DESIGN AND TESTING OF AN AUTONOMOUS GROUND ROBOT FOR AGRICULTURAL APPLICATIONS

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ABSTRACT

This senior project discusses the design and testing of an autonomous ground robot for agricultural applications such as strawberries. The vehicle will feature a robotic arm that will be programmed to perform various tasks, such as collecting soil and leaf samples of the crop or measuring soil moisture and salinity. Various components were chosen to be implemented on the vehicle due its power requirements and operating environment. Finite Element Analysis testing was done on the frame of the vehicle to ensure the adequacy of the design.

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INTRODUCTION

Agriculture is a significant part of our past as human beings, and it will need to be a significant part of our future, especially with the growing world population. Technology and Agriculture will continuously be associated with each other, as both will have to work harder and smarter to feed our world. In more ways than one, California is representative of a growing world that will always rely on agriculture, but will also become increasingly reliant on technology due to the difficulties it can alleviate. California is known for being “America’s Salad Bowl” due to its large agricultural presence, as well as home to several of the largest technology companies in the world. That being said, it was inevitable that technology would become increasingly incorporated in agriculture here in California. Today, technologies such as drones, robots, GPS, and thermal and 3-D imaging are widely used in agriculture to gather and analyze data, with the goal of decreasing labor and increasing production. Specifically, the use of ground robots is becoming more widely used in agriculture to gather data across a large field area, sometimes autonomously. In this growing field, the greatest challenge is to “develop smarter machines that are intelligent enough to work in an unmodified or semi natural environment” (*Design and development of the architecture of an agricultural mobile robot).* In other words, these robots are usually not designed for a typical indoor, controlled environment, which poses exciting new challenges for engineers and designers. In *Time-optimal guidance control for an agricultural robot with orientation constraints*, the author says this well by explaining that, “Differently from the well-structured environment, the working environment of agricultural robots imposes varied constraints on the movements of the vehicles due to contact surface of loose soil and the specialties of crop cultivation features.” Robots such as these can be used to gather and analyze soil samples, use thermal or 3D imaging, apply nutrients or pesticides, as well as many other different tasks associated with agricultural data. However, these robots are sometimes limited to only one of these tasks, and for a hefty price tag, a farmer or field manager might only get one aspect of data out of it. These robots also sometimes require user operation, as some of them are not autonomous. This senior project is to bring all of these aspects together into one robot. A robot will be designed and built so that multiple sensors, cameras, and robotic arms can be added or removed from the robot, depending on the specific operation. This would make it possible to accomplish several different tasks that collect many kinds of data that a farmer or field manager would find useful. Designers that have created similar robots in the past have had to deal with the challenges associated with designing a robot that could simulate the intricacies and complexities in dealing with agricultural products. This fact sets apart agricultural robots from similar robots in different applications, as fruits, vegetables, and nuts are more delicate in handling and most processes still require a human eye to determine the state of the product. In *Evaluation of a Strawberry Harvesting Robot in a Field Test*, this is reinforced when the author states that “it is necessary to design an intelligent robot with human-like perceptive capabilities; for instance, the machine would need to calculate fruit position, assess maturity level and pick the fruit without damaging the pericarp.” This will likely displace some of the labor associated with managing a farm, either by replacing certain workers, or by simply adding to the work force by working at off-hours, because the robot can work 24/7. In addition to this, the robot would also be designed to be autonomous, making it more convenient for the user, without adding any unnecessary labor. Such a robot would prove useful in agriculture, as it would be able to give a good overall representation of different kinds of data in a field. The goal of this project is to design a prototype that utilizes the current technologies seen in similar agricultural robots in use today, while experimenting with new ideas in an attempt to keep the project innovative and original.

LITERATURE REVIEW

Research was done in order to order to determine existing ground robotics applications in agriculture. Because there are various robotic applications that are used for many different types of crops in agriculture, the research was limited to robots that are used in ground crops. This is due to the fact that this project will be designed and built for ground crops organized in rows such as strawberries. The literature review will be focused exclusively on the frame design for the agricultural robot, given the components that the robot will need and the applications this specific robot will be used for. Because there are several different students working on this project, this individual literature review will not include information on the steering and drive design, electronics, sensors, or machine vision systems, all of which are crucial components to the robot's design as a whole.

Existing Designs

Before beginning the preliminary design of the robot, research was done in order to discover what was already being implemented in agriculture, and how those robots operate in ground crops. Because there are a great number of designs in existence, only robots that operate in ground crops will be included in this literature review.

One design that was found was developed by the College of Engineering at Nanjing Architectural University in China and the Department of Agricultural and Biological Engineering at the University of Illinois. This robot is designed to navigate throughout corn fields using a machine vision guidance system. It provides this autonomous guidance by using a fuzzy logic control system. The robot design can be seen in Figure 1 below.

Figure 1: Example Robot 1 from the University of Illinois

This robot is a good reference point for the robot that will be designed in this senior project. It is a well developed example of an autonomous ground robot that operates within row crops based on machine vision. Although it is a good starting point for research, there are a few constraints that the robot for this senior project would have to address. If a design similar to this were used, it would limit the range of motion of the robotic arm. This is because the robotic arm would have to be placed on top of the robot, which greatly reduces its ability to perfom tasks. Additionally, the base of the robot would likely have to be higher up off of the ground, in order to be able to operate in the varying ground conditions of the fields. This design was similar to many of the other designs found while researching. Most of the ground robots found were relatively small, relatively low to the ground, and did not have the ideal framework for housing the given robotic arm.

A few larger designs were found, many of them the size of typical farm tractors. One example that was found was designed and built by Agrobot, a company that has developed several harvesting robots. This specific design is a strawberry harvesting robot, which features a machine vision system and several robotic arms used to havest the strawberries. The robot itself is about the size of medium-sized tractor and drives over the rows of strawberries in order to view and harvest the strawberries easily. The Agrobot SW6010 stawberry harvester is shown below in Figure 2.

Figure 2: Agrobot SW6010

The Agrobot SW6010 and other designs that were found during research that addresses the inadequacies of the smaller robots. These designs that were found feature a “bay” type frame design, allowing the robot to drive over rows of crops, with the robotic arm mounted on the underside of the frame.

Additional designs were considered during research and a pros and cons list was formulated in order to evaulate these designs.

Table 1: Pros and Cons of existing designs

ROBOT	PROS	CONS
Univ. of Illinois/Nanjing Univ.	Autonmous guidance, machine vision, small overall footprint	Could not accommodate current robotic arm
Agrobot SW6010	Able to harvest strawberries, features mutiple actuating arms, machine vision, autonomous guidance	Size of a typical tractor, is rather expensive due to a lack of similar robots
Mobile Robot for weeding, Univ. of Denmark	4 wheel drive and 4 wheel steering, experimented with RTK/GPS, low turing radius for easier operation	Mostly experimental, was made in 2001, lacks a suspensio system to protect components from shock damage
Hakotrac 3000 Tractor, Germany	Operates autonomously, uses Trimble RTK/GPS for guidance, has several safety features	This project is an add on to an existing tractor and uses typical tractor implements, this senior project will be built from the ground up
Autonmous Christmas Tree Weeder	Operates autonomously, utilizes RTK/GPS, uses control algorithms developed in Simulink	Was developed by modifying an exisiting riding mower, is used soley for mowing weeds
Supportive Autonomous Vehicle for Agriculture (SAVAGE), Piraeus Institute of Technology, Greece	Features 4 wheel drive and 4 wheel steering, frame would be easy to fabricate, operates autonomously, feature the "bay" type design	may not be tall enough to accommodate the current robotic arm, may not be large enough to accommodate all of the batteries
The Weedy Robot, University of Applied Sciences, Osnabrueck, Germany	Similar to SAVAGE, has 4 wheel drive and 4 wheel steering for operation in compact spaces, features extra storage for batteries and other electrical components	current size could not accommodate the robotic arm, current design is only used for pulling weeds
Autonomous Crop Treatment Vehicle, Tillet and Hague Technology Ltd	Features a "bay" type design, utilizes differential steering	was developed in 1993-1996, features 2 wheel drive, frame is very low to the ground and would not be able to operate in a strawberry field

Frame Design

For this project, it has been decided that the robot must be large enough to hold the robotic arm that is already available. It was also required that the robot work easily with various row crops and to be of a reasonable size as to power it electrically. The original thought for the frame design was either an aluminum or steel base frame that would be strong enough to hold all of the components, but still able to move about in an agricultural environment. Therefore, designs similar to the end goal of this project were researched. *Figure 3* below shows a design that was found during research that will house a robotic arm. However, this design is built so that the robotic arm would be placed upside-down on the underside of the frame.

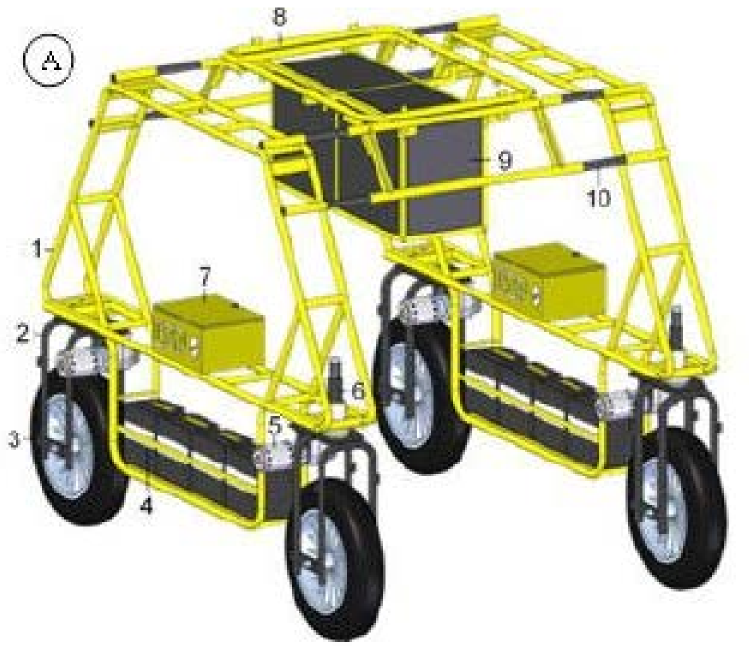


Figure 3: Example Frame Design (Courtesy of Design and development of the architecture of an agricultural mobile robot)

This design seemed like it would work well for row crops, as the wheels can travel along the rows of crops and the robotic arm could have direct access to the plants below by hanging upside down. Another benefit of this design is the truss-type frame design. A frame design such as this can be quite strong while using less material when compared to other designs. This will ultimately make the robot lighter as a whole, as well as being able to withstand wind loads more effectively. However, the manufacturing difficulty and what type of material to use for the frame must be carefully considered for this design. Another design that was looked at for the frame design was quite similar to the one shown earlier, however it has not been built yet, so the design is much more abstract. In theory, this robot is designed to seek out weeds within a field and apply herbicide to them. As can be seen in *Figure 4*, it also features robotic arms that are attached to the underside of the robot itself, so the arms can reach down and have easy access to the plants below.

