Systems Engineering Process for Robotic Mining Robot

Auburn University Robotic Mining Competition Team

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Faculty Sponsor Statement

I, undersigned, have completely read the following document created by the Auburn University Robotic Mining Competition Team. I give my permission for this paper to be presented to the NASA Robotic Mining Competition in the Systems Engineering Paper category.

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Abstract

The purpose of this project is to develop a mining robot that adheres to NASA competition regulations and to compete autonomously in the 2016 NASA Robotic Mining Competition. The NASA Robotic Mining Competition is an annual competition in which university students design and build a mining robot that can transverse a simulated Martian terrain. During each run the robot will be required to excavate basaltic regolith simulant (Black Point-1 or BP-1) and return the excavated BP-1 to a collection bin. Auburn University has fielded a team in 2015 and 2016 to compete in the Robotic Mining Challenge. The robots developed are known as “Shia,” after Shia LaBeouf due to his role digging holes in the movie “Holes.”

Engineering tools such as the Vee Chart, the 11 system engineering functions, 2015 competition results, trade studies, and the design of Shia 2.0 were used to design a new mining robot for competition in the 2016 NASA Robotic Mining Competition. The excavation subsystem from Shia 2.0 was improved upon slightly during this revision cycle with restructuring of the actuation system and conveyor and resizing of the bin to fit the current frame. The auger system proved to be very effective and efficient during the 2015 NASA competition, however the length of Shia 1.0 was too close to the limit. Therefore the auger was repositioned to a more vertical angle which also required a shorter auger. This modification increased the space between the auger and the conveyor so the bin was stretched and enlarged to interface the two subsystems while also increasing the storage capacity. The upgraded conveyor subsystem utilizes timing pulleys and a single sided timing belts to carry carbon fiber scoops that will excavate more efficiently and mitigate slipping. The mobility subsystem from Shia 2.0 was improved upon with standard plastic wheels with grousers and the implementation of a chain driven drivetrain. The frame subsystem was improved upon with the addition of an aluminum frame structure to provide stability and structure and avoid making the carbon fiber bin a structural component as in Shia 1.0.

In order to accomplish a fully autonomous design, a pancake load cell will be used to actively measure the amount of BP-1 that is currently in the collection bin. This with a combination of navigation and location systems will provide an efficient solution with simple functions for autonomous control. Each subsystem uses the same kind of CIM motors for programming simplicity.

A LIDAR will be used to detect objects in the obstacle area of the arena, while a rangefinder and camera system will determine the robot's location. This information will be passed through the Raspberry Pi™ and into the roboRIO®. The roboRIO® will then process that information into a path for the robot to move through, eliminating the threat of running into obstacles or walls. When the robot reaches the digging area, it will get information from the pancake load cell to determine how full the collection bin is. When the bin is full, the robot will use the already mapped obstacle field from its trip to the digging area to retrace its steps and return to the dumping area.

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I. Introduction

The Auburn University Robotic Mining Competition team followed the Vee Chart, shown in Figure 1 and applied the 11 systems engineering steps, shown in Figure 2, in the systems engineering design process for building the robot, known as Shia 3.0.

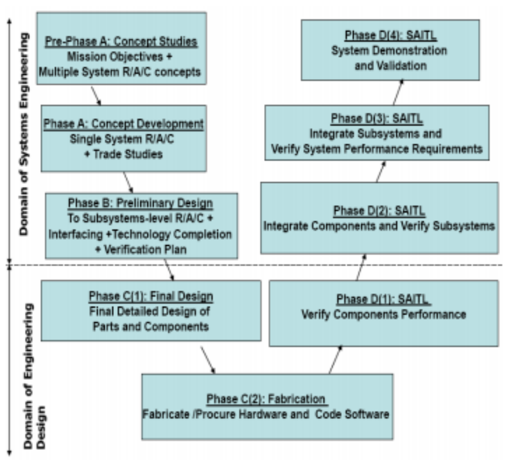


Figure 1: Systems Engineering Vee Chart[1]

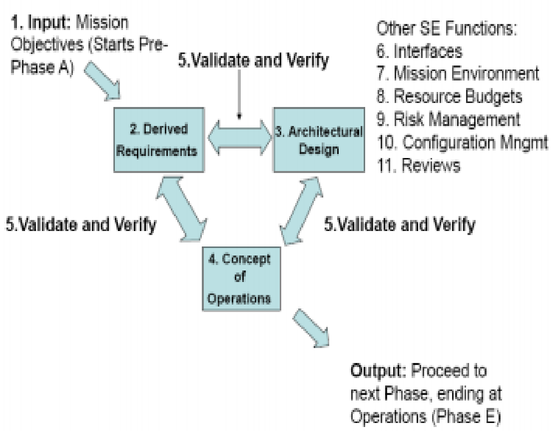


Figure 2: Systems Engineering Functions[1]

The team consists of a group of Mechanical Engineering students, participating in a two-semester senior design course, and volunteer students. Pre-Phase A and Phase B of the Vee chart take place in the first semester of the senior design course and Phases C-D occur in the second semester. Both senior design students and volunteer students follow this systems engineering design process schedule.

Auburn has fielded two teams in the Robotic Mining Challenge Competition in 2015 and 2016. The 2015 competition team designed and built Shia 1.0. The Senior Design Team of Summer 2015 developed a redesigned robot (Shia 2.0) utilizing the 2015 NASA guidelines and results from the 2015 competition in Pre-Phase A and Phase B. The current team repeated Pre-Phase A and Phase B in Fall 2015 to build on and correct the Shia 2.0 design and to develop Shia 3.0.

All subsystems have been completed and tested. The frame and mobility systems have been integrated. The bin and auger require more modifications and will be integrated once completed. Because it was determined during testing that the available LIDAR is incompatible with the roboRIO® a Raspberry Pi™ 3 model B is being tested to achieve object avoidance.

The goal of this paper is to provide an overview of the systems engineering process leading to the development and manufacturing of Shia 3.0 throughout the 2015-2016 academic year.

II. Systems Engineering

1. Mission Objective

The mission of the Auburn University Robotic Mining Competition Team is to build the team's infrastructure and successfully compete in the 2016 NASA Robotic Mining Competition.

2. Budget

Technical mass and power budgets can be found in Appendix A and B respectively. A bill of materials can be found in Appendix C.

3. Subsystem Hierarchy

The design of the robot was divided into the mechanical and electrical systems. The mechanical system was further divided into the frame, excavation, storage/ejection, and mobility subsystems. The electrical design was subdivided into the controls, autonomous sensors, and power subsystems. A full breakdown of the subsystem hierarchy can be found in Appendix E.

4. System Requirements

In the process of designing Shia 3.0, special attention was paid to following the rules for the NASA Robotic Mining Competition. It is the team's goal to construct Shia 3.0 to collect at least 100 kg of regolith, exceeding the competition requirement by 90 kg. The systems requirements were evaluated in five areas: functional, performance, interface, verification, and supplementary.

System Requirements		Ref.#
Functional	Excavate, carry and eject 50 kg of simulant into a collection bin .55 m high	F1
	Maneuver across an obstacle course with rocks and craters carrying a load	F2
	Operable from command station	F3
	Completely shut down utilizing a big red button	F4
Performance	Excavate, carry and eject 50 kg of lunar simulant into a collection bin within 10 minutes.	P1
	Autonomy	P2
Interface	Operable within NASA's wireless network	I1
Verification	Functional within arena	V1
Supplementary	Weigh less than 80 kg mass	S1
	Fit within 1.5 m length, 0.75 m width, 0.75 m height	S2
	Average bandwidth usage under 5Mb/s	S3
	Report all power consumption and bandwidth usage	S4
	Designed, fabricated and verified using less than $4000.00	S5
	Minimize dust	S6

Table 1: Systems Requirements

Table 1 shows a breakdown of systems requirements and a reference to be used throughout this paper.

