Vanderbilt University

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Vanderbilt University Robotics
Systems Engineering Report

NASA Robotic Mining Competition

2017 - 2018

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1 Introduction

1.1 Competition Purpose

As the Earths population increases and its natural resources deplete, it is essential that the world looks to the solar system for its surplus of natural resources. The aerospace industry has made huge strides towards interplanetary travel, and Mars colonization missions are now on the horizon. It is not feasible to frequently supply natural resources from Earth due to launch costs and the lead time on interplanetary travel. With the recent discovery of hydrated minerals in the Martian regolith, it is clear that In-Situ Resource Utilization (ISRU) would be essential to the development of a sustainable Mars civilization. Therefore, it is necessary to develop autonomous robotic systems for efficient water collection on Mars. The NASA Robotic Mining Competition (RMC) was established to promote the development of Mars excavation rovers and inspire the future generation of engineers to pursue ISRU technologies. Each team is tasked with designing, building, and testing a robotic excavation system in a simulated Martian environment.

1.2 Problem Statement

The robot must be capable of mining and depositing at least 1 kg of icy regolith simulant in a collector bin within 10 minutes. The mining arena consists of a 7.38 meter by 3.88 meter container with three zones: the starting zone, obstacle zone, and mining zone. The robot begins the competition run in the starting zone with an unknown orientation and must traverse the obstacle zone, mine gravel from the mining zone, and return it to the collector bin. Performance of the robot is quantified using a point system. Points are awarded and deducted based on the amount of collected gravel as well as design parameters including the mass of the robot, energy consumption, communication bandwidth utilization, level of autonomy, and dust-free operation.

To simulate the limitations in the Mars environment, the robot must also adhere to certain operating limitations. The robot cannot use sound ranging systems, barometers, magnetometers, GPS, hydraulics, foam cells, or foam-filled tires, as these technologies do not work in the Martian environment. This constraint necessitates researching novel solutions to challenges which already have well-established solutions on Earth.

1.3 Purpose of Systems Engineering

The Vanderbilt Robotics Team followed a systems engineering design process outlined by the V-chart presented below. The excavation robot has many conflicting constraints and multiple subsystems that all need to perform equally well in order to accomplish the presented challenge. The systems engineering process provides a structured methodology to optimize competing requirements and available resources. It provides a holistic, big-picture approach to the decision making process.

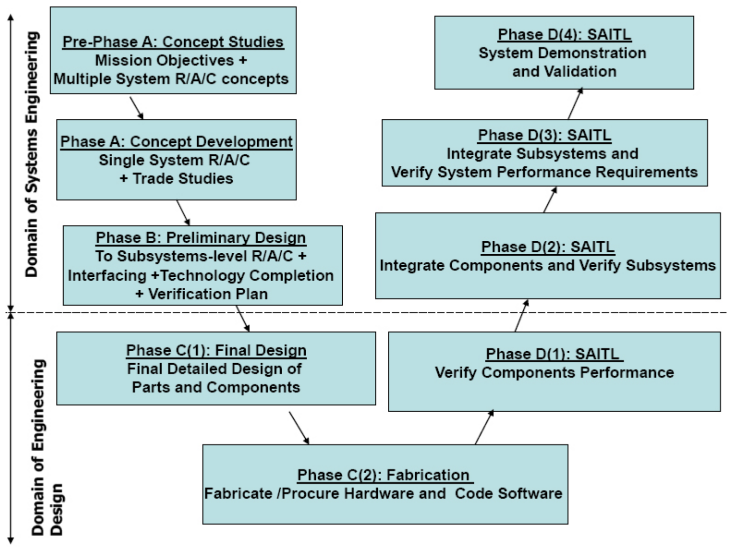

Figure 1: Systems Engineering Vee Chart

2 Systems Engineering

2.1 Concept Development

2.1.1 Design Philosophy

An entirely new rover design had to be developed for the teams first year competing in the RMC. With so many design parameters, it was essential to identify a few key design considerations to focus the brainstorming and concept development process. The team focused on maximizing gravel collection, optimizing all systems for autonomy, and simplifying the fabrication process.