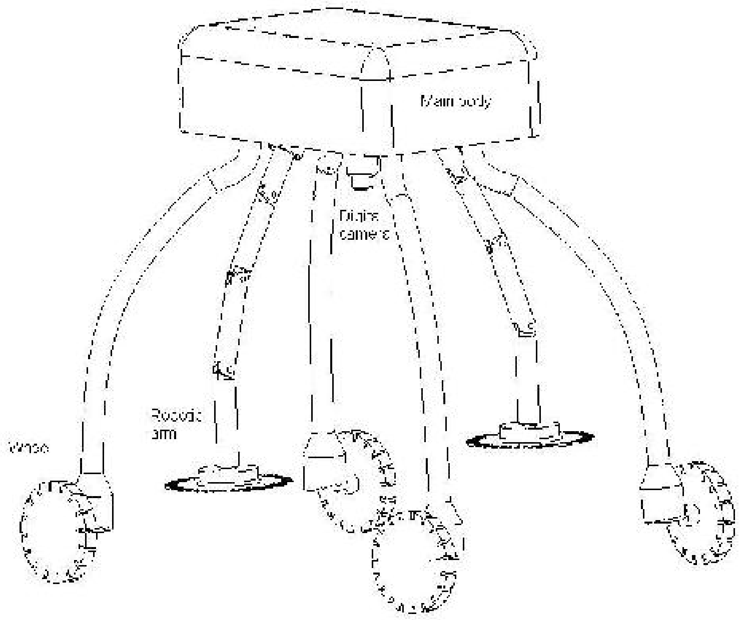


Figure 4: Body Design (Direct Herbicide Application With an Autonomous Robot for Weed Control)

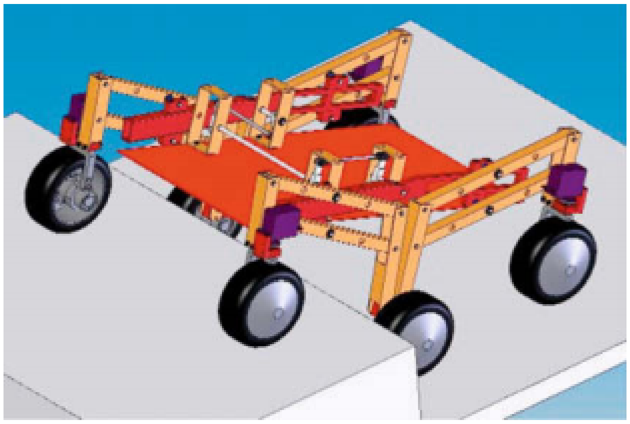
The frame design for this senior project will have to be strong enough to support to the robotic arms and other components, but not too rigid, as the robot needs to be able to articulate while it is making small movements. This is especially necessary if a differential drive system is used, as the wheels would be moving at different speeds at times to steer the robot. These designs were chosen as resources because they feature a taller frame, which allows for more clearance when driving over the row crops. This also allows the robot arm to hang on the underside of the body, which maximizes its range of motion and ability to access the plants in the rows.

Articulation

When considering frame design, it can be easy to forget that the rigidity of the design is not always a good thing. Because this robot is designed to operate in an agricultural setting, it must be designed to handle rough and uneven ground, wet soil, and other various obstacles. A design that is too rigid would not work well in an agricultural setting because the drive system would not work properly if each wheel does not have proper contact with the soil. There are a few different ways to ensure articulation when designing the frame of the robot.

The first of these articulation techniques is to allow flexure in the frame. This is not an easy design task, as the frame itself must be allowed to handle the loads subjected to it, while being allowed to flex enough to provide the articulation needed. If too much flexure is allowed however, the frame could experience deformations or failures *(Design and development of the architecture of an agricultural mobile robot).* This method of allowing articulation is also designed for one specific loading or loading range for the robot. This may pose a problem, as it allows for less flexibility in the components that can be added to the robot. If this method for allowing articulation is chosen, it should be done concurrently with creating the parts list for the robot and deciding which components will be featured on the robot and where they will be placed, in order to estimate a proper loading condition.

Another method for allowing articulation in the robot is to design the frame to have linkages, which allows parts of the frame to move, making it no longer completely rigid. The movement of different parts of the frame ensures that each wheel experiences full contact with the soil, providing traction. In an article entitled *The ExoMars Rover Locomotion System*, different Mars Rover robot designs are examined on their ability to drive over various obstacles. Figure 5 shows the CRAB design and how it is designed to climb up a step.



CRAB

Figure 5: CRAB Rover Step Climbing Example

This design clearly implements articulation of the robot frame in order to climb up the step with all of the wheels still contacting the ground and experiencing full traction. This is a dramatic example of an uneven surface where articulation is required, but it shows the benefits and capabilities of articulation of the frame of the robot using linkages. When considering using linkages to provide articulation, it is important to note that flexibility of components is not recommended, as proper linkages rely on dynamic equations based on rigid components. This is observed in a study on mechanical linkages entitled *Dynamics of Nonrigid Robot Linkages*, where the authors “examine the problem of modeling the kinematic and dynamic motion of flexible articulated linkages…for the control of structural deformations in such linkages.” In other words, it is crucial to ensure as little flexure in the members in question as possible, in order to be able to model the system dynamically using standard kinematic equations.

PROCEDURES AND METHODS

Constraints

In order to begin the design of the robot, many constraints had to be considered. First of all, it was decided that the vehicle should be able to run completely on electrical power. This would eliminate the need for a small engine and the additional drive train design that would be needed. The decision of making it completely electrically powered could also present the possibility of adding a solar panel to help power the vehicle. Another constraint that was considered was the size of the vehicle. Because this robot will be primary used in strawberry fields, this limits the width of the vehicle to the width in between rows, as the vehicle will have to be able to drive over the rows. Due to these size constraints, the vehicle frame ended up being quite large. This added a weight constraint, as the vehicle should be able to operate without an unreasonably large power requirement from the drive motors to move the vehicle. Additionally, the frame had to be designed in a way that maximized the functionality of the UR5 robotic arm, as it is the main component needed for the vehicle to accomplish tasks in the field. This would ensure that the robotic arm can efficiently perform tasks in a way that would justify the choice to use this specific arm.

Weight Budget

In order to design the frame correctly, a preliminary weight budget had to be done. The weight budget included the batteries, the UR5 robotic arm (shown in Figure 6), the wheel and tire assemblies, the computer and navigation equipment, and the frame itself, is shown in Table 2. The frame had to be designed to be able to handle this loading. However, if the frame is too robust, it will weigh more, which would require more power to be able to move. Therefore, a balance must be found between its strength and weight characteristics.

Table 2: Weight budget

Item #	Description	Weight (lbs.)	Quantity	Weight (lbs.)
1	Interstate SRM-27 Deep Cycle Batteries (210A-h reserve)	60	8	480
2	Universal Robotics UR5 Arm and Control System	100	1	100
3	Frame	150	1	150
4	Wheel and Tire	35	4	140
5	Computer and navigation equipment	35	1	35
6	Payload	200	1	200
			TOTAL =	1105

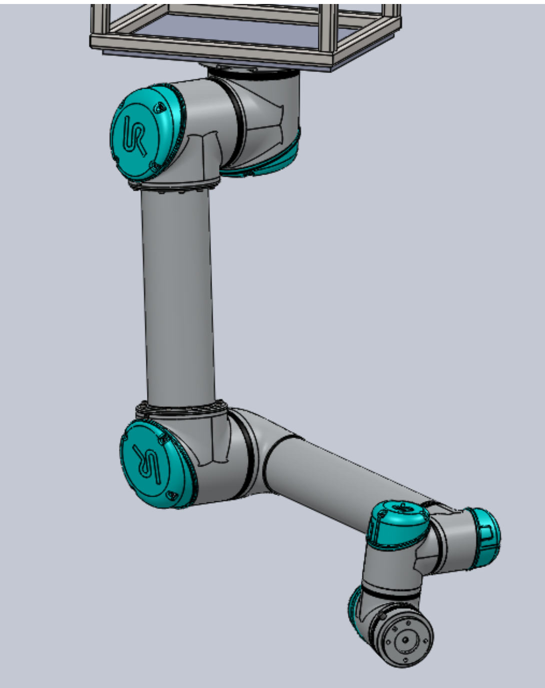


Figure 6: Universal Robotics UR5 Robotic Arm

Initial Frame Design

Because the rows of strawberries are around 5 feet apart, a relatively large frame was needed to span over the row of strawberries, so that the robotic arm could have direct access to the crop. This design would have each wheel base placed on separate sides of the crop. A truss type design was chosen for the frame because trusses are relatively light for how structurally sound they are. A truss type design also has relatively low surface area, making it less susceptible to wind loads when out in the field. This truss design was used for each side of the frame, where both wheel bases would be. The initial design featured this truss type design for the frame of each wheel base. The steel tubing chosen for this design was 2”x2”x1/4”. This entire assembly is shown in *Figure 7*.

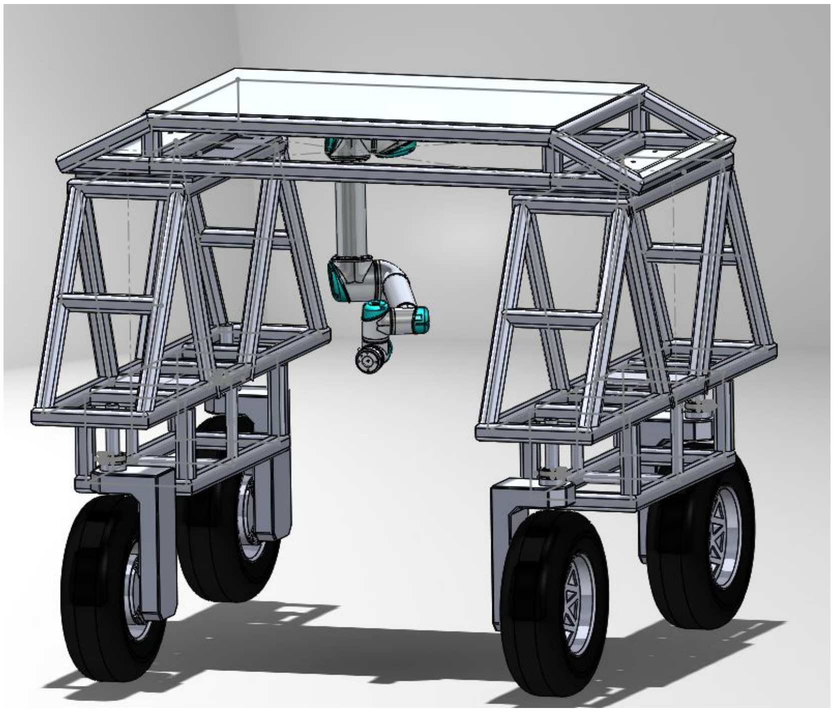


Figure 7: Initial Design

The cross span that connects both wheel bases also supports the robotic arm. This allows the robotic arm to hang upside down, increasing its functionality. In order to make the frame adjustable to accommodate different widths between rows, a bolt and slot plate design was initially chosen to connect the cross span to the wheel bases. This proved to be a simple way for the user to change the width of the wheel base of the robot. *Figure 8* shows the slot plate, which would be welded to the top of the wheel base, and the bolt plate, which would be welded onto the bottom of the cross span truss.

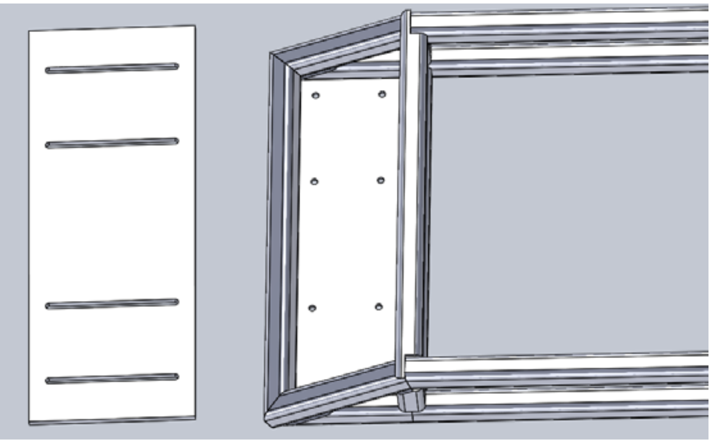


Figure 8: Bolt and slot plate design

The cross span also needed a way to mount the UR5 robotic arm so a ¼” steel plate was used and welded to the top of the cross span. This component can be seen in Figure 1 above. Additionally, in the extra space between the front and rear wheels, an addition to the frame was made with the purpose of storing additional components such as batteries or the UR5 control box.