5. Concepts of Operations

The system was initially divided into two fields: Mechanical and Electrical. The system Con-Ops were developed based on the system requirements in these areas. The mechanical Con-Ops were developed based on the functional requirements in Table 1 and can be seen in Figure 3.

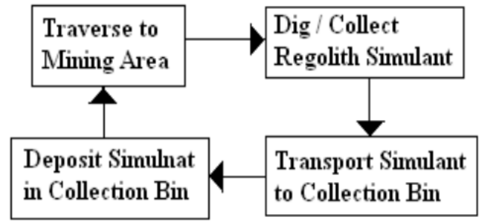


Figure 3: Mechanical Con-Ops

The Electrical Con-Ops were developed based primarily on functional and performance requirements in Table 1 and can be seen in Figure 4.

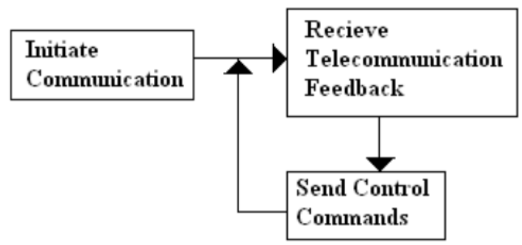


Figure 4: Electrical Con-Ops

6. Major Reviews and Schedule of Work

The robot design has been checked and adjusted in coordination with professors to verify that the system meets requirements. Due to the requirements of the Senior Design course the mechanical team was formally reviewed by professors of mechanical engineering. A preliminary design review was conducted on October 28, 2015 and a component design review was completed on December 4, 2015. The electrical team underwent frequent informal reviews with professors of electrical engineering. Both teams will be formally reviewed in an Operational Readiness Review on May 1, 2016. A Gantt chart containing the full schedule of work can be found in Appendix D.

7. Interfaces

Shia 3.0's design is divided into two main subsystems: mechanical and electrical. The mechanical subsystem was further divided into three more subsystems, Excavation, Frame, Storage/Ejection, and Mobility. All of the subsystems will interface seamlessly with one another. Each subsystem has been explained in greater detail in the following sections.

III. Excavation Subsystem

Operational Concept

The primary function of the excavation system is to extract BP-1 from the competition arena and deposit it into the collection bin. Two operational concepts were considered: vertical digging and horizontal digging. Vertical digging provides the advantage of maximizing gravel collection whereas horizontal digging provides the greatest volume of regolith collected. A pro/con matrix is shown in Table 2 with the anticipated pros and cons.

Dig Style	Pros	Cons
Dig Straight Down	Extract higher point gravel	
	Stationary during excavation	
		May dig wheels in to regolith
		Requires long actuation stroke
		Must design conveyor and auger to robustly handle gravel
Gather Across Surface	Fast	
	No actuation during digging	
		Less points per kg

Table 2: Analysis of Design

The second method was chosen due to the potential problems with vertical digging. This method requires deep penetration into the arena and puts the wheels at risk of being becoming embedded. Horizontal digging adds simplicity to the design. It is also more reliable for two reasons: it eliminates a lot of possible failure methods and is a proven design in past competitions.

Interfaces

A linear actuator will be used to dynamically lift and lower the entire conveyor system to provide optimum regolith digging. It is attached to the cross bar on the outside of the conveyor system. The actuator will be mounted on the base frame of the robot and positioned vertically. This will result in a fully vertical translational movement of the conveyor system, shown in Figure 5. The cross bar is mounted on a vertical linear bearing system to aid in movement. A strut will be implemented that can change the angle of the conveyor by bolting a small steel rod in different hole configurations. This will allow for testing to determine the optimal angle for the conveyor for the competition. The timing pulleys and the sprockets will be fastened to the shafts by keyways. This will be held in place by clips.

The conveyor and the timing belt are both made of neoprene, and U1 Urethane Adhesive has been chosen to attach them. Originally a mechanical attachment like a rivet was considered, but this was ruled out due to space constraints; no rivet was small enough to fit between belt teeth. Two belts will also be epoxied to the conveyor. The buckets will be attached to the conveyor with rivets.

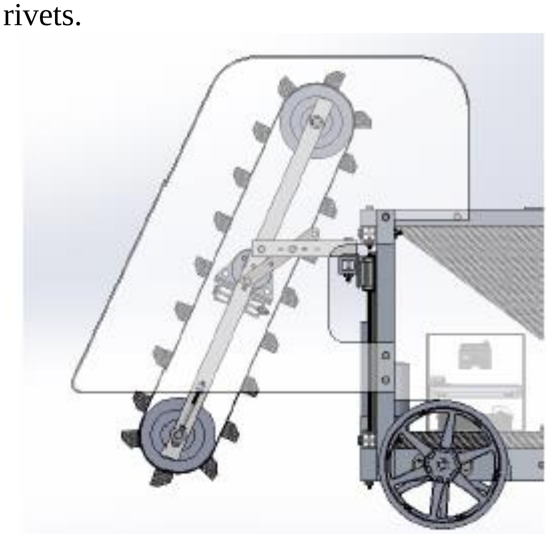


Figure 5: Excavation Subsystem

Requirements

The overall purpose of the competition is to mine regolith, so the excavation subsystem has many stipulations due to its importance. These are in accordance with system requirements F1, P1, S1, and S2, found in Table 1.

Trade-Off Assessment

A number of designs were considered for the excavation subsystem. The decision matrix for these designs is shown below in Table 3. The conveyor design was considered due to its simplicity and history with the Auburn Robotic Mining Competition Team. Scoops were considered based on research into past competition. The wheel design was first proposed by a former Auburn University mechanical engineering senior design team. It consisted of a wheel outfitted with scoops that flung dirt into a bin. Although this design was very innovative, the conveyor system ultimately was chosen based on its superiority in the digging rate, capacity, and stability.

	Dig Rate	Reliability	Capacity	Simplicity	Stability	**Total**
Conveyor	10	7	10	6	7	40
Scoop	5	8	8	9	6	36
Wheel	7	4	10	3	5	29

Table 3: Decision Matrix for Excavation Design

A conveyor/bucket design was thus chosen as our concept of operation for the excavation system for our robot because of its legacy on Auburn's robots, success in competition, and the decision matrix.

Risk Assessment

The risk analysis for the excavation system is summarized in Table 4. Some of these risks have been partially discussed above. Ground clearance was the primary concern of the excavation subsystem. In the 2015 competition, this resulted in some of the scoops breaking. Implementing the actuator so that the conveyor will translate upwards, instead of arc out has mitigated this risk by allowing more clearance during mobility. The timing belt system corrects for the slippage with the previous friction system. The scoops have been made bigger to collect more regolith and to give more room above the collection bin so that the regolith will fall into it.

Components	Failure/Results	Code	Mitigation
Scoops	Little clearance between conveyor and bin	2	New scoop design to create a greater clearance and greater volume
Rollers	No traction between rollers and belt	3	Timing pulleys replacing the rollers
Conveyor belt	Belt slipping off the rollers	2	Timing belt with teeth and flange to fit in the pulleys
Actuator	Conveyor too close to the ground during movement	3	Vertical conveyor with an actuator lifting upwards to create more clearance

Table 4: Risk Assessment for Excavation Subsystem

Reliability

Conveyor systems have been proven to be reliable throughout past competitions. In addition, a factor of safety has been introduced to the gear ratio to give the outer conveyor the ability to easily extract over twice the load expected.

Verification

The verification plan for the conveyor system entails testing the various parts. To ensure the new scoop design can support the weight of the regolith and hold the contents as the timing belt moves. The vertical conveyor clearance also has to be tested during movement. A verification plan to ensure the success of these concepts will be implemented upon complete physical interfacing of Shia 3.0. After the stability of the system has been verified, tests will be run with a simulant to determine the actual excavation rates and the power drawn.