Optimizing gravel collection was the highest priority. The rover must excavate gravel to fulfill its main purpose. Weight and power requirements were considered as well, but it was decided to provide the weight and power necessary to reach the desired goal of excavating 40 kg of gravel. Autonomy was also essential to the design, as the success of future manned missions to Mars depends on reliable autonomous robotic aid. All systems were optimized to be fully autonomous, with the implementation of SLAM and path planning algorithms a major priority for the programming team. With only a nine month project timeline, it was important to eliminate complexity with the use of off-the-shelf components. Stock parts increase system reliability since they are manufactured to higher tolerances than possible in-house. Fabricating custom parts increases lead time and halts progress on dependent systems. However, the team decided to fabricate custom parts when needed so to not limit the design process.

2.1.2 System Requirements

The robot was designed according to the system requirements defined by NASA as well as requirements defined by Vanderbilt Robotics. The system requirements were classified by the following categories: functional, performance, and budget. All of the requirements are presented in Tables 1 and 2 below.

Functional
The robot shall fit within dimensions of 0.75 m x 1.5 m x 0.75 m at the beginning of the competition run.
The robot shall weigh no more than 80 kg.
The robot must report the amount of energy it has consumed since its power-on.
Performance
The robot must be able to capable of collecting and depositing a minimum of 1 kg of icy simulant within 10 minutes.
The robot shall be designed to minimize dust kickup and have a dust tolerant design.
The robot shall be able to function fully autonomously and failover to human control in the case of an error.
Budget
The robot design shall be complete and verified by May 1, 2018

Table 1: NASA Defined System Requirements

Functional
The robot must be capable of elevating the collected simulant a minimum of 3 inches above the height of the collector bin.
Performance
The robot must be able to capable of collecting and depositing a minimum of 10 kg of icy simulant within 10 minutes.
Budget
The project cost for development of the robot shall cost no more than $8000.

Table 2: Vanderbilt Robotics Defined System Requirements

2.1.3 System Hierarchy

The system hierarchy is depicted in Figure 2. The frame consists of the structural base of the robot, drive system, and the power distribution systems. The drivetrain was designed for direct drive. Without a suspension system, it was important to be able to control each wheel independently to maneuver obstacles and improve turning capabilities. The excavation system must dig through BP-1 and collect gravel. It was considered making these two independent processes so to not collect BP-1. The collected gravel The robot controller software handles all input and output for the robot and maintains a state machine for higher-level control of the robot. The autonomy module includes all of the sensors for localizing the robot and mapping the environment. Additionally, all of the software associated with localization, mapping, and path planning are included in the autonomy module. The teleoperation module provides the human robot drivers with control inputs and data readouts. The autonomy module and driver station interface with the robot controller identically.

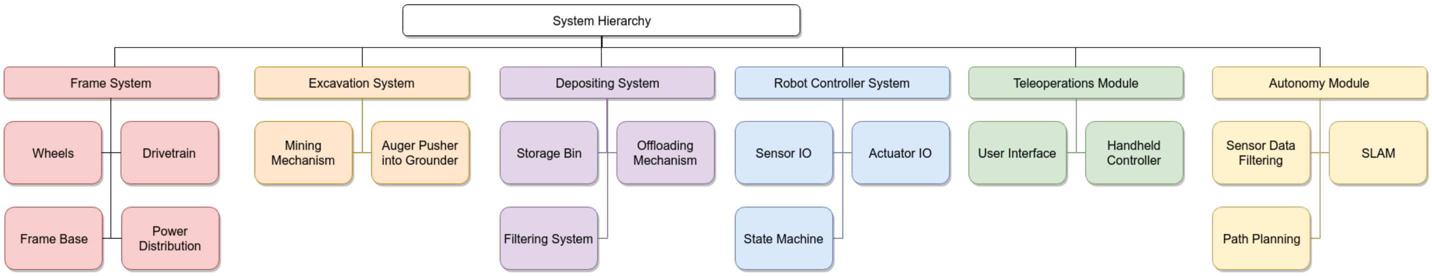

Figure 2: Robot System Hierarchy

2.1.4 Concept of Operations

The concept of operations are described in Table 3 below. The order of operations was derived from the system requirements and key design considerations listed in Section 2.1.2.