After some consideration, there appeared to be several issues with this initial design. First, the frame was too tall. Because of this, the robotic arm would not have enough functionality if it were forced to stretch out too far. This significantly reduces the robotic arm’s range of motion and ability to accomplish certain tasks. To address this issue, either the frame has to be shorter, or there has to be some type of way to lower the robotic arm, or simply a place to mount it that is lower than the top of the frame, such as a spacer of some sort. Additionally, although the 2”x2”x1/4” steel square tubing would provide adequate support for the vehicle and its components, it may make the vehicle too heavy, requiring more powerful drive motors. Also, the ¼ inch steel plate on top of the cross span is seen as unnecessarily heavy, as all it needs to do is provide a surface to bolt the robotic arm to. The vehicle frame also needs a place to store the UR5 robotic arm control box, as the current design does not provide a place for the control box that the user could easily access it.

New Design

The new design featured several improvements from the old design. The new design features a spacer that can be added to the bottom of the cross span, which allows the robotic arm to be mounted lower. This will give the robotic arm more functionality when working with strawberries because it will be closer to the ground. If the spacer is removed, the vehicle could then be useful in crops that grow taller than strawberries, as the robotic arm would be mounted higher. An additional improvement that was made was that the structural members were changed to 1”x1”x1/4” tubing, as the 2”x2”x1/4” was seen as unnecessarily large. Figure 9 shows the new design for each wheelbase. It is now taller and the inside support tubing has been moved more toward the outside, resulting in more open space in the center to allow easier access to the UR5 robotic arm control box as well as additional electronics.

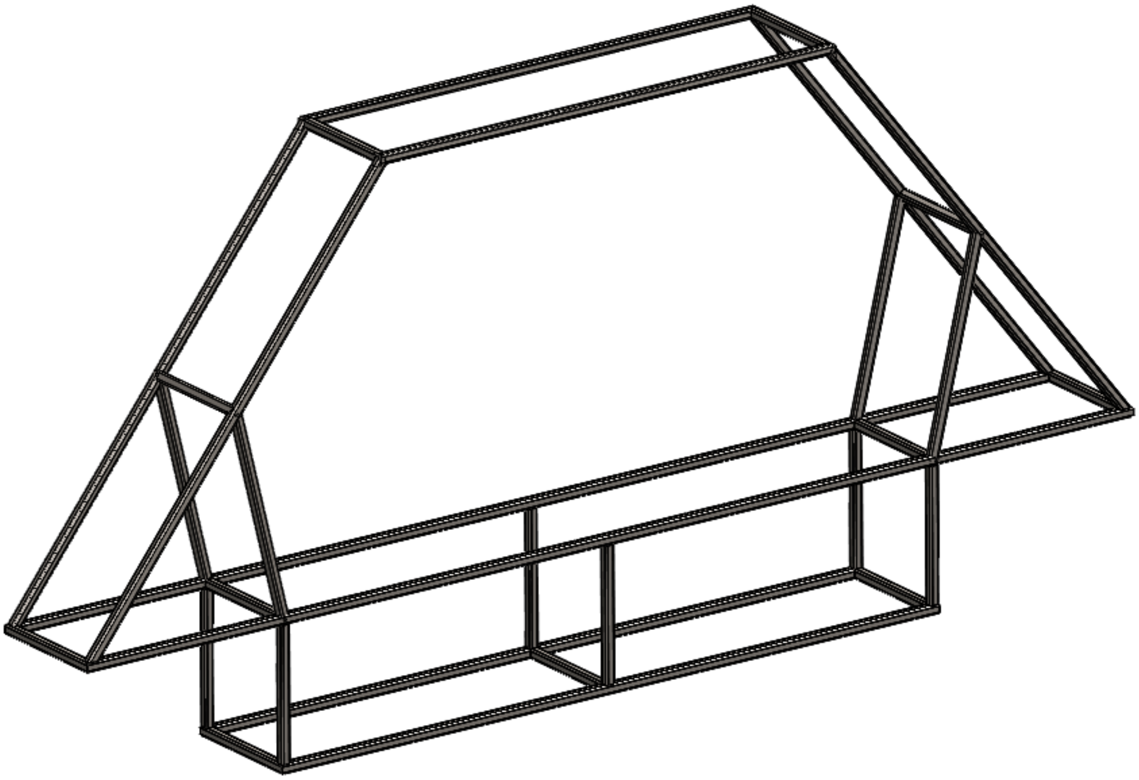


Figure 9: New Wheel Base Design

Figure 10 below shows the new cross span assembly, featuring the spacer and UR5 robotic arm. The new cross span assembly provides additional structural supports with the goal of minimizing the movement of the base that the robotic arm is attached to. Connected to the spacer is a ¼ inch steel plate that the robotic arm is mounted to.

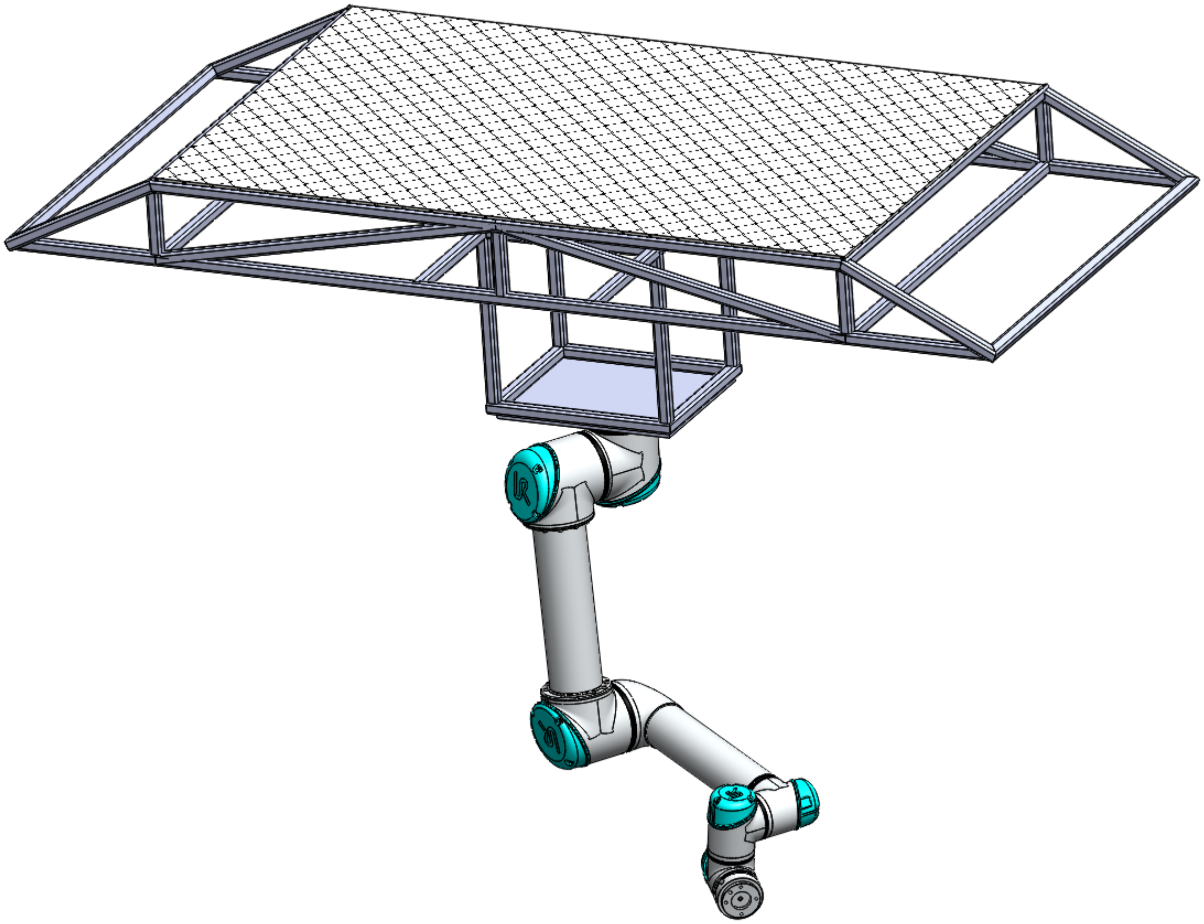


Figure 10: Cross Span Assembly with Spacer

Further along in the project, it was proposed that there be a space on top of the frame where UAV’s or drones would be able to land. This would allow these drones that are travelling throughout a field to track where the robot is with GPS, and land on the robot. The drone can do this when it is low on battery and cannot travel all the way back to the operator. Instead of the ¼” plate on top of the robot, it was decided that expanded metal would be used to create this platform. Expanded metal would be much lighter than the ¼” steel plate, and it would provide enough strength to simply support a drone. The expanded metal chosen was a 0.04” thick that weighs 82 pounds per 100 ft^2, so the 10 ft^2 piece needed to cover the top of the cross span would weigh only 8.2 pounds

Another option for the top platform of the vehicle would be to implement a solar panel to provide extra power to the robot. This option will be left open for the user to decide whether or not to include a solar panel. The top platform will be left relatively simple and open in order to accommodate a solar panel in the future.

This new design also allows for more space to store the UR5 robotic arm control box, which also makes it more accessible to the user. Because the frame was also lengthened, there is now more space available to store batteries in between the front and rear wheels. Figure 11 below shows this battery storage area, and where the angle iron will be welded onto the frame to hold the batteries. The angle iron used was 2”x1 ½”x1/4”

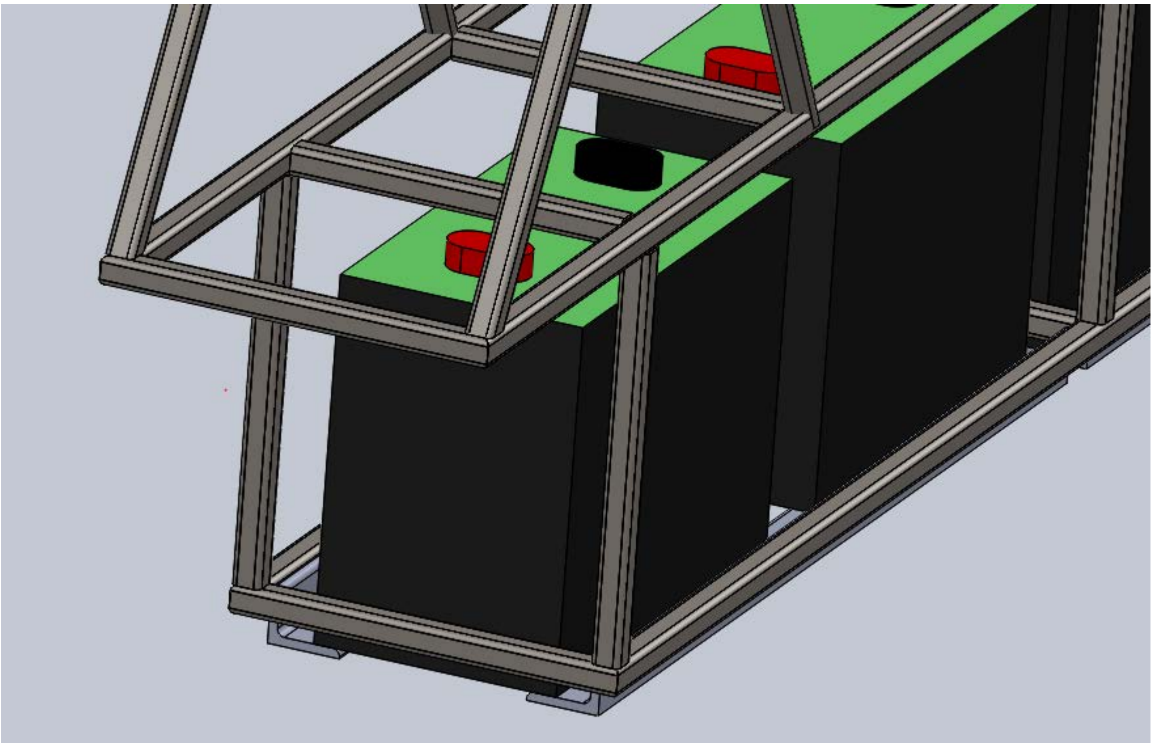


Figure 11: Battery storage area

<u>Power Requirements</u>

In order to choose the correct drive motors and the correct number of batteries, a power requirements calculation table was created. An AutoCAD drawing in Figure 12 illustrates all of the inputs that are used in the calculation table. The table demonstrates the power requirements for the vehicle to be able to operate on different slopes and at different speeds, with all the other inputs staying constant. The calculations for each of the values are shown in APPENDIX B.