IV. Structure Subsystem

Operational Concept

Shia 1.0 and 2.0 utilized a carbon fiber regolith storage bucket as a major structural component. To improve upon this design the team decided to include a more robust aluminum structure to reduce the load bearing necessity of the bucket and to bring more organization to the robot as a whole. The frame will allow each subsystem to be mounted and work in conjunction, while also ensuring that the load is distributed evenly. The structure subsystem consists of the base plate and the frame. The frame is shown in Figure 6, while the base plate is shown in Figure 7.

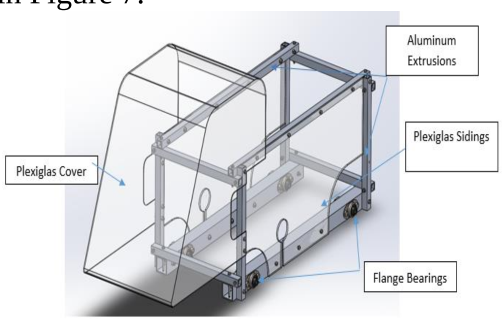


Figure 6: Frame

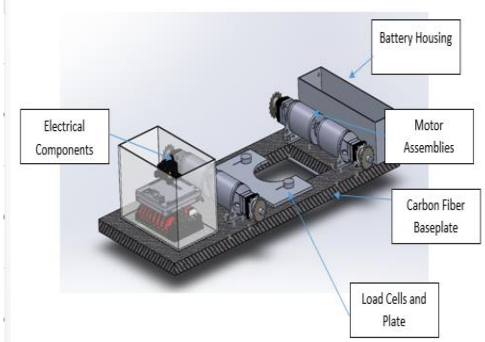


Figure 7: Base Plate

Interfaces

The frame and baseplate will interface with nearly every other component on the robot. As a result, the components will be crucial to the integration process. The structure will also provide mounting plates and zones for electrical components, as well as allow for organized routing of wires and/or powered components. The frame will interface with the excavation system in the use of linear bearings that will be mounted to the front upright structure of the frame. These will be mounted to carriages that mount directly to the T-Bar mounting plates. Flange bearings integrate directly into the 2"x2" Aluminum extrusions that make up the longitudinal portion of the frame allow the frame to absorb any shocks due to obstacles, therefore eliminating the need for any type of traditional spring damper suspension system.

The frame also allows for the bucket and auger system to be mounted and placed into the frame on top of the pancake load cell that will be used to measure the bucket capacity and status during the competition.

Requirements

The frame must be structurally sound enough to absorb any instances of shocks that the robot undergoes during its operation. It must allow for integration of each subsystem to a central hub where components can be stored, updated, and fixed should a component break. It must provide a system that can allow mounting points for motors and controllers to be placed and protected from any dust that may enter the structure. Any additional modularity of the frame is encouraged, as previous team's assembly and disassembly processes have been difficult. These requirements correspond to F1, F2, P1, S1, and S1 in Table 1.

Trade-Off Assessment

The choice to add a frame into the structure was made from both research from past competitions, as well as feedback from previous teams. In our research, nearly every team had some type of structural frame that allowed for each subsystem to integrate more fluidly. The decision matrix for adding a frame is shown in Table 5.

Design Characteristic	Importance	No Frame	Vertical Box Frame
Additional Weight	2	5	3
Reliability	2	3	4
Complexity	4	4	3
Structural Integrity	5	1	4
Manufacturability	2	5	3
Integration	5	1	5
Total	X	52	77

*Table 5: Frame Decision Matrix**
**Note- Importance: 1 = poor, 5 = excellent*

Risk Assessment

Risks associated with the structure of the robot are shown in Table 6.

Components	Failure/Result	Code	Mitigation
Baseplate	Bottom out on Regolith	3	Used 8" diameter wheels and minimized auger protrusion out of bottom
Aluminum Extrusions	Four Bar Mechanism Movement	1	Incorporated stiffening elements into frame: Plexiglas siding/Battery Storage
Chain/Motors	Chain loosens	1	Chain tensioning system incorporated into base
Electrical	Dust Entering structure	1	Plexiglas siding and cover added and modeled

Table 6: Structure Risk Management

Reliability

Adding an established structure to the robot will allow for a higher degree of reliability in that it will anchor each subsystem to a central frame, while maintaining modularity in its design.

Verification

The structure of the robot will be built, tested and validated over the course of the next several weeks. The team will also verify the validity of the Plexiglass siding and cover as mounting points for LIDAR and other electrical systems.

V. Storage and Ejection Subsystem

Operational Concept

The storage and ejection subsystem must receive regolith from the excavation subsystem and deposit it into the collection bin. This subsystem is made up of a carbon fiber bin and an auger. Regolith that has been collected from the designated mining site will be gathered by the conveyor system and deposited into the bin by the auger. The bin will store the regolith until a desired amount has been mined. Then, the robot will navigate to the collection bin located on the other side of the competition area. The robot will then align itself with the competition collection bin and engage the ejection system. The ejection system will deposit all of the regolith stored in the system's bin to the designated competition container. Figure 8 shows the complete subsystem including the auger and bin.

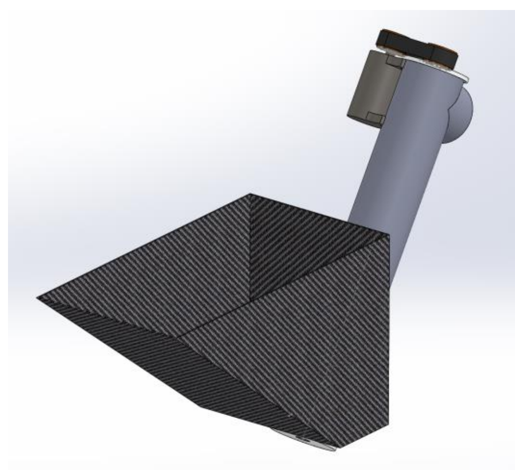


Figure 8: Storage/Ejection Subsystem

Interfaces

The bin and auger will be connected by carbon fiber. This subsystem is attached and completely housed by the aluminum frame structure via bolts and brackets. The motor of the auger is control by a signal from the autonomous operation.

Requirements

In order to accomplish the system goals, the robot must complete two runs in the competition area from the mining area to the designated collection bin. Collected regolith must be carried across the obstacle course and delivered into the collection bin. In order to qualify for placement in the competition, at least 10 kg of regolith must be deposited. The auger needs to be able to completely deposit the regolith from the storage bin into the designated collection bin in a timely manner to ensure qualification and allow the excavation and maneuvering processes an adequate amount of time during each run. These subsystem requirements include P1, V1, S1, S2, and S5 referenced previously in Table 1.

Trade-off Assessment

Previous design revisions included an auger. Due to the proven efficacy of the auger system with the program it was the primary design choice. Two augers were considered to increase the speed of ejection. A decision matrix located in Table 7 was used to compare the two designs. The matrix results led to a one auger system being chosen.

Design characteristic/ subsystem options	Two Augers	One Auger
Cost	2	5
Reliability	5	4
Design Complexity	2	3
Power consumption	2	3
Weight	2	3
Ease of autonomous control	3	3
Time	4	2
Regolith Collection Capacity	4	2
Manufacturability	2	4
Total	26	29

*Table 7: Ejection Decision Matrix**
**Note- Importance: 1 = poor, 5 = excellent*

The use of a chain and sprocket to drive the auger is being implemented based on the previous semester's design. During the concept portion of the design process a comparison study was done to determine whether a sprocket and chain or a two gear system was optimal for the auger subsystem. The gear system would be less susceptible to the environment and wouldn't have any slippage, but the adjustment process would be complicated. Although the chain may wear over time, it is more advantageous to use the sprocket and chain for this design. A decision matrix was used to compare the two designs and is shown in Table 8 below.