Setup	Place robot at starting location and set up control station
	Power on robot and establish network communication link
	Perform calibration for sensor and control systems on the robot
Competition Start	Autonomously scan environment to determine current pose
	Navigate to excavation zone while avoiding obstacles
Excavation	Mine gravel until section is depleted or storage limit is reached
Post-Competition Run	Record power consumption and turn off the robot
	Clean the robot to remove particulate
	Verify system integrity for next round

Table 3: Robot Concept of Operations

2.1.5 System Requirements Review

On October 15, 2017, the executive team members met with the teams faculty advisor and reviewed the system requirements in preparation for the preliminary design process. The system requirements were confirmed to align with the teams design philosophy and the competition objectives.The system hierarchy was well modulated to allow for efficient task distribution and system integration. The team agreed that the concept of operations was the correct approach to satisfy both NASAs requirements and the team-imposed autonomy and gravel collection requirements. The team received approval to proceed to the next design phase.

2.2 Preliminary Design

Each system on the robot went through multiple design iterations during the preliminary design process. Significant background research was conducted into the Mars environment, potential excavation systems, drivetrain, and path planning and SLAM implementations. Trade studies were combined with testing to determine the best and most realistic rover design.

2.2.1 Drive System

Significant research was done on the drive systems of other RMC teams from previous years. Many robots encountered wheel slippage and struggled to maneuver out of steep ditches. The primary goal of robot drive system was to provide traction in BP-1 and avoid obstacles and ditches in the terrain.

Two potential drive mechanisms were considered: a 4-wheel direct drive and tank tread drive. A trade study for the drive systems considered is shown in Table 4. Both systems present unique fabrication challenges. The tank tread drive has more moving parts than the wheels, but the wheels would require significantly more custom manufacturing since few off-the-shelf wheels are available that meet the system requirements. As a result of the increased number of moving parts, the tank tread drive is also less power-efficient than the four wheel direct drive. Both systems present unique fabrication challenges. The tank tread drive has more moving parts than the wheels, but the wheels would require significantly more custom manufacturing since few off-the-shelf wheels are available that meet the system requirements. As a result of the increased number of moving parts, the tank tread drive is also less power-efficient than the four wheel direct drive. The ability to independently drive each wheel improves maneuverability and stability when climbing obstacles. However, this comes at the cost of increased control system complexity over the tank tread drive. The 4-wheel direct drive also provides redundancy as the system is fail-operational in the case a of single drive motor failure. Due to the simple design implementation and the increased maneuverability, the four-wheel skid-steer system was selected.

Factor	**Weight**	**Tank Tread Drive**	**Score**	**4-Wheel Direct Drive**	**Score**
Fabrication	0.7	8	5.6	4	2.8
Obstacle Avoidance	0.9	7	6.3	9	8.1
Control System Complexity	0.6	9	5.4	6	3.6
Power Efficiency	0.4	5	2	9	3.6
Obstacle Traversal	0.7	8	5.6	7	4.9
Reliability and Simplicity	0.6	4	2.4	9	5.4
Total			**27.3**		**28.4**

Table 4: Trade Study Matrix for Drive System

2.2.2 Wheels

The wheels were designed to find a compromise between traction, obstacle-traversal ability, weight, and build complexity. The preliminary wheel design can be seen in Figure 3. The wheels have a 30 cm diameter to be able to climb over smaller obstacles. Based on research into rover wheel design, the team determined that grousers were required to provide traction in the loose BP-1. 12 grousers were chosen to be a good compromise between traction and a smooth ride to vibration and sensor noise. The red spacers are 3D printed to fasten the grousers, wheel sides, and rim together. 6061-T6 aluminum was selected due to its low weight, relatively high strength, and machinability.