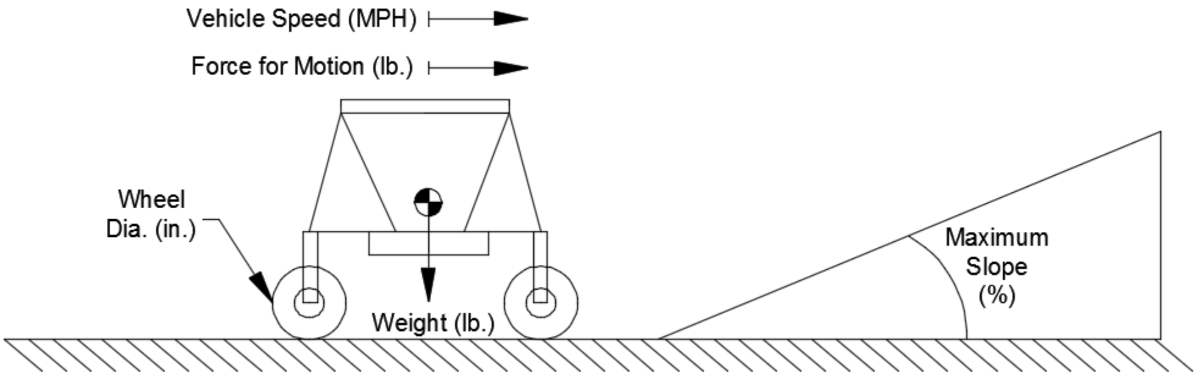


Figure 12: Power requirement variables

Table 3: Power Requirements

Input Values														
	Variable	*Units*	*Value*											
1	Vehicle Weight	lbs	1100	1100	1100	1100	1100	1100	1100	1100	1100	1100	1100	1100
2	Estimated Force for Motion	lbs	200	200	200	200	200	200	200	200	200	200	200	200
3	Max Vehicle Speed	mph	0.5	1	2	3	4	5	6	7	8	9	10	11
4	Max Slope	%	50	50	48	46	44	42	40	38	36	34	32	30
5	Tire Diameter	in	20	20	20	20	20	20	20	20	20	20	20	20
Derived Values														
	Description	*Units*	*Value*											
1	Req'd Flat Ground HP	HP	0.3	0.5	1.1	1.6	2.1	2.7	3.2	3.7	4.3	4.8	5.3	5.9
2	Req'd Incline HP	HP	0.9	1.8	3.6	5.3	6.9	8.3	9.7	11.0	12.2	13.3	14.3	15.1
3	Req'd Incline Power Per Motor	HP	0.2	0.5	0.9	1.3	1.7	2.1	2.4	2.8	3.1	3.3	3.6	3.8
4	Req'd Flat Ground Power	Watts	199	398	796	1194	1591	1989	2387	2785	3183	3581	3979	4377
5	Req'd Incline Power	Watts	688	1376	2690	3937	5117	6226	7263	8226	9113	9920	10648	11293
6	Req'd Propulsion Force for Vehicle	Lb	692	692	676	660	643	626	609	591	573	554	535	516
7	Torque at Each Motor	lb ft	144	144	141	137	134	130	127	123	119	115	112	108
8	Wheel RPM	RPM	8	17	34	50	67	84	101	118	134	151	168	185
9	Constant Torque at Each Motor	Nm	56	56	56	56	56	56	56	56	56	56	56	56
10	Peak Torque at Each Motor	Nm	195	195	191	186	182	177	172	167	162	157	151	146
11	Req'd Incline Power Per Motor	Watts	172	344	672	984	1279	1557	1816	2057	2278	2480	2662	2823
12	Req'd Flat Ground Power Per Motor	Watts	50	99	199	298	398	497	597	696	796	895	995	1094

For the drive system of the vehicle, a hub motor was chosen for this application because it would be much easier to implement onto the frame of the vehicle due to the fact that a chain or belt drive would not be needed. This is because the motor and wheel would all be one assembly that would be connected onto the frame. Figure 13 shows a SolidWorks model of a hub motor and wheel assembly that will be implemented onto the frame.

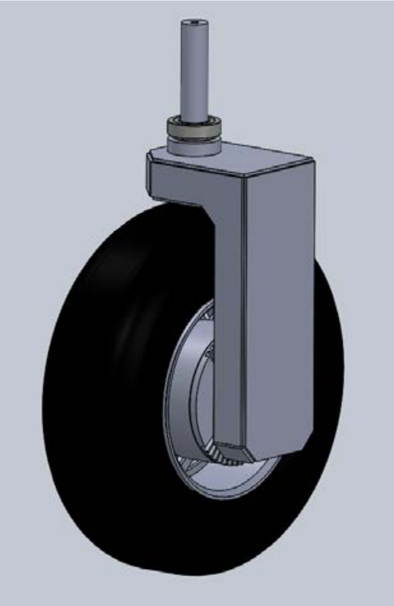


Figure 13: Hub motor assembly

Table 4 below shows the power requirements of the additional components that will be featured on the vehicle.

Table 4: Power consumption

Item	*Power Required (Watts)*	*Quantity*	*Total (Watts)*
UR5 Robotic Arm	200	1	200
UR5 Control Box	48	1	48
Industrial Computer	60	1	60
Drive Motors	1500	4	6000
Steering Motors	40	4	160
		SUM =	6468

In order to power all of the components of the vehicle, it was decided to use deep cycle batteries, such as those used in marine and RV vehicles. These batteries were chosen because deep cycle batteries can be deeply discharged, using much more of their capacity than typical starter batteries in cars. This will allow for a much longer operation time for the vehicle, while powering all of its components. The deep cycle battery chosen was the Interstate 27M Deep Cycle Marine Battery, which can run at 12 volts for 67 Amp-Hours.

Once the frame was designed and the components for the vehicle were selected, a cost analysis was done for the final assembly. This cost analysis takes into account the steel, batteries, robotic arm, motors, and is shown in Table 5. Comments on the cost analysis of the vehicle as a whole can be found in the discussion section.

Item #	**Description**	**Price ea.**	**Qty**	**Unit**	**Price**
1	Universal Robotics UR5 Arm and Control System (used demo version)	$ 20,000	1	ea.	$ 20,000
2	Onboard Computer	$ 1,000	1	ea.	$ 1,000
3	Cyclone Geared Motor 1800-3000watt 24-72V	$ 216	4	ea.	$ 864
4	Interstate SRM-27 Deep Cycle Battery	$ 79	8	ea.	$ 632
5	AIMS Power 2000 Watt 48 Volt Pure Sine Inverter	$ 631	1	ea.	$ 631
6	Brushed Worm Drive Steering Motor	$ 100	4	ea.	$ 400
7	Cyclone Brushless Motor Controller	$ 52	4	ea.	$ 208
8	3/16" Plate	$ 120	1	4'x8' plate	$ 120
9	Steering Motor Controllers	$ 20	4	ea.	$ 80
10	1.5" Round Bar	$ 70	1	20' section	$ 70
11	1"x1"x1/16" Square Tubing	$ 12	11	20' section	$ 132
12	16" Off Road Tire 4.80/4.00-8	$ 28	4	ea.	$ 112
13	Dexstar 8" Standard Painted Trailer Rim (3.75" Width)	$ 7	4	ea.	$ 28
					$ 23,855

After all of the components were chosen for the vehicle, a wiring diagram was created to show how all of the components are powered. Figure 14 shows the wiring diagram, which was drawn in AutoCAD.

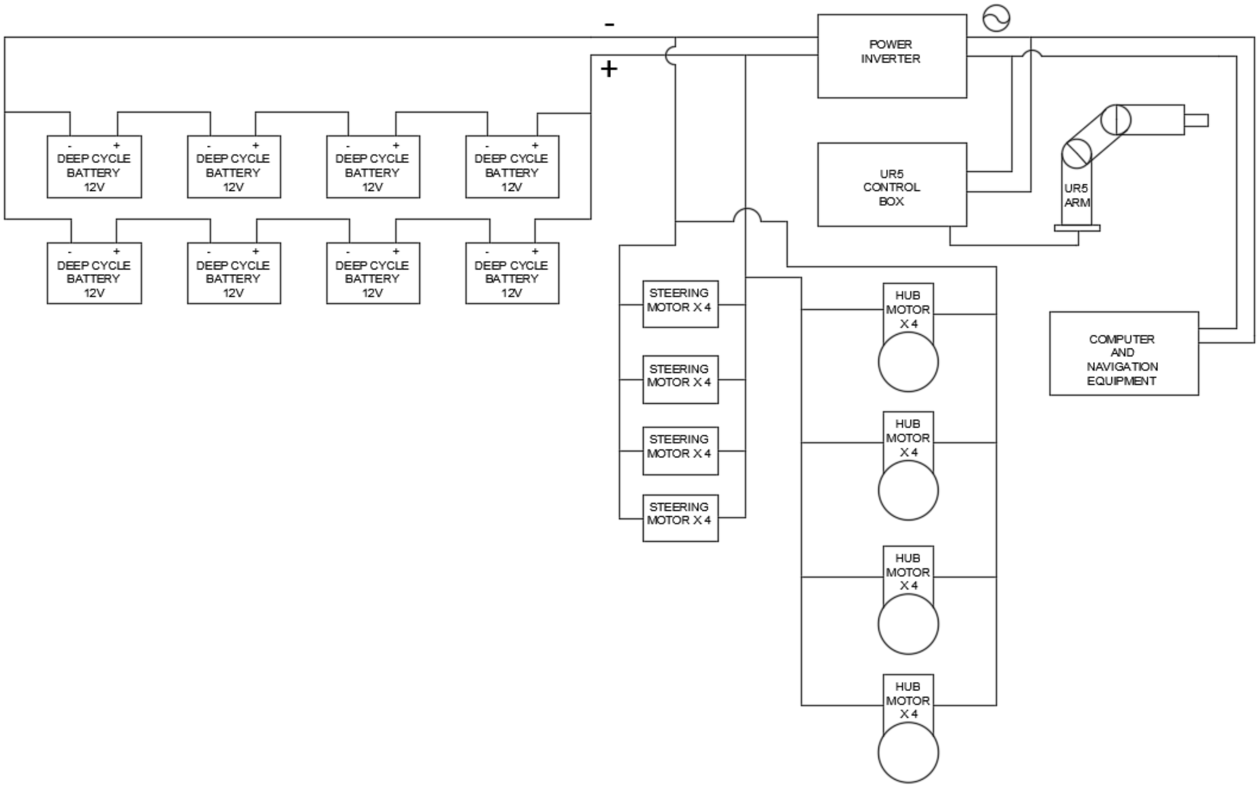


Figure 14: Wiring Diagram

The second design is superior to the initial design in several ways. First, it decreases the overall weight of the vehicle frame by decreasing the square tubing from 2”x2”x1/4” to 1”x1”x1/4”. This weight reduction puts less load on the drive and steering motors and less load on the frame itself. The FEA testing on the new frame design is shown in the Results section, which justifies the switch to smaller steel tubing. This also results in a cost reduction, as the smaller steel square tubing weighs much less than before. Further weight reduction was also seen in the slot and bolt plates, as extra through holes were cut into the material, as a large steel plate was not needed for its current function. Additionally, the large steel plate that was placed on the top of the cross span in the initial design was much too heavy, so it was replaced with expanded metal. Expanded metal is sufficient for this application because the only loads that the top of the frame would be subjected to would be a drone landing on it on occasion. The weight reduction of the slot and bolt plates and the cross span plate results in a cost reduction as well, as much less steel is being used.