Subsystem Option/Design Characteristic	Two Gear System	Chain and Sprocket System
Design Complexity	3	4
Reliability	4	4
Cost	3	5
Accuracy	4	4
Susceptibility to Environment	3	2
Ease of Maintenance	3	5
Degree of Wear	4	2
Amount of Slippage	5	5
TOTAL	**29**	**31**

*Table 8: Gear vs. Chain Decision Matrix**
**Note- Importance: 1 = poor, 5 = excellent*

Risk Assessment

The analysis of risks for the storage/ejection system is summarized in Table 9. The risks for this subsystem were very low with no major failures. Only one major improvement was made which was the increase in bin size. The old bin size was smaller and could only contain a small amount of regolith at one time. This mitigation was necessary in order to make the subsystem perform more successfully.

Components	Failure/Result	Code	Mitigation
Storage Bin	Too small	2	Increase size to hold more Regolith
Motor	No failure	1	Keeping same motor
Auger Tube	No failure	1	Keeping same design

Table 9: Storage/Ejection Risk Management

Reliability

With the increase in storage volume, more Regolith can be collected. A storage bin of this size ensures the ability to collect a minimum of 60 kilograms in one run. The auger proved to be very reliable during testing and previous competition runs.

Verification

The original size of the collection bin was based on the need to carry the minimum amount of regolith to qualify for the competition. The bin was redesigned to hold more than double the amount of regolith.

The bin and auger are sealed as one unit and do not leak. The ejection system was tested and determined to be able to empty a bin full of regolith in approximately twenty-two seconds. This verification was found experimentally by filling the bin with a known amount of dirt and recording the elapsed amount of time to empty the bin.

VI. Mobility Subsystem

Operational Concept

The Mobility Subsystem, shown in Figure 9, must transport all of the electrical and mechanical components safely and quickly throughout the competition runs. This subsystem is made up of two components: the drivetrain and the wheels. Whereas previous revisions of the robot design utilized tread-like and wheel-leg combination concepts, Shia 3.0 uses four independent wheels to reliably transport the entire system to and from the bin and over obstacles. The drivetrain must provide a steady and powerful force to move the four independent wheels. It will accomplish this through the use of motors, gearboxes, motor mounts, chains, sprockets, and shafts.

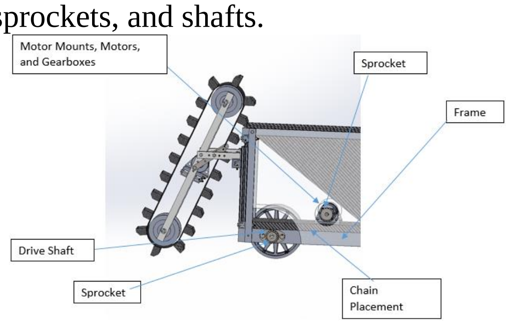


Figure 9: Mobility Subsystem

Interfaces

The wheels are attached to the drivetrain system through Versa Hubs (hubs made by Vex Robotics to fit with the wheels chosen) with a 1/8 inch keyway and ½ inch bore, shown in Figure 10. These wheel hub assemblies are then attached to the driveshaft from the drivetrain which transfers torque to the wheels.

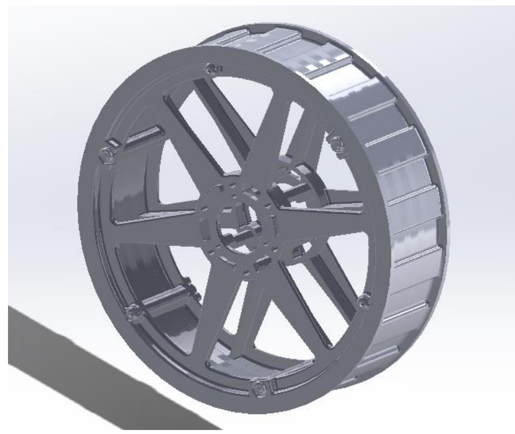


Figure 10: Vexpro Wheels

The drivetrain subsystem will be attached to the frame and wheel shaft as shown in Figure 28. There will be four motors with gearboxes outfitted to each. These will be attached via mounts and bolts to the specified locations. Two different lengths of roller chains will be used with sprockets of the same size. The sprockets will be placed in designated locations with fasteners restricting any sort of lateral motion. The motors will receive commands from the control subsystem that will control the robot's speed.

Requirements

First, Shia 3.0 must maneuver into the digging area from the starting area. Then it must travel to the desired excavation site while simultaneously avoiding obstacles. After the excavation is completed, it must travel back to the bin for the ejection system to deposit the regolith. These subsystem requirements are both functional and supplementary, which are referenced in Table 1. The specific references include F1, F2, F3, P1, S1, and S2.

Trade-off Assessment

Based on Shia 1.0 and 2.0 several potential design changes were eliminated. The wheel-legs on Shia 1.0 that were used in the 2015 competition were not operational. Therefore, the major designs considered were standard wheels and treads. Ultimately, pre-fabricated wheels were chosen over treads because of manufacturing and time constraints. The decision matrix in Table 10 shows the comparisons made between wheels, Whegs, and Tiger Treads and Table 11 shows the decision matrix for pre-fabricated and manufactured wheels.

Design	Cost	Time to make	Reliability	Robustness	Turnability	Obstacle climbing	Total
Wheels	4	5	4	3	4	3	23
Whegs	4	3	1	1	3	3	15
Tiger Treads	2	1	4	5	2	4	18

*Table 10: Wheel decision matrix**
**Note – importance: 1 = poor 5 = excellent*

Option	Cost	Time	Robustness	Reliability	Total
Buy	4	4	4	3	15
Manufacture	1	1	3	3	8

*Table 11: Buy vs Manufacture Decision Matrix**
**Note – importance: 1 = poor 5 = excellent*

Once it was determined what type of drivetrain system would be used, the next decision was to determine whether a chain or a belt would be more appropriate for the given situation. The decision matrix in Table 12 shows why a chain was chosen over the belt.

Decision Matrix for Belt and Pulley vs. Chain and Sprocket (1-5)		
1-Poor, 3-Avg, 5-Excellent		
Objectives	**Belt and Pulley**	**Chain and Sprocket**
Cost	2	4
Weight	3	3
Dimensions	1	4
Environmental Effects	3	1
Connection Factor	3	4
Assembly	3	3
Wear	3	2
Slip	2	4
Total	**20**	**25**

*Table 12: Decision Matrix for Belt and Pulley vs. Chain and Sprocket**
**Note – importance: 1 = poor 5 = excellent*

While the main concern for the chain was the damage it could sustain from the competition environment, this was not enough of a major issue to use the belt instead. The belt would be too large and have a higher chance of slipping. The connection factor for a chain/sprocket system was also much smaller than a belt/pulley system, thus reducing the amount of overhung load the output shaft on the motor would sustain.

Risk Assessment

The mobility subsystem of Shia 1.0 was not functional at competition and provided a number of major risks which led to the selection of new gearboxes and mounts. Table 13 shows the risks identified in the previous design. To correct these issues, new gearboxes and mounts were selected, the frame size was improved, and four independent wheels were incorporated. These improvements provide simplicity and reliability in the design of Shia 3.0.

Components	Failure	Code	Mitigation
Suspension	Springs would get clogged with dirt	1	Bearing system reduces shock in motors
Feet	Dug itself in holes	4	Four wheel system

Table 13.Control System Risk Assessment

Reliability

Through our research into past competitions and common robot designs by other design teams it was determined that the independent wheel design is the most popular and reliable. Glass-filled nylon wheels were selected to sustain the weight of the large amount of Regolith that Shia 3.0 will be carrying.