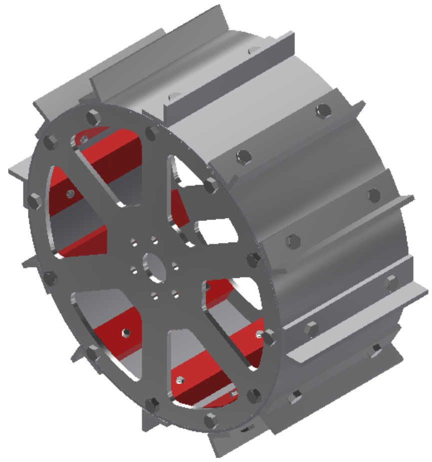

Figure 3: CAD model of preliminary wheel design.

2.2.3 Excavation

The driving requirement for the excavation system was to dig through the 30 cm of BP-1 and collect the gravel underneath. The primary design considerations for the digging mechanism were reliability, dust tolerance, complexity, and weight. Research was performed on existing digging mechanisms in the mining industry. Refer to Table 5 for a trade study of the designs. The backhoe and bucket wheel excavator were eliminated from the solution space as they are primarily effective for surface mining. The bucket wheel excavator is capable of removing a large amount of material, but it does not fit within the size constraints of the robot., but its large size would make it hard to fit within the size constraints.

The chain trencher would be able to excavate significantly more gravel than an auger. However, the power requirements are immense, which is why chain trenchers are always gasoline-powered. After consulting with engineers at Ditch Witch, it was determined that a chain trencher of the correct scale for the RMC would require at least 4 HP to run. This power requirement was not worth the increased gravel collection. The auger was the teams chosen digging mechanism. It provided a compromise between weight, power consumption, and the mass of gravel collected. The biggest concern was whether the auger would be able to excavate large gravel particles, as augers are generally used for liquids and fine particulate. The team ran experiments to test the augers ability to dig through sand and gravel with a tube covering that funnels up gravel. The tube covering was successful in allowing material to be conveyed up the blade. Refer to Appendix A for data from the experiment.

.	Cost	Fabrication	Power	Operative Complexity	Robustness	Scoring Potential	Mass	Ease of Integration	Size	
Decision Weight:	**0.1**	**0.15**	**0.1**	**0.05**	**0.05**	**0.2**	**0.1**	**0.1**	**0.15**	**Weighted Score**
Auger and Tube	8	8	7	8	6	3	6	5	7	**6.15**
Chain Trencher	6	8	1	9	7	10	2	3	2	**5.5**
Bucket Excavator	6	5	4	7	3	1	7	10	6	**4.05**
Plow and Back-hoe	5	5	4	5	2	2	3	2	2	**3.2**
Circular Excavator	5	2	6	8	3	6	2	7	1	**4.2**

Table 5: Trade Study Matrix for Digging Mechanism

2.2.4 Depositing

Excavating the icy regolith with an auger requires additional systems to sort, hold, and deposit the collected material. Since the auger needs to be on either the front or back end of our robot, placing our depositing system on the opposite side removes the need to rotate the robot after leaving the excavating zone. This is replaced however, with the new requirement of transporting all collected material from one side of the robot to the other. Our original, and most abstract design, was a sieve, over a collection bin, which emptied into a conveyor. This three part system was combined into one conveyor, featuring a volume capacity to hold our predicted maximum of gravel, the ability to quickly deposit into the collector bin, and a plastic mesh as the conveyor belt allows the BP-1 to be sorted without need for an additional mechanism. This combination of mechanisms allowed for great simplifications and fewer possible points of failure.

2.2.5 Autonomy

The autonomy module is responsible for localizing the robot and providing control commands to navigate the robot around the field. The following requirements were defined for the system:

- The autonomy module shall be capable of localizing the robot from an unknown starting position
- The autonomy module shall be able to detect and avoid obstacles such as boulders and ditches
- The autonomy module shall be capable of navigating the robot back and forth from the starting zone to the mining zone
- The autonomy module shall communicate with the robot controller with standard control commands
- The autonomy module shall be able to detect failover to human control in case of an error mode

Multiple sensor options for localization and obstacle avoidance were researched. 2D/3D LIDAR systems, cameras, Microsoft Kinect (Figure 4), telemetry sensors such as encoders, and inertial measurement units were all considered. These sensors were each evaluated based on performance parameters such as update rate, computational complexity, price, and noise.