RESULTS

A final assembly including the two wheel bases, batteries, cross span, slot and bolt plates, spacer, UR5 robotic arm, and UR5 control box is shown in Figure 15.

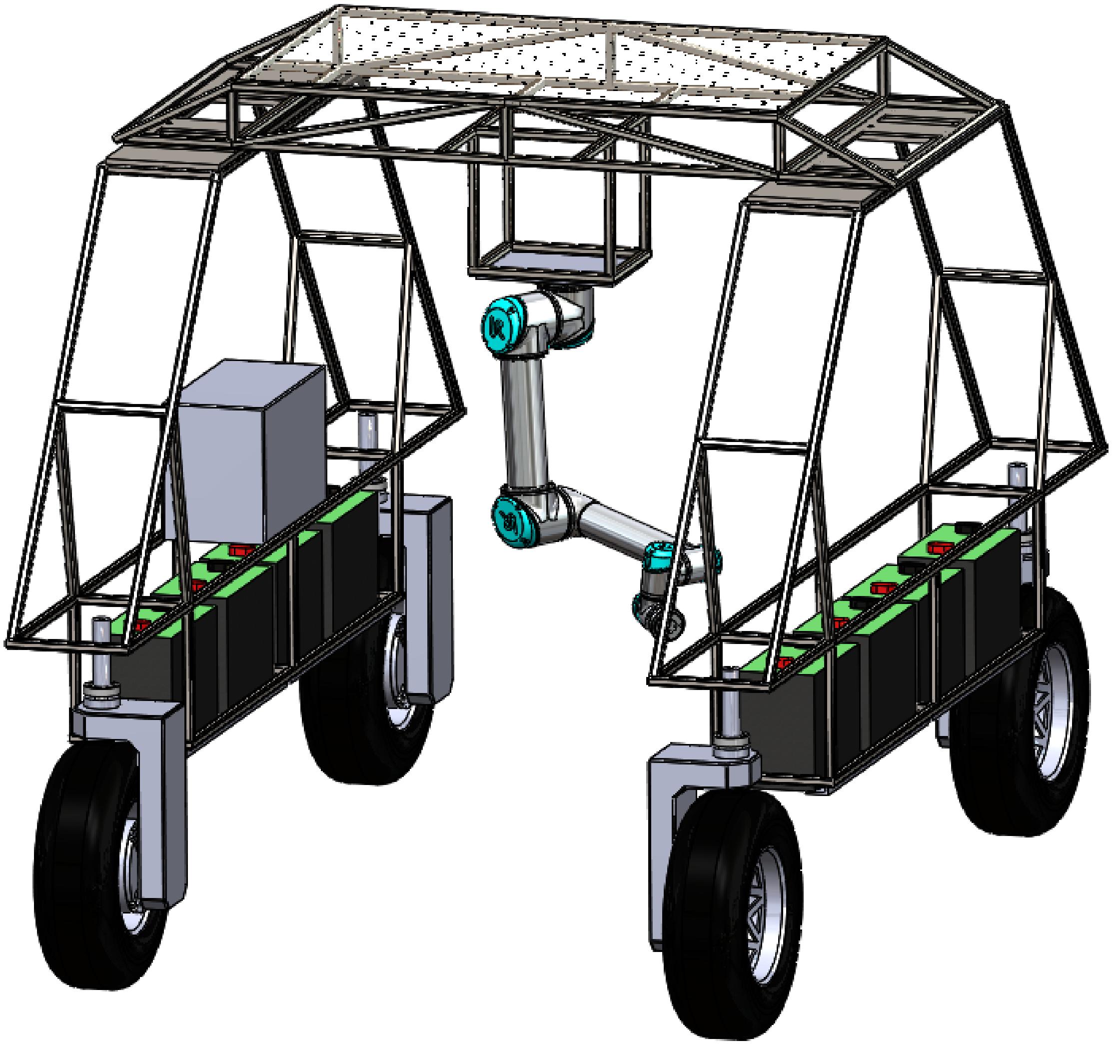


Figure 15: Final Assembly

In order to ensure the adequacy of the current design, Finite Element Analysis testing was done in SolidWorks. Finite Element Analysis is simulation within SolidWorks that can be used to find displacement of material and stresses within a material when it is exposed to internal or external loads. FEA is used to simulate real-life situations that the model may be exposed to, in order to see how the model will react. FEA testing was done on the frame to ensure that the vehicle frame would not experience too high of stresses under the loads the vehicle would experience during operation. The testing was also done in order to justify the switch from 2”x2”x1/4” to

1”x1”x1/4” steel square tubing. For the cross span and wheel base tests, the material assigned in SolidWorks was carbon steel in order to receive accurate results from the FEA analysis. For all of the tests, static studies were done, as it was assumed that this vehicle will not be operating at high enough speeds or in rough enough terrain to have to worry about any cyclic loading that may occur. The static loading tests include all of the components on the vehicle that would cause a load on the frame, as well as all the areas on the frame that would act as points for reaction forces.

The first test that was done on the frame was a distributed load on the cross span, replicating the load from the added spacer and the UR5 robotic arm. The UR5 robotic arm weighs 40 pounds and is capable of a 10 pound payload, and the steel tubing spacer was estimated at 15 pounds, so the cross span testing was done with a load of 65 pounds. The reaction forces used for this simulation were the 4 joints on each side of the cross span, as this is where the cross span will rest on the bolt plate which will be attached to the wheel base. These reaction forces can be seen in Figure 16 as the green reaction force arrows at each joint. Figure 16 shows the deflected model and the stress diagram that shows the areas of greatest stress. The middle of the cross span where the spacer is to be attached experienced the greatest amount of stress, at 11.78 ksi. This is well below the yield strength of 89.98 ksi, resulting in a factor of safety of 7.64.

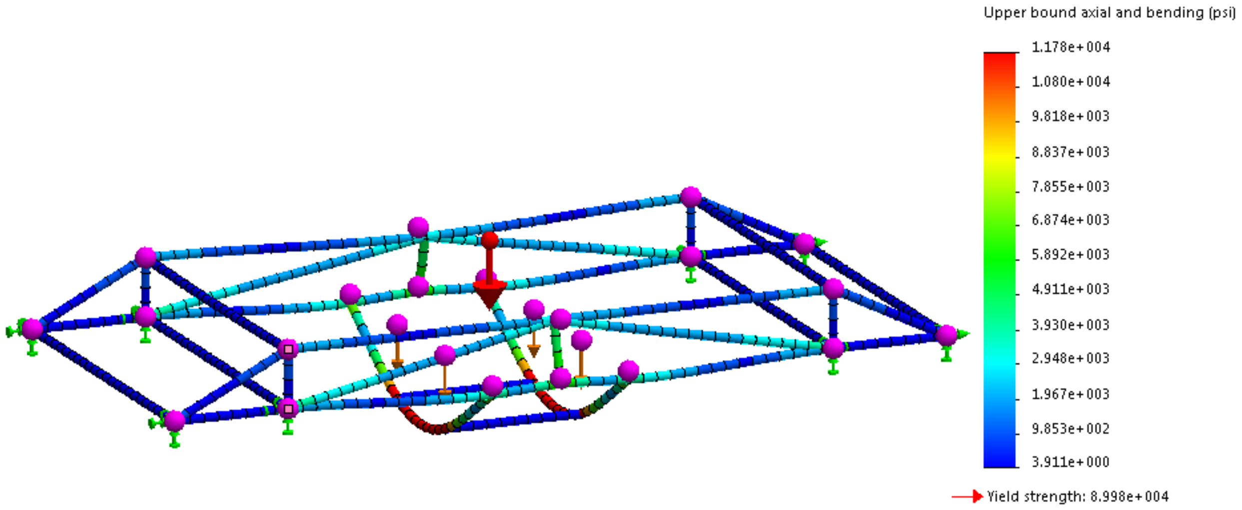


Figure 16: Cross Span FEA

The maximum deflection for this test was also in the middle of the cross span, 0.094 inches, or 2.39 millimeters, a deflection small enough to neglect.

The next test was done is on the wheel base of the vehicle, in order to simulate the load of the cross span, including the spacer and the robotic arm, the load from the control box, and the load from the batteries. The steel cross span weighs 44 pounds, and the expanded metal weighs 8.2 pounds, resulting in a total load of 118 pounds when the spacer and robotic arm were added. Because this load rests on both wheel bases, a single 59 pound load was used for the load on one wheel base. Additionally, one of the wheel bases will accommodate the UR5 control box, which weighs 60 pounds. The eight batteries will be stored in the additional area between the front and rear wheels on both wheel bases. These batteries are 60 pounds each, so four of these batteries result in a 240 pound load on the bottom are of the wheel base previously mentioned. These four batteries will have very little space in between them, so the batteries were treated as a distributed load along the bottom of the wheel base. For this testing, the reaction forces that were used to counteract the load were the four joints on each end of the wheel base, as can be seen in Figure 17. These were chosen as the reaction forces on the wheel base because this is where the wheel and hub motor assembly will be connected to the frame, which will have contact with the surface it is driving on.

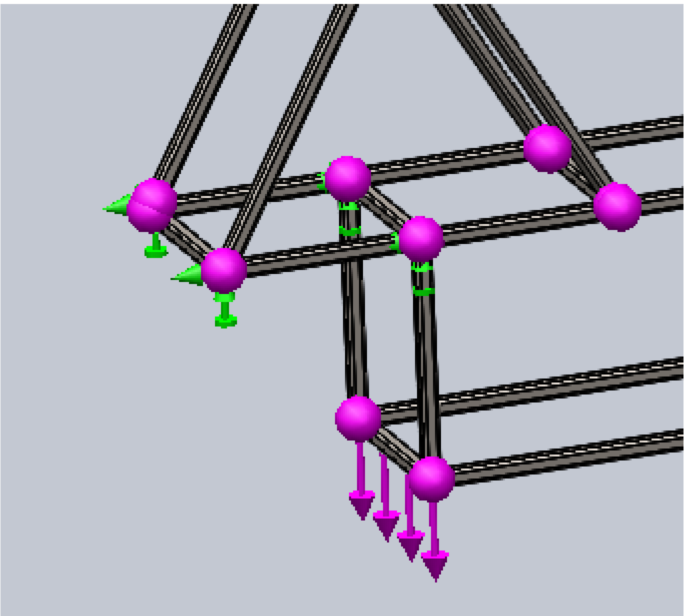


Figure 17: Reaction forces on wheel base

Figure 18 shows the results of the FEA testing done on the wheel base, with the distributed load from the cross span and control box shown on the top of the frame, as well as the distributed load from the batteries, shown on the bottom on the frame.