It was found through careful analysis of past competitions that the belt or chain drive operated robots have been found to withstand the obstacles with greater frequency than those that directly mount the wheels to the motors. The chain driven system that was selected eliminates virtually all of the vertical load on the motors and keeps them operating more efficiently.

Verification

The mobility subsystem was designed to be robust enough to maneuver over or around obstacles while carrying a full bin of regolith. Using soil bins located at USDA on Auburn University's campus, the mobility testing will consist of placing robot in soil and verifying that the robot can travel a distance of at least 30 meters. The bin will be filled with soil with a weight of at least 50 kilograms while traveling. After testing, modifications and improvements will be made if necessary to better the design.

The drivetrain subsystem will be tested by running the robot over an environment similar to the competition arena. After testing, modifications will be made to improve the efficiency of the design.

VII. Control Subsystem

Operational Concept

The primary function of the control subsystem is to receive information from the user or sensors. In the case of full autonomy, a Raspberry Pi™ will be used to input information from the LIDAR and camera systems into the roboRIO®. The roboRIO® will then process that information, along with what it receives from the rangefinder, and use it to determine a path. It will then manipulate the motors, via the motor controllers, as well as linear actuators and other devices, to move across the arena, dig, return, and dump. In the case of manual control, the system will take the user's input from the game controller, connected to the driver station, and manipulate the components appropriately.

Interfaces

The roboRIO® will interface with all other electrical components. The game controller will interface with the driver station in order to allow for user input in case of manual control. The driver station will interface with the roboRIO® through the router located inside of the arena. The motor controllers will interface with the motors (four drive train motors, two conveyor motors, and an auger motor), taking the information from the roboRIO® and processing it into motor rotation. A full representation of the electrical system interfaces can be found in Appendix F.

Systems Requirements

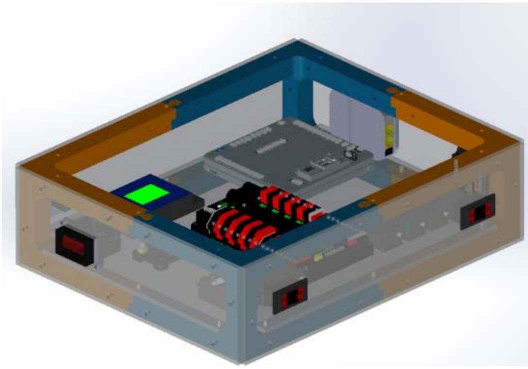
The control subsystem must take data from either the user or sensors and transfer it to the robot using a wireless access point. Then it must process the data into useable commands for the motor controllers while optimizing power and data usage. These subsystem requirements include F3, P2, I1, V1, and S3 referenced in Table 1.

Trade off Assessment

After the Raspberry Pi™ was selected to interface with the LIDAR, the team discussed removing the roboRIO® altogether, and replacing it with the Raspberry Pi™ as our main processing unit. The Raspberry Pi™ is small, lightweight, has low power consumption, and works well with most languages. The roboRIO®, is still small and light (Although larger than a Raspberry Pi™), and has a familiarity to several of the students working on the project, due to their work with FIRST and BEST robotics. The roboRIO® was kept due to the experience that the team has had with it in the past, and it's built in heat sinks to keep overheating to a minimum.

Risk assessment

The primary risk for the control subsystem is dust penetration. If dust penetrated the electrical components in the system it could result in an electrostatic discharge. An electrostatic discharge would destroy the



microcontroller. To make sure that our microcontroller does not experience an electrostatic discharge the controller is enclosed and grounded. To correct for the dust penetration the microcontroller has a case built around it.

Figure 11: Dust Retardant Electronics Box

It will also be enclosed, with the other electronics, in a Plexiglass box shown in Figure 11 that is sealed from dust. A short circuit could also cripple the robot. There will be a test before each run to make sure every connection is secured properly. An assessment of risks for this system is shown in Table 14.

Risk	Mitigation
Electrostatic discharge destroys the microcontroller	Microcontroller is enclosed and grounded
Microcontroller is introduced to dust from the arena	The microcontroller has a case built around it. It will also be enclosed with the other electronics in a Plexiglas box that is sealed from dust
Short circuit	Every connection is secured properly

Table 14: Risk Assessment for the Controls System

Reliability

The roboRIO®, Raspberry Pi™, and motor controllers are off the shelf units that have been tested for reliability extensively before purchase. Additionally, the roboRIO® and motor controllers were used in previous competitions, and have shown to be reliable.

Verification

Nominal testing has been done on the connection of the Raspberry Pi™ to the LIDAR and roboRIO®. These connections will be tested more extensively to ensure that the data can be transferred at an optimal rate for autonomy.

VIII. Autonomous Sensors Subsystem

Operational Concept

The primary function of the autonomous sensors subsystem is to feed in data to the control subsystem. The camera, rangefinder, and visual beacon will be used to determine the location of Shia 3.0. The visual beacon is located in the starting area of the arena. The beacon is made of a visual image that incorporates reflective tape to ensure that it is easy to locate. The camera and rangefinder are located on the robot, nearest the auger. The rangefinder will be used to determine good and bad sectors of the path in front of Shia. The load cell will be used to determine the amount of regolith that has accumulated in the bucket during the digging process.

Interfaces

All devices will interface with the roboRIO® in order to feed it information about Shia 3.0's surroundings. The rangefinder is attached to the camera with industrial Velcro. The camera and rangefinder are mounted to a servo for rotation when finding the beacon. The servo, in turn, is connected to the mechanical frame.

System Requirements

The system must enable the robot to function autonomously. The robot must avoid all obstacles in its path when travelling to and from the mining area. Because it is not allowed to dig in other areas of the arena, the system must recognize when it has reached the digging zone. It must recognize the robot's distance from the bin so it can locate the dumping area. These subsystem requirements include F2, P1, P2, and V1 referenced above.

Trade off Assessment

A two-camera system was discussed to replace a rangefinder. The rangefinder, however, retrieved the same data with less power usage than a second camera. The rangefinder also had easy to use data retrieval, while the two camera system would have required more time and effort to implement. Several alternatives to the load cell were discussed, including camera and laser detection. The load cell did the job as simply as possible, and fit well into our mechanical design.

Risk Assessment

The risk assessment for the Autonomy system is shown in Table 15.

Risk	Mitigation
Load cell fails to read the mass properly	The load cell will be tested extensively prior to the competition to ensure its reliability.
The LIDAR fails to read the obstacles properly	The LIDAR will be tested extensively prior to the competition to ensure its reliability. In case of an unforeseen complication occurring in the LIDAR being unusable, SHIA is equipped to handle most obstacles.

Table 15: Risk Assessment for Autonomy Subsystem

Reliability

The LIDAR, rangefinder, and load cell are off the shelf units that have been tested for reliability extensively before purchase. The camera has been used in past competitions, and has been shown to be reliable.

Verification

Although only nominal testing has been done thus far, the system has proven to accurately provide information to the roboRIO®. More extensive testing for each component will be done at the Auburn soil bins in an attempt to replicate the mining arena.

IX. Power Subsystem

Operational Concept

The primary function of the power subsystem is to control the supply of power to the electrical devices. The battery, a 12V lead acid, will supply the power for the full ten minute run. The battery is directly connected to the emergency stop button, which will disconnect any device from the power source when pressed. The breaker will prevent voltage spikes that could potentially harm the rest of the electronics. The power logger is off the shelf model that fits the requirements of the competition and monitors the power usage of the system. The power distribution board and voltage regulators disperse the power from the battery into the other electronics.