LIDAR based systems were considered due to their widespread use in mapping and localization tasks such as self-driving cars. LIDAR produces high-resolution depth maps of the environment and function well in environments with limited visibility. However, many 3D LIDAR sensors, which produce a three dimensional scan of the environment, are cost-prohibitive and are not feasible within the teams budget. While some 2D LIDAR systems fall within the budget,they only produce a planar scan of the environment. Since the obstacles on the field are low to the ground, it would be difficult to find a suitable place to mount the LIDAR system on the robot.

Figure 4: The XBox Kinect, V1

In order to localize the robot using a camera system, fiducial markers are often placed at a predefined location to serve as a landmark. The robot then determines its pose using a coordinate transformation. The OpenCV library has pre-built functions for determining robot pose by detecting AruCo markers, which are binary square fiducial markers. This method of localization is advantageous because the time required to implement is relatively low compared to other options. However, since the camera is operating in the visual light spectrum, it may be prone to error measurement due to dust kickup. Additionally, ranging with a single camera may not be as accurate because it relies solely on the relative image size instead of time of flight measurements or stereoscopy.

The Microsoft Kinect is a robust, low-cost, 3-dimensional vision system. The Microsoft Kinect outperforms LiDAR systems in dusty conditions due to its use of structured light three dimensional scanning. [1] The kinect has an extensive amount of libraries for collecting and utilizing data for depth mapping and feature detection that could be adapted to match the autonomy module requirements.

An Inertial measurement unit (IMU) measures acceleration and angular velocity at a high refresh rate. However, since double integration is required to estimate position, the error accumulation rate makes the data unreliable. Instead, an IMU can be used in combination with encoder telemetry data on the drive motors to correct wheel slippage error. By comparing the acceleration and angular velocity measurements from the encoder to the expected values based the IMU data, erroneous data can be eliminated and the wheel velocities can be adjusted to correct for slippage

Based on research conducted for each sensor system, it was determined that the best suited option for the robot would be a combination of a Microsoft Kinect, a camera for AruCo marker tracking, an inertial measurement unit, and encoders for telemetry data. The camera, encoders, and IMU will be used to localize the robot while the Kinect will be used to track obstacles on the field.

2.2.6 Robot Controller

The robot controller is responsible for interpreting sensor inputs, controlling motors, and making autonomous decisions. Each of these tasks have different hardware requirements. Sensor interpretation and motor control require a variety of IO protocols and real-time operation, whereas autonomy requires high computational power and the ability to parallelize operations (see Figure 5). Each of these systems must also maintain low profiles to fit in a restricted space and must minimize power consumption. Multiple low-powered computers were considered:

- Raspberry Pi provides a high level of community support and computational power, but remains limited by its IO, lack of real-time operation, and ARM architecture.

- Arduinos provide a large amount of IO but provide very little computational power and difficulty interfacing with Linux based controllers.

- BeagleBone Black provides similar IO to an Arduino with Linux support but lacks computational power.

- BeagleBone Blue has the most IO ports and interfaces of the considered controllers. Its layout is designed for robotics applications and for interfacing with common sensors and actuators.

- The UP Board provides the best computational power whie maintaining the form factor of the Raspberry Pi, but draws substantially more power and retains the Pis limited IO.

The BeagleBone Blue was selected to meet the high level of connectivity required on the robot and the UP Board was selected to provide the computational power required by the autonomy module.

The robot controller software must support a high level of performance, interface with open-source robotics software, and run across multiple connected controllers. However, it also must be simple enough to minimize the training time required for novice team members to begin contributing to software development.