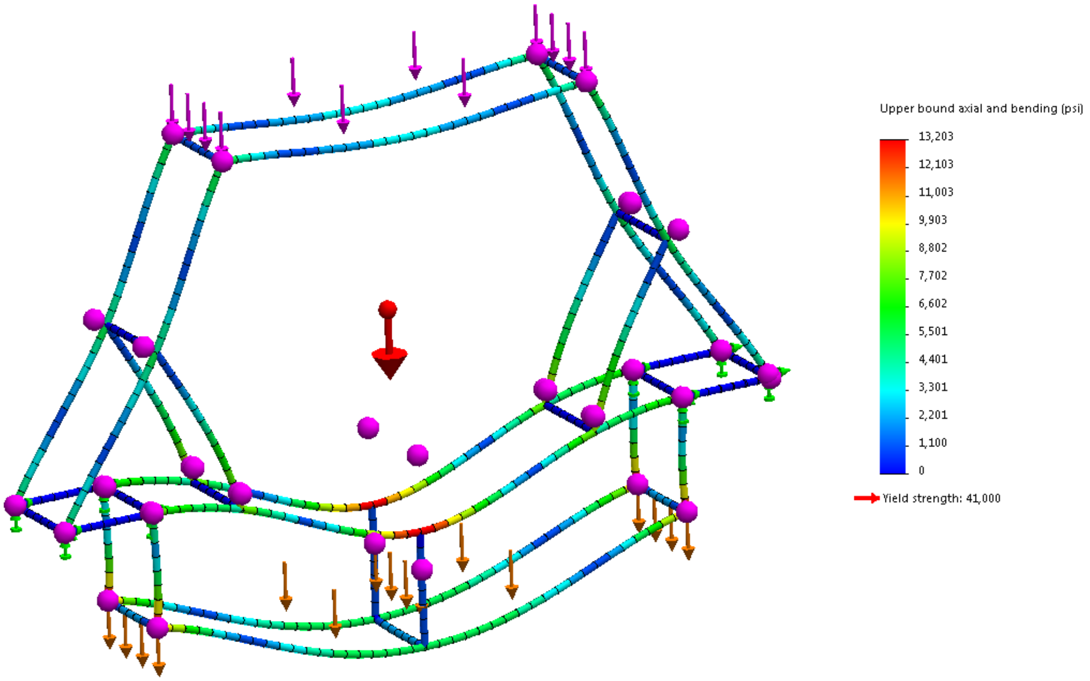


Figure 18: Wheel Base FEA

The maximum stress seen in this this simulation was in the middle of the bottom of the frame where is little support (seen in red). Although this is where the maximum stress occurs, it is still less than the yield strength of 41 ksi, as it is only 13.2 ksi. This results in a factor of safety of 3.1. Additionally, the maximum displacement that was seen in the model is in the same area where the maximum stress occurred. The displacement profile can be seen in Figure 19.

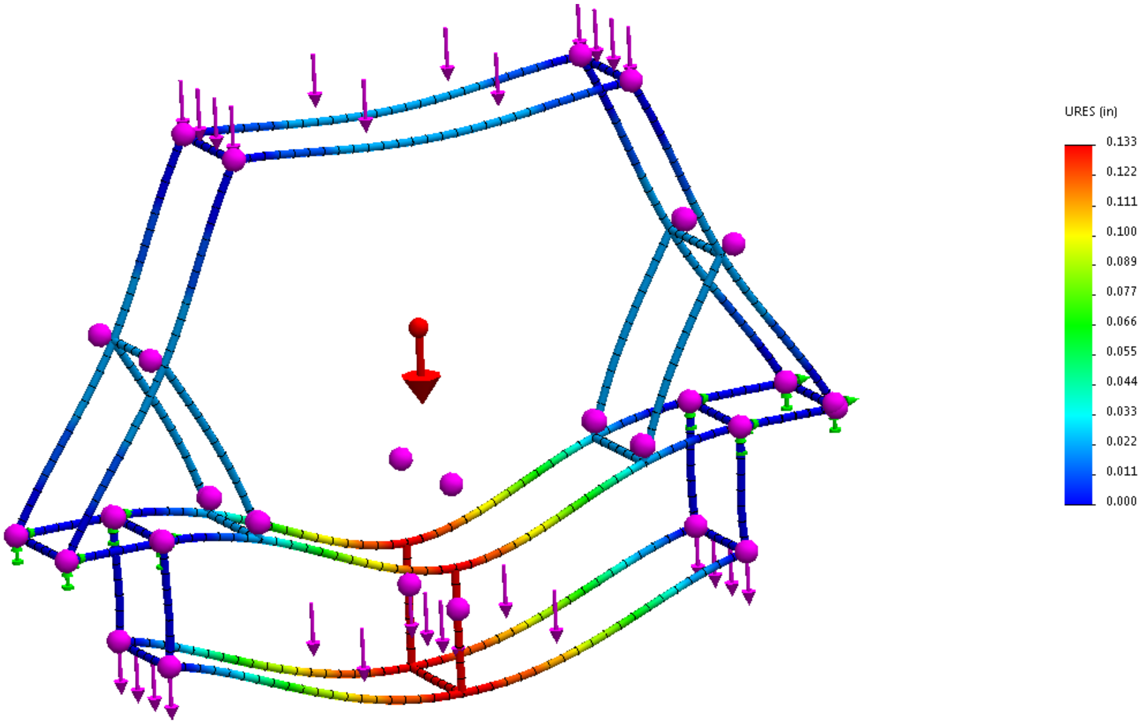


Figure 19: Wheel base displacement

The maximum displacement that was seen in the model was 0.133 inches, or 3.38 millimeters, which is slightly larger than the maximum displacement that was seen in the cross span FEA study, but it is still permissible, as the maximum stress that is seen in the frame does not exceed the maximum yield strength of the material. It is important to note that the center point of the battery bay between the front and rear wheel wells was the area that experienced the most stress and was displaced the most from its original position.

DISCUSSION

The FEA testing has clearly shown which areas of the vehicle frame will experience the most stress while under the given loadings. The battery bay between the front and rear drive wheels experienced the largest amount of stress and saw the largest amount of displacement. This loading situation is unavoidable because it is simply due to the weight of the batteries, as each one weighs 60 pounds each.

The current vehicle frame as a whole was designed in order to accommodate the UR5 robotic arm, as the UR5 was purchased by the BioResource and Agricultural Engineering Department earlier in 2016 for educational purposes. The cost of the vehicle components including the steel, motors, batteries, wheels, and other electronic components are relatively inexpensive when compared to the UR5 robotic arm itself. Therefore, if a user is willing to invest in the robotic arm, the cost for all of the other components is not a significant factor in the overall cost. Because of this, the user may decide to invest in

RECOMMENDATIONS

Because this project will be passed on to other students in the future, it is important to give a few necessary recommendations to these students based on what was observed and discovered while working on this project. The first recommendation to these future students is in regard to battery placement. In the FEA testing that was done on the wheel base model, the area that experienced the most displacement and the area that experienced the most stress was the middle of the bay where the batteries are placed. This testing was done using the total weight of the batteries applied as a distributed load along that section, implying that the batteries were all equally spaced apart. To slightly reduce the displacement and stress on the middle section, it is advised that the batteries be spread out from the middle, maximizing the distance in between the two batteries in the middle.

Another recommendation that could be given to these future students is in regard to the current slot plate and bolt plate design, which allows the vehicle to be set to different widths depending on the dimensions of crop's rows. Other designs may need to be considered, as this design could potentially put large amounts of stress on the bolts that are used in the bolt plates. A type of telescoping tubing design could be considered that allows the vehicle to change widths, although this will likely require different sizes of steel tubing, as one tube would have to slide into a larger one. However, if this method is used it may require a redesign of the cross span section as well.

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APPENDIX A

HOW PROJECT MEETS REQUIREMENTS FOR THE BRAE MAJOR

Major Design Experience

Establishment of objectives and criteria: This project is to be designed to meet the needs and expectations that other robots do, according to ASABE standards.

Synthesis and analysis: This project will incorporate power requirement calculations, bending stress calculations, and deflection analysis.

Construction, testing, and evaluation: This project will be tested and evaluated using SolidWorks FEA analysis.

Incorporation of applicable engineering standards: This project will utilize AISC standards for allowable bending stresses.

Capstone Design Experience

Incorporates knowledge/skills from these key courses: 133 Engineering Graphics, 152 SolidWorks, 328 Measurements & Computer Interfacing, 421/422 Equipment Engineering, 470 Fundamentals of Robotics, Engineering Statics/Dynamics, Strength of Materials

Design Parameters and Constraints

Physical: The size of the robotics reasonable, as the weight doesn't require unreasonable power from the motors to operate.

Economic: The majority of the cost is the robotic arm, so if the user is willing to invest the money, the rest of the assembly is reasonable.

Environmental: If the robot is spot treating the field using chemicals, much less chemicals will be used.

Sustainability: The vehicle operates solely on electrical power.

Manufacturability: The majority of the assembly is made of square tubing, making manufacturing more feasible.

Health and Safety: The robot should be operated in a way that does not put other humans in danger, as it operates autonomously.

Ethical: Because it is an autonomous robot, it should operate in a way that keeps the humans around it free from harm.

Social: The use of this robot will likely lead to the displacement of labor on a farm.

Political: There are no emissions to worry about.

Aesthetic: Because of its weight requirements, not much of the design was based around aesthetic. However, the robot was designed in a way that makes it look approachable to users, without being too complicated.

Other-Productivity: If the robot can run autonomously, it could run 24/7, working much more hours than a human.

APPENDIX B
DESIGN CALCULATIONS

I. Design calculations for power requirements

$$\boldsymbol{Flat\ Ground\ Power\ (HP)} = (Force\ Required\ (lbs.)) * \frac{\left(Max\ speed\ \left(\frac{miles}{hour}\right)\right) * \left(\frac{5280\left(\frac{ft}{mile}\right)}{3600\left(\frac{s}{hour}\right)}\right)}{550\ \frac{ft-lbs}{s-HP}}$$

$$\boldsymbol{Power\ Req'd, Slope\ \theta} = \left(\left(weight(lbs.)\right) * \sin(\theta) + Force\ Req'd\ (lbs.)\right) * \frac{\left(Max\ speed\ \left(\frac{miles}{hour}\right)\right) * \left(\frac{5280\left(\frac{ft}{mile}\right)}{3600\left(\frac{s}{hour}\right)}\right)}{550\ \frac{ft-lbs}{s-HP}}$$

$$\boldsymbol{Slope\ (Degrees)} = Tan^{-1}\left(\frac{\%\ Slope}{100}\right)$$

$$\boldsymbol{Power\ per\ Motor} = \frac{Total\ Power\ Required}{\#\ of\ Motors}$$