Interfaces

The emergency stop button will be directly connected to the battery, allowing for a direct shutdown of power to the system. The power logger will be connected to the battery to log the use of power during the run. It is shortly after the emergency stop in the chain. The distribution board will be connected to the battery to get a supply of power to then distribute to other components. It is shortly after the power logger in the chain. All other components are connected to the distribution board so that it can supply power.

Trade off Assessment

The use of a lithium ion battery was discussed in place of the lead acid. While the lithium ion battery would achieve the same power output in a smaller form factor, the lead acid battery was cheaper, and so was kept as the system's power supply. Additionally, the added weight of the lead acid battery will help to offset the weight of the conveyor.

Risk Assessment

The risk assessment for the power subsystem is shown in Table 16 below.

Risk	Mitigation
Battery does not hold a charge	Batteries will be tested thoroughly prior to competition and charged before each run
Various issues with power connections and cables	Connections and cables will be checked prior to each run
Batteries over heat during the run	Tests will be conducted to ensure that the battery can run for periods of time longer than the ten minute run

Table 16: Risk Assessment for Power Subsystem

Reliability

All components are off the shelf units that have been tested for reliability extensively before purchase. The batteries and power distribution board have been used in previous competitions, and have shown to be reliable.

Verification

In previous years, the battery and power distribution board were tested to prevent overheating in hot climates. The emergency stop button and power logger will be tested to ensure that each satisfies its requirements.

X. Conclusion

The 2016 Auburn University Robotic Mining Competition Team sought to improve on previous designs to meet mission requirements for the 2016 competition. Through careful trade-off and risk assessments included in the systems engineering design process these mistakes were corrected. After the development of the design the team manufactured the robot and tested.

Although the system has not been fully integrated at this time, extensive component testing is taking place and full integration will occur within two weeks. During the integration phase the team will work to mitigate a few lingering issues. For the electrical side the concerns primarily involve dust prevention and the processing power of the roboRIO® to achieve fully autonomous function. To mitigate these risks, the electrical team is working to make the electrical component box dust retardant and considering diverting some processing to the Raspberry Pi™ in order to decrease the demand on the roboRIO®. The mechanical team is currently testing the actual capabilities of the wheels on sand and whether the conveyor will clear the ground and the storage bin. If the wheels are not adequate an alternate wheel design will be considered. Currently the conveyor is undergoing more testing to determine if clearance will be an issue.

References

1 NASA Systems Engineering Handbook. 2007. Print.

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3 RMC Rules and Rubric. Web. <http://www.nasa.gov/sites/default/files/atoms/files/rmc_rules_and_rubrics_for_2016_rev_2.0_-_01.08.2016_.pdf>.

4 "Raspberry Pi™ 3 Is out Now! Specs, Benchmarks & More - The MagPi Magazine." The MagPi Magazine. 2016. Web. 10 Apr. 2016.

5 "Community." roboRIO® Details and Specifications Version History. Web. 10 Apr. 2016.

4 Ontiveros, M. et al., “Mech 4250 Component Design Review (CDR)” Senior Design Report, Department of Mechanical Engineering, Auburn University, Auburn, AL, 2016.

5 Beale, D. and Bonometti, J. “Chapter 2: Systems Engineering (SE) – The Systems Design Process”.

Appendix A: Mass Budget

Subsystem	Total Mass (kg)
Conveyor	4.395
Frame/Bin/Auger	16.075
Mobility	17.175
Fasteners	4.536
Electrical	9
Tolerance	9
Total	**60.181**

Appendix B: Power Budget

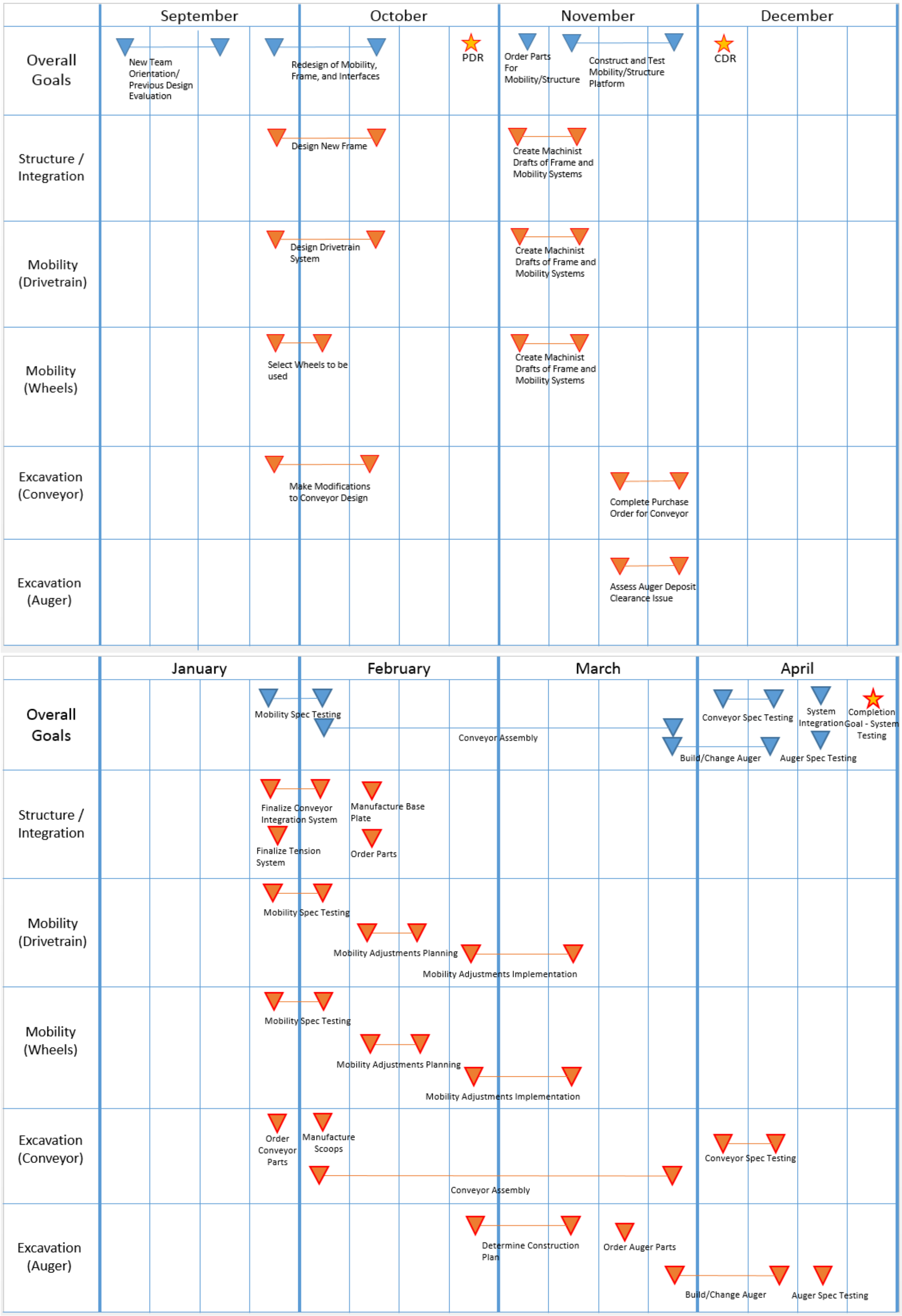
Item	Voltage [VDC]	Current [A]	Power [W]	Time [hr]	Energy [Whr]	[Ahr]
Camera	5	.5	2.5	0.5	1.25	.25
Camera Servo	5	0.0088 to 0.400	0.044 to 2	0.5	0.022 to 1	0.0044 to 0.2
roboRIO®	12	0.417 to 3.75	5 to 45	0.5	2.5 to 22.5	0.2085 to 1.875
Raspberry Pi™	5	0.31 to 0.58	1.55 to 2.9	0.5	0.775 to 1.45	0.155 to 0.725
FR Motor	12	16 to 24	192 to 288	0.5	96 to 144	8 to 12
FL Motor	12	16 to 24	192 to 288	0.5	96 to 144	8 to 12
RR Motor	12	16 to 24	192 to 288	0.5	96 to 144	8 to 12
RL Motor	12	16 to 24	192 to 288	0.5	96 to 144	8 to 12
Auger Motor	12	16 to 24	192 to 288	0.5	96 to 144	8 to 12
Conveyor Motor	12	16 to 24	192 to 288	0.5	96 to 144	8 to 12
Conveyor Actuator	12	8	96	0.5	48	4
Access Point	12	1	12	0.5	6	0.5
LIDAR	5	0.1	0.5	0.5	0.25	0.005
Range Finder	5	0.1	0.5	0.5	0.25	0.05
Total Power:	1270W to 1889 W					