Based on these criteria, ROS (Robot Operating System) was identified as the primary software platform for the robot controller. It provides access to an extensive collection of pre-written robot libraries, greatly reducing the amount of code that needs to be written. In addition, ROS provides a network layer

[1] C. Hall, "Comparing the Performance Of Structured Light Depth Sensors and Traditional Time-of-flight Depth Sensors For Use in a Lunar Mining Environment", Master's, University of Alabama, 2014.

for running applications across a network of devices, supporting the requirement of easy communication between devices on the controllers distributed system.

ROSMOD, an application developed by the Institute for Software Integrated Systems at Vanderbilt, allows for the development of distributed ROS applications in a graphical user interface. It simplifies code development by abstracting the hardware from the software. All software is ready to run on any device connected to it which meets the software requirements. ROSMOD helps to reduce the large amount of knowledge and boilerplate code required to properly implement distributed systems in ROS. The final decision was made to use ROSMOD to gain the full advantages of the ROS library with an easy way to develop and deploy code.

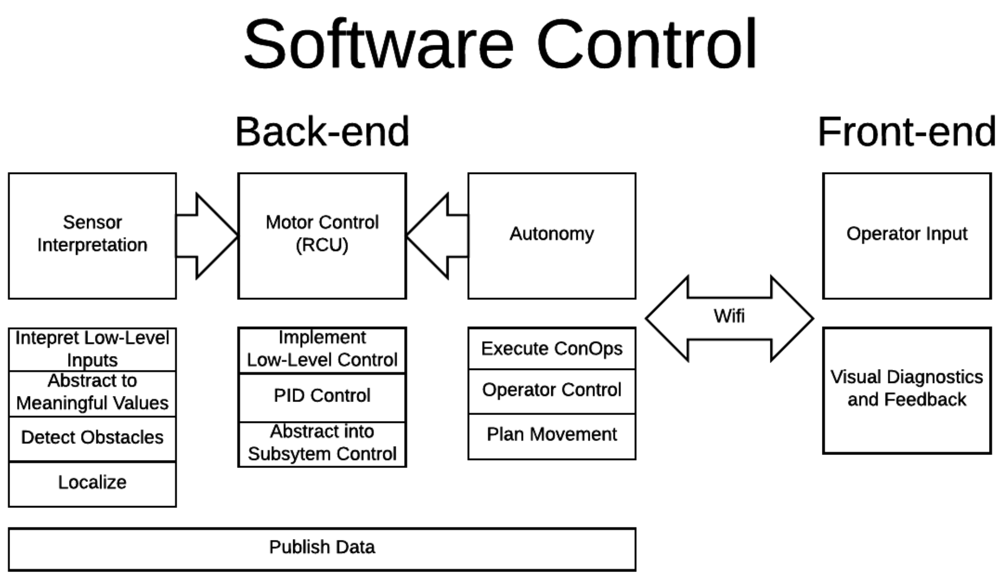

Figure 5: Robot Controller flow diagram

2.3 Preliminary Design Review

On January 10th, the executive team members met with the teams faculty advisor to review the proposed preliminary designs. The preliminary design of each subsystem was verified to satisfy the design requirements. The team was cleared to move on the final design stage.

2.4 System Assembly and Testing

2.5 Project Management

2.5.1 Work Schedule

2.5.2 Cost Budget

2.5.3 Management Structure

Team members were distributed among three subgroups, mechanical, electrical, and programming, based on their area of interest and expertise. Members of each subteam were assigned to specific subsystems of the robot and worked in cross-disciplinary groups with other members from each subteam to fully design the subsystem. The purpose of the cross-functional groups was to ensure that all aspects of the design are considered simultaneously. Each of the subteams were managed by a subteam lead, whose responsibility was to allocate work and track progress for the design of their respective part of the robot. The subteam leads reported their progress to the team captain. The captain was responsible for tracking objectives, facilitating integration between various subteams, and ensuring that the high-level requirements are met.

2.6 Technical Management

3 Conclusions

By applying the systems engineering process, Vanderbilt Robotics has developed a robotic excavation system to collect icy gravel simulant in a Martian environment. With the experience and prototype developed this year, the team expects to continue to optimize the design of this robot to maximize other factors such as power and mass efficiency.