$$\boldsymbol{Power\ Required\ (Watts)} = Power\ (HP) * \frac{746\ Watts}{HP}$$

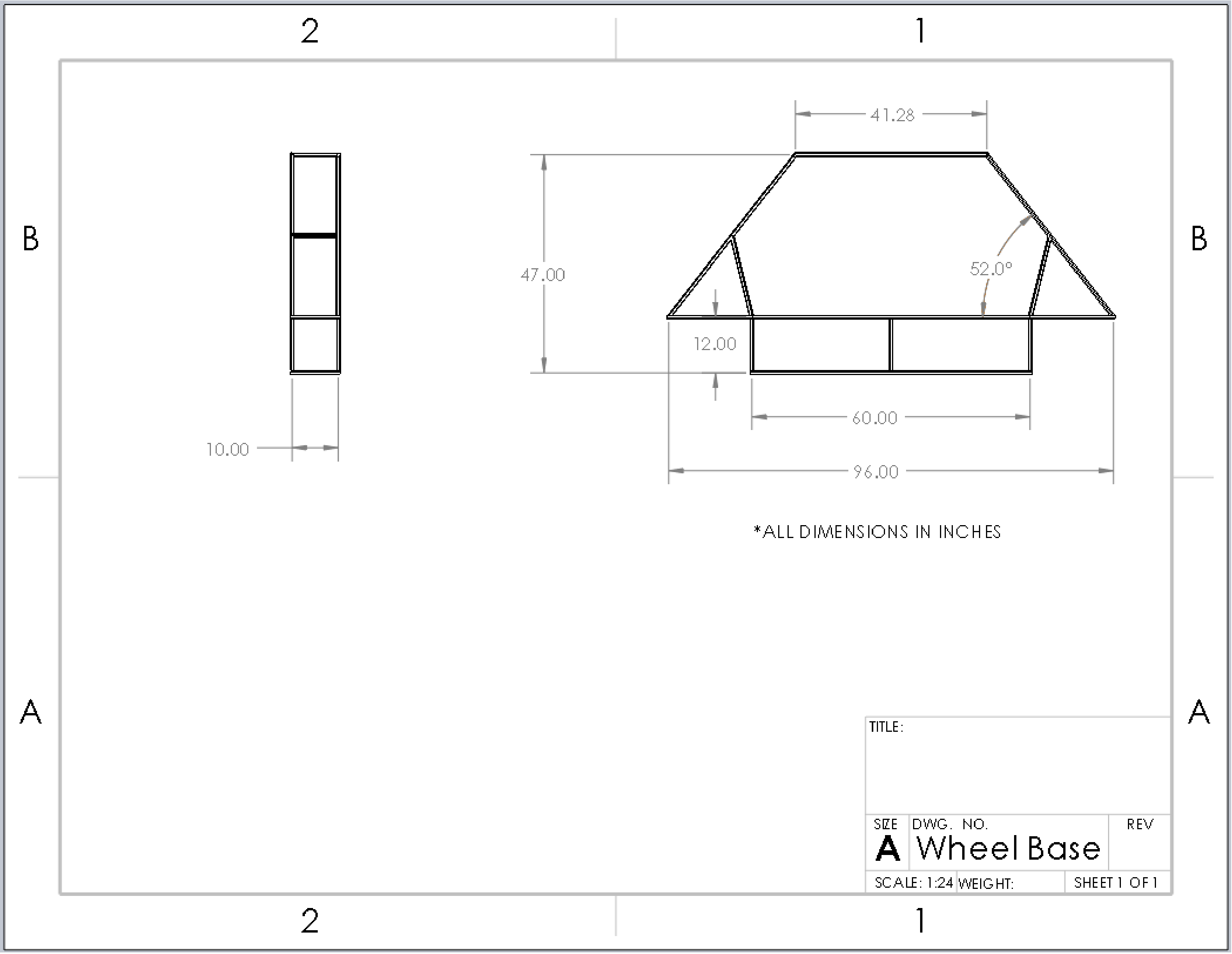
$$\boldsymbol{Propulsion\ Force\ for\ Vehicle\ (lbs.)} = \frac{Incline\ Power\ Required\ (HP)}{Speed\ \left(\frac{miles}{hour}\right) * 5280\left(\frac{ft}{mile}\right) * \frac{1}{3600\left(\frac{s}{hour}\right)}} * 550\frac{ft-lbs}{s-HP}$$

$$\boldsymbol{Motor\ Torque\ (ft-lbs.)} = \frac{Propulsion\ Force\ (lbs.)}{4\ Motors} * \frac{Tire\ Diameter\ (in.)}{2} * \frac{1\ ft}{12\ in.}$$

$$\boldsymbol{Wheel\ Speed}\ (\boldsymbol{RPM}) = \frac{Max\ Speed\ \left(\frac{miles}{hour}\right) * \frac{5280\,\frac{ft}{mile}}{60\,\frac{min}{hour}}}{\frac{Tire\ Diameter\ (in.)}{12\ \frac{in.}{ft}} * \pi}$$