Appendix C: Bill of Materials

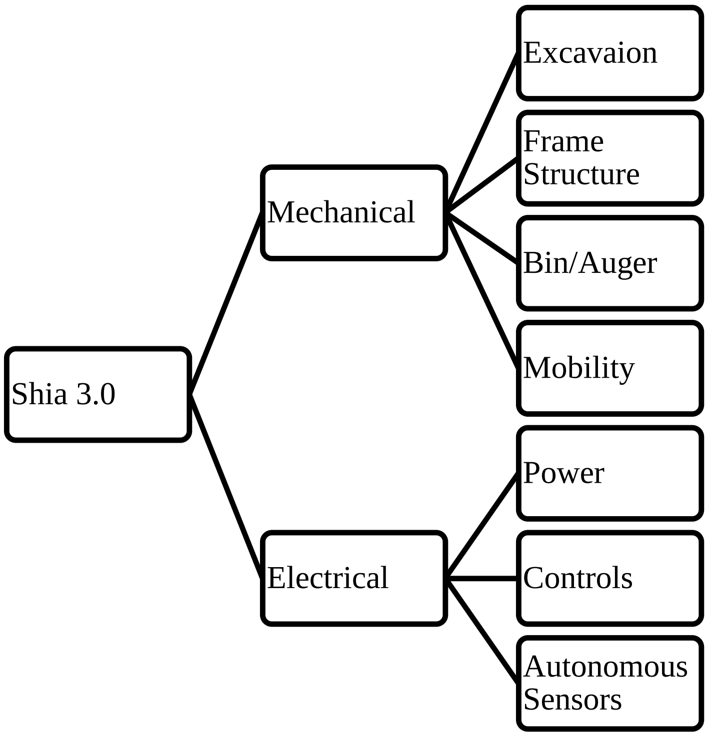
Items	Budget Amount	Total Cost	Unit Cost	Quantity	Returns	Total Budget Spent	"20% Extra"
	$4,000						
1" X 1" Aluminum Tubing [1 ft] (Part # 6ALR5)	$3,985.44	$14.56	$3.64	4			
1" X 1" Aluminum Tubing [3 ft] (Part # 6ALR4)	$3,864.60	$120.84	$10.07	12			
2" X 2" Aluminum Tubing [3 ft] (Part # 6ALP2)	$3,816.56	$48.04	$24.02	2			
Sheet, Aluminum, 1/8" x 6" x 12" (Part # 15V221)	$3,785.76	$30.80	$15.40	2			
Finished-Bore Sprocket with Hardened Teeth for #35 Chain, 3/8" Pitch 16 Teeth (Part # 2500T18)	$3,615.56	$170.20	$17.02	10			
Roller Chain ANSI Number 35, 3/8" Pitch [3 ft] (Part # 6261K172)	$3,603.86	$11.70	$11.70	1			
Fully Keyed 1045 Steel Drive Shaft 1/2" OD, 1/8" Keyway Width, 18" Length (Part # 1497K953)	$3,473.66	$130.20	$21.70	6			
Roller Chain ANSI Number 35, 3/8" Pitch [7 ft] (Part # 6261K172)	$3,446.36	$27.30	$27.30	1			
Steel Flange-Mounted Ball Bearing for Shaft Diameter 1/2", Overall Length 3-3/4" (Part # 7208K52)	$3,227.24	$219.12	$27.39	8			
Side-Mount External Retaining Ring [E-Style] (Part # 97431A340)	$3,217.46	$9.78	$9.78	1			
Medium-Strength Grade 5 Zinc-Plated Steel Cap Screw 1/4"-20 Thread, 3-1/2" Long (Part # 91247A556)	$3,209.59	$7.87	$7.87	1			
Medium-Strength Grade 5 Zinc-Plated Steel Cap Screw 1/4"-20 Thread, 2-1/2" Long (Part # 91247A552)	$3,190.61	$18.98	$9.49	2			
Medium-Strength Grade 5 Zinc-Plated Steel Cap Screw 1/4"-20 Thread, 1-1/2" Long (Part # 91247A546)	$3,179.40	$11.21	$11.21	1			
Grade 5 Steel Hex Nut Zinc Plated, 1/4"-20 Thread Size, 7/16" Wide, 7/32" High (Part # 95462A029)	$3,175.00	$4.40	$4.40	1			
Medium-Strength Grade 5 Zinc-Plated Steel Cap Screw 7/16"-14 Thread, 3" Long (Part # 91247A681)	$3,160.24	$14.76	$7.38	2			
Grade 5 Steel Hex Nut Zinc Plated, 7/16"-20 Thread Size, 11/16" Wide, 3/8" High (Part # 95462A520)	$3,148.44	$11.80	$11.80	1			
8" Traction Wheels (Part # 217-2605)	$3,004.52	$143.92	$17.99	8			
2" Wide Wedgetop Tread, 10ft long (Part # 217-2892)	$2,954.54	$49.98	$24.99	2			
Tread Attachment Rivet [13-pack] (Part # 217-0396)	$2,942.62	$11.92	$1.49	8			
Versa Hub [1/2" Round with 1/8" Keyway] (Part # 217-0396)	$2,798.78	$143.84	$8.99	16			
CIM Motor (Part # 217-2000)	$2,658.83	$139.95	$27.99	5			
Versa Planetary CIM Adaptor (Part # 217-4018)	$2,633.88	$24.95	$4.99	5			
Versa Planetary 10:1 Gear Kit with Ring Gear (Part # 217-3570)	$2,508.93	$124.95	$24.99	5			
Versa Planetary 3:1 Gear Kit with Ring Gear (Part # 217-3565)	$2,383.98	$124.95	$24.99	5			
Base Versa Planetary 1:1 with 1/2" with 1/8" Keyway Round Output (Part # 217-3562)	$2,209.03	$174.95	$34.99	5			
2mm Key [5-pack] (Part # 217-2761)	$2,203.05	$5.98	$2.99	2			
CIM Motor Bracket (Part # am-2488)	$2,158.05	$45.00	$9.00	5			
Lathe Tool Blank for Steel, Brass & Aluminum 1/2" Shank Size (Part # 3200A26)	$2,139.52	$18.53	$18.53	1			
Shim for Keyway Broaches 1/8"Keyway, for Broach Style A, .031" Thick (Part # 8836A11)	$2,136.26	$3.26	$3.26	1			
Keyway Broach Uncoated High-Speed Steel, 1/8" Keyway, Broach Style A (Part # 3153A16)	$2,088.56	$47.70	$47.70	1			
Spring Steel Standard Key Stock 1/8" x 1/8", 12' Length (Part # 98535A130)	$2,084.42	$4.14	$2.07	2			
Black-Oxide High-Speed Steel Jobbers' Drill Bit 1/4", 4" Overall Length, 2.4" Drill Depth, 135 Degree Point (Part # 2901A124)	$2,081.58	$2.84	$2.84	1			
Edge Finder Economy Single-End, .200" Tip, 1/2" Body Diameter (Part # 20535A755)	$2,070.77	$10.81	$10.81	1			
Uncoated High-Speed Steel Jobbers' Drill Bit 5/8", 7-1/8" Overall Length, 4.3" Drill Depth, 118 Degree Point (Part # 8870A54)	$2,050.26	$20.51	$20.51	1			
Black-Oxide High-Speed Steel Jobbers' Drill Bit 7/16", 5-1/2" Overall Length, 3.4" Drill Depth, 135 Degree Point (Part # 2901A137)	$2,041.88	$8.38	$8.38	1			
Medium-Strength Grade 5 Zinc-Plated Steel Cap Screw 7/16"-20 Thread, 3" Long, packs of 10 (Part # 91247A328)	$2,025.40	$16.48	$8.24	2			
Flat Head Phillips Screw for Sheet Metal, 316 Stainless Steel, Number 6 Size, 3/4" Length, packs of 100 (Part # 90198A158)	$2,016.38	$9.02	$9.02	1			
T-Handle Roller Chain Breaker for Single & Double Strand Chain, ANSI NOS. 25-60 (Part # 6051K15)	$1,985.90	$30.48	$30.48	1			
Point for 1/4" to 3/4" Pitch T-Handle Roller Chain Breaker (Part # 6051K22)	$1,983.23	$2.67	$2.67	1			
Type 316 Stainless Steel Socket Head Cap Screw, 8-32 Thread, 2-1/4" Long, packs of 10 (Part # 92185A181)	$1,968.99	$14.24	$7.12	2			
Type 316 Stainless Steel Nylon-Insert Locknut, 8-32 Thread, 11/32" Wide, 15/64" High, packs of 100 (Part # 90715A009)	$1,960.50	$8.49	$8.49	1			
Socket Head Cap Screw, 316 Stainless Steel, #10 Thread Dia., 1/2" Length under Head [pack of 25] (Part # 1GB93)	$1,959.50	$1.00	$1.00	1			
Adhesive-Ready Neoprene Rubber 1/16" 6' (Part # 86015K31)	$1,889.54	$69.96	$69.96	1			
SAE 863 Bronze Sleeve Bearing 1/2" SD, 3/4" OD, 1" Length (Part # 2868T14)	$1,886.04	$3.50	$1.75	2			
Guide Rail, 15mm Wide Length 280mm for Ball-Bearing Carriage (Part # 6709K33)	$1,706.84	$179.20	$89.60	2			
Ball-Bearing Carriage, Threaded Hole, for 15mm Rail Width (Part #6709K12)	$1,455.94	$250.90	$125.45	2			
Timing Pulleys (Part # A 6Z 4-36DF07516)	$1,371.74	$84.20	$21.05	4			
Timing Belts (Part # A 6R 4-152075)	$1,313.32	$58.42	$29.21	2			
316 Stainless Steel Clevis Pin with Cotter Pin, 5/16" Diameter, 2-1/2" Long, 2-1/4" Usable Length (Part # 92401A669)	$1,287.40	$25.92	$6.48	4			
Galvanized Steel Eyebolt with Nut for Lifting, 1/4"-20 Thread Size, 3" Long Shank (Part # 3016T150)	$1,271.04	$16.36	$4.09	4			
Steel Rod End, 1/4"-20 Thread Size, 1/4" Hole ID, 2" Length, 3/4" Long Thread (Part # 6066K670)	$1,247.52	$23.52	$5.88	4			
Low-Carbon Steel Bar, 1/8" Thick, 3/4" Width, 1/2' Length (Part # 8910K394)	$1,242.88	$4.64	$1.16	4			
Low-Strength Zinc-Plated Steel Cap Screw, 1/4"-20 Fully Threaded, 4-1/2" Long (Part # 91309A560)	$1,236.85	$6.03	$6.03	1			
Multipurpose 6061 Aluminum Rectangular Tube, 1/8" Wall Thickness, 1" x 2" [6 inches] (Part # 6546K39)	$1,230.92	$5.93	$5.93	1			
18-8 Stainless Steel Reusable Cotter Pin, Hairpin, Fits 1/4"-1/2" Pin Diameter, 1-5/8" Length (Part # 92391A140)	$1,223.60	$7.32	$7.32	1			
Zinc-Plated Steel Clevis Pin, 1/4" Diameter, 3-1/2" Length, 3-5/16" Usable Length (Part # 97245A272)	$1,217.76	$5.84	$5.84	1			
Hammer-on Steel Alligator Belt Lacing #1A, 12" Length, for .06"-.09" Belt Thickness (Part # 6110K135)	$1,187.71	$30.05	$30.05	1			
Multipurpose 6061 Aluminum, Rectangular Bar, 1" x 1-3/4", 1' Long (Part # 8975K626)	$1,174.40	$13.31	$13.31	1			
						$2,825.60	$565.12
						$3,390.72	

