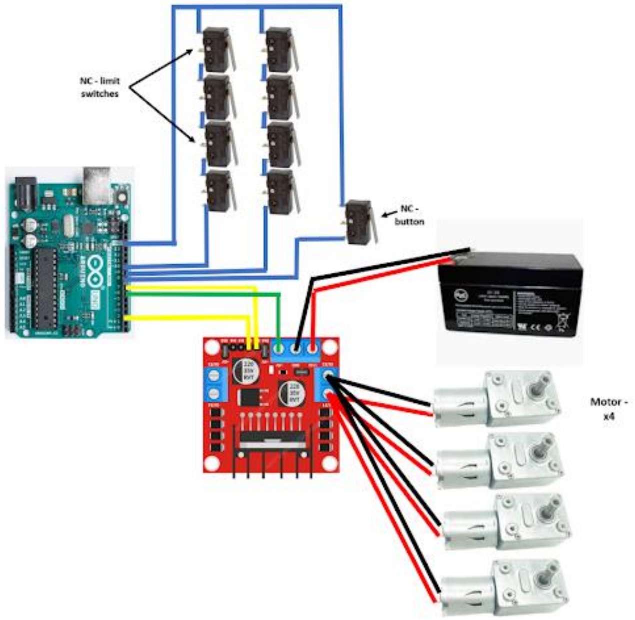

Figure 25: Modular Interface Electrical Configuration

Uses for this mounting device include a lockable landing pad for a drone, bringing supplies, ammunition, and other payloads to restock or aid soldiers on the battlefield. The size of this component also allows for the housing of all of the vehicle's electronic components, both for this mounting system and for the vehicle itself. This allows for an additional benefit of the reduction in the number of electrical boxes, and thus lowers the amount of waterproofing the vehicle needs as a whole

4. CONCLUSION

In the design of the Rigid Chassis UGV, the team was required to make a compact, low-cost robotic vehicle that can conduct remotely controlled underbody operations. Our design allowed the user to have remote access and have a clear look at what the rover sees, so the design requirements were met. However, when it came to the capability requirements, we as a group ran into issues. The first issue was that the user could not switch between feeds and instead had both running simultaneously. The second issue came when the wheels were not printed to the desired infill level. Both of these issues were a consequence of the time constraint that we had. The wheels, with the minimal infill used, still had a print time of 30 hours and the ability to only print one at a time on each available printer due to the size, whereas the previous, smaller wheel designs were able to be printed two at a time, cutting the waiting period on replacements or updates in half. The cost of the rover was low compared to rovers of similar capability. When using new methods such as injection molding as stated before, the cost would increase but would still be a budget alternative.

The design of the Modular Assembly UGV was found to be somewhat more effective. Over the course of a semester, a practicable prototype was constructed and tested, and served as a physical proof of concept that the theoretical work developed for an optimal military inspection vehicle was a success. Within reason, it is believed that with more time and a more modest budget, a “perfect” inspection vehicle could be developed and implemented for the military. A larger budget would allow for purchase of several parts that were deemed necessary for the durability, reliability, and longevity of the desired inspection vehicle. For instance, the in-hub motor wheel assemblies would be used, ridding the event of any drivetrain issues such as sprockets breaking or chains popping, and would also give more room on the vehicle itself for possible payloads. Buying larger tires that were designed specifically for the inspection vehicles suspension purposes would allow it to climb and navigate even more treacherous terrains. Purchasing a better remote controller, receiver, and motor drivers would allow for the vehicle to be controlled from much further away, and would mitigate electronic associated failures that bring the vehicle to a halt. Overall, a lot of knowledge was learned during the duration of this project and if continued, it is believed that this inspection vehicle could go on to be a powerful tool for the U.S. military.

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