APPENDIX C

PART DRAWINGS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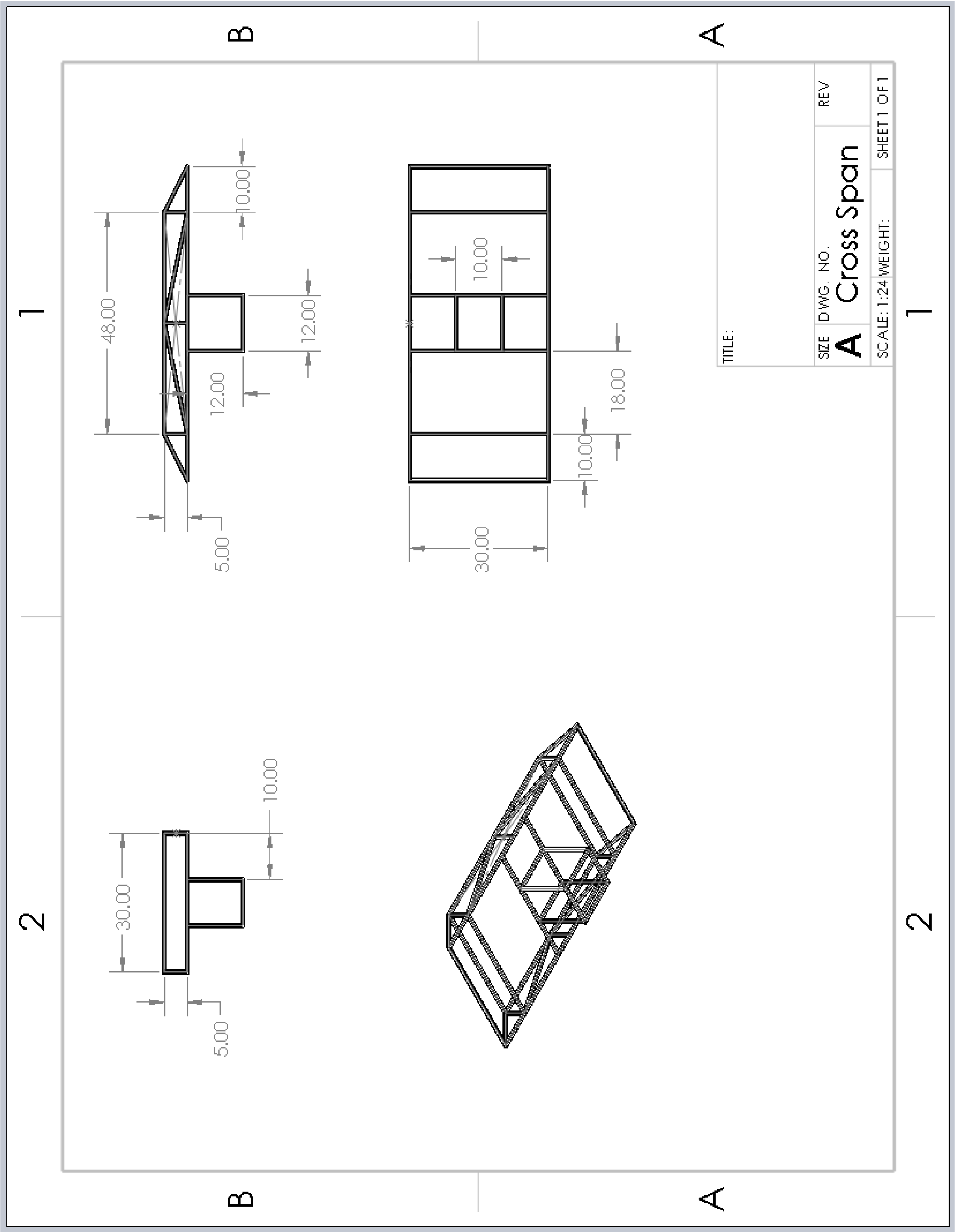
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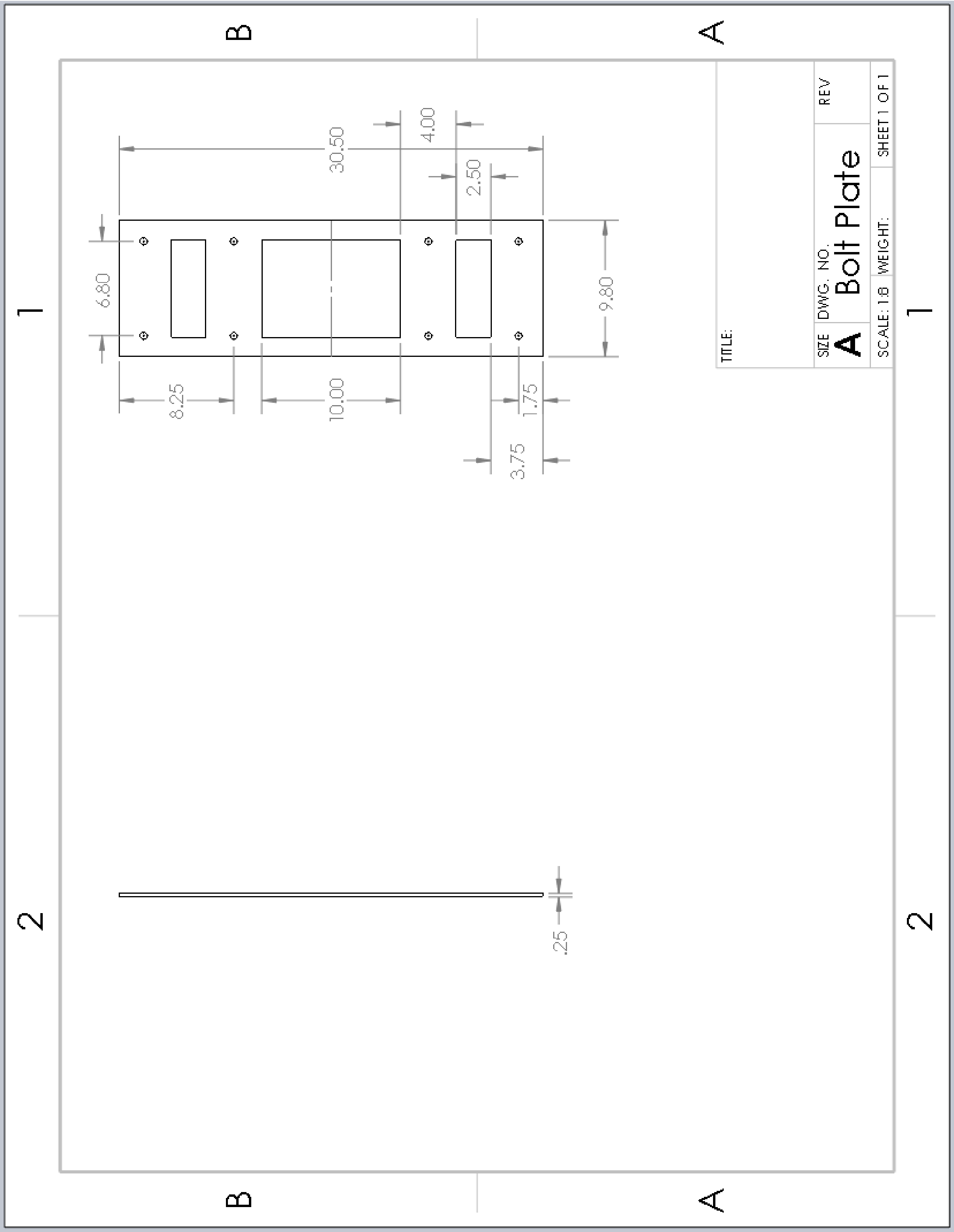
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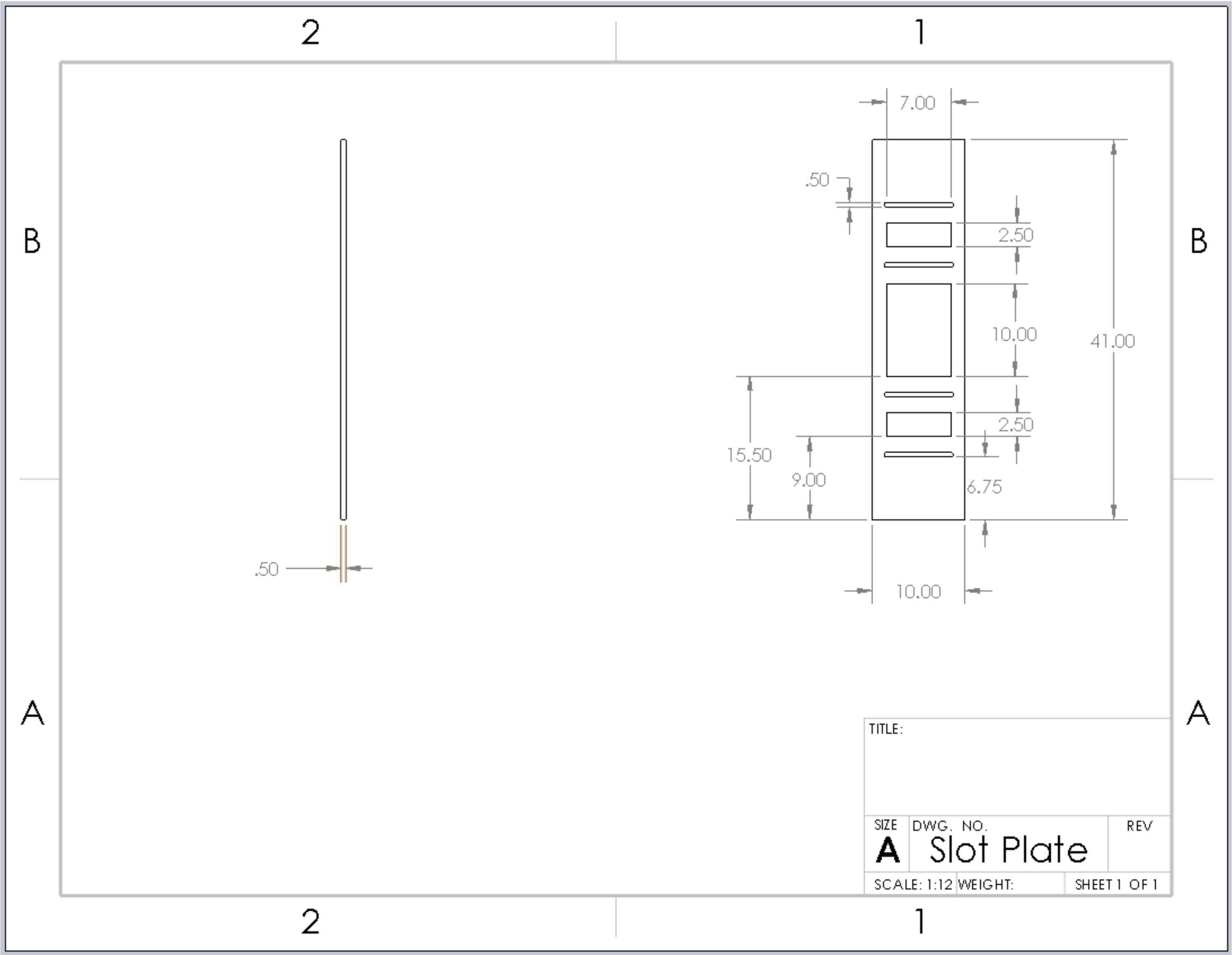
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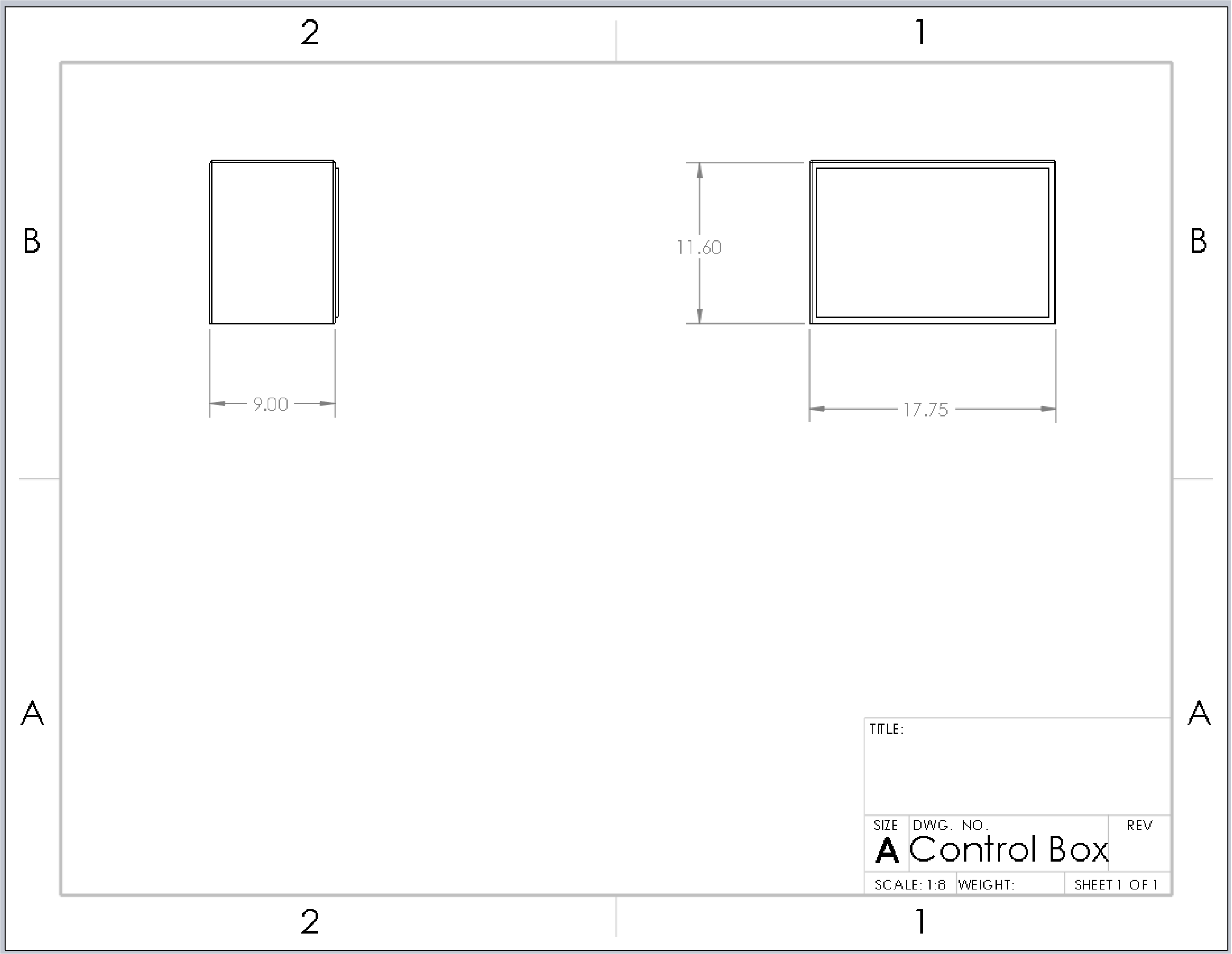
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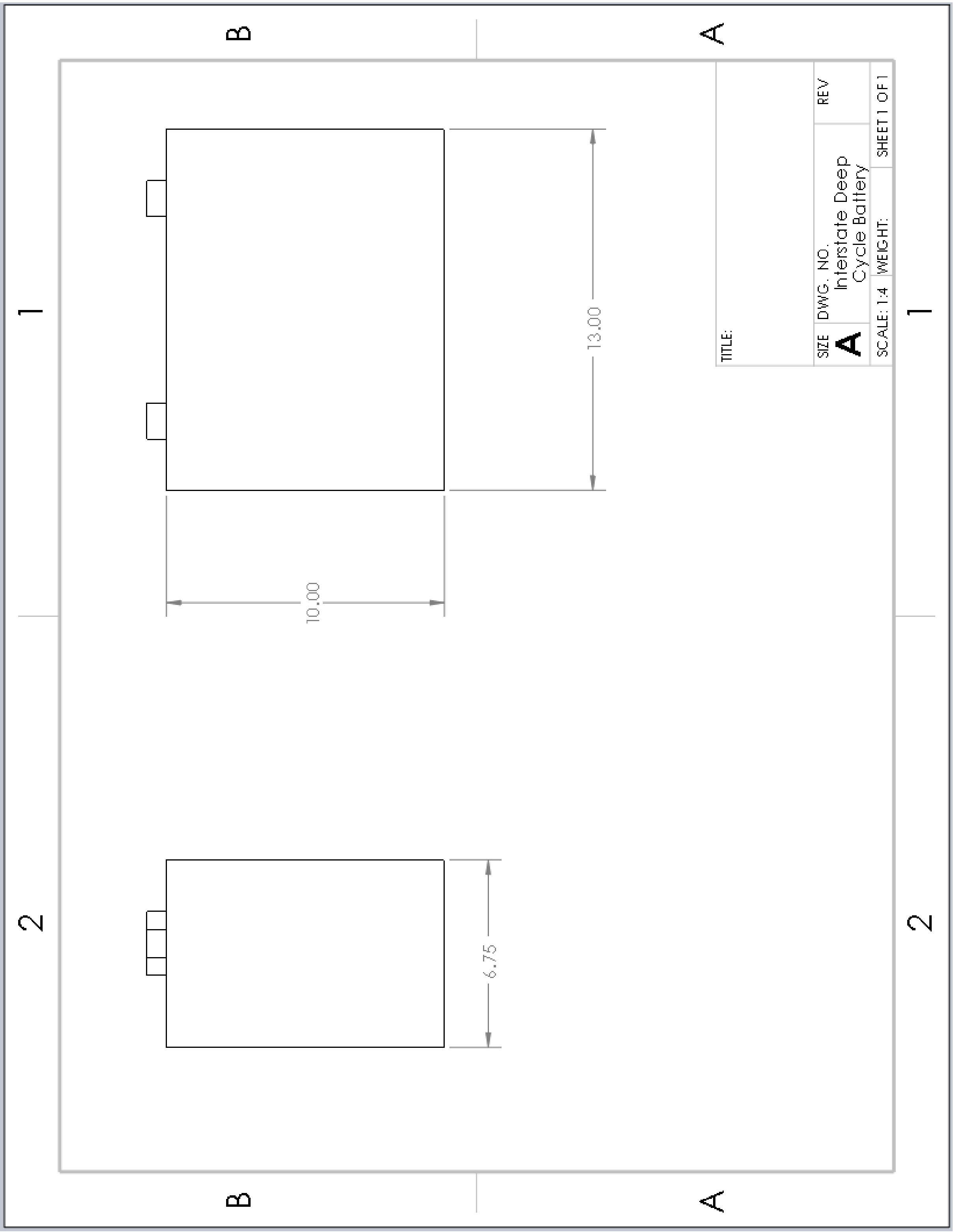

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