Items	Budget Amount	Total Cost	Unit Cost	Quantity	Returns	Total Budget Spent
	$4,000					
Talon SRX Speed Controller (Item # am-2854)	$3,370	$630	$90	7		
Robot Power Cable Kit (Item # am-0975)	$3,330	$40	$40	1		
DC Power Cable with 5.5 mm OD/2.1 mm ID connector, 36" (Item # am-2298)	$3,314	$16	$4	4		
Dual Band Radio, OM5p-AN Access Point (Item # am-3277)	$3,179	$135	$135	1		
Battery Power Cable, custom length (Item # am-0339)	$3,159	$20	$20	1		
Voltage Regulator Module (Item # am-2857)	$3,067	$92	$46	2		
Sauro Connector CTF020V8 (Item # am-2076)	$3,064	$3	$3	1		
Panel Mount Digital Voltage Meter (Item # am-2761)	$3,044	$20	$20	1		
20 Amp Snap Action Breaker (Item # am-0289)	$3,020	$24	$6	4		
30 Amp Snap Action Breaker (Item # am-0290)	$3,008	$12	$6	2		
40 Amp Snap Action Breaker (Item # am-0288)	$2,952	$56	$7	8		
CAN Bus cable (Item # am-3071)	$2,946.50	$5.50	$5.50	1		
Power Supply at 1A (Item # am-3278)	$2,941.50	$5	$5	1		
Force Sensors & Load Cells Force Sensor 20mV/V 250 lbf Compression (Item # 824-FC23-1-100000250)	$2,795.17	$146.33	$146.33	1		
Powerpole Mounting Clamp Pair for 4 or 8 PP15/30/45 Powerpoles (Item # 1462G3)	$2,780.01	$15.16	$3.79	4		
Powerpole Mounting Clamp Pair for 2 or 4 PP15/30/45 (Item # 1462G1)	$2,768.05	$11.96	$2.99	4		
45 Amp Permanently Bonded Red/Black Anderson Powerpoles [100-pack] (Item # WP45-100)	$2,641.06	$126.99	$126.99	1		
Powerwerx Retention Clips for PP15/30/45 Powerpole Connectors (Item # PCLIP)	$2,626.36	$14.70	$0.49	30		
Red/Black Zip Cord 12 Gauge 50 ft [12 AWG 50 ft] (Item # PCLIP)	$2,586.24	$40.12	$40.12	1		
Neutrik NC3FP-1 Panel Mount XLR Controller Female Nickel (Item # NC3FP-1)	$2,577.27	$8.97	$2.99	3		
Neutrik NC3MX-1 Male XLR Controller Connector Nickel (Item # NC3MX-1)	$2,569.59	$7.68	$2.56	3		
						$1,430.41

Appendix D: Gantt Chart



Appendix E: Subsystem Hierarchy



Appendix F: Electrical Interfaces