Vanderbilt University

2301 Vanderbilt Pl Nashville, TN 37235

Vanderbilt University Robotics
Systems Engineering Report

NASA Robotic Mining Competition
2017 - 2018

April 10, 2018

Dr. Nabil Simaan: Faculty Advisor

VANDERBILT®
SCHOOL OF ENGINEERING

Contents

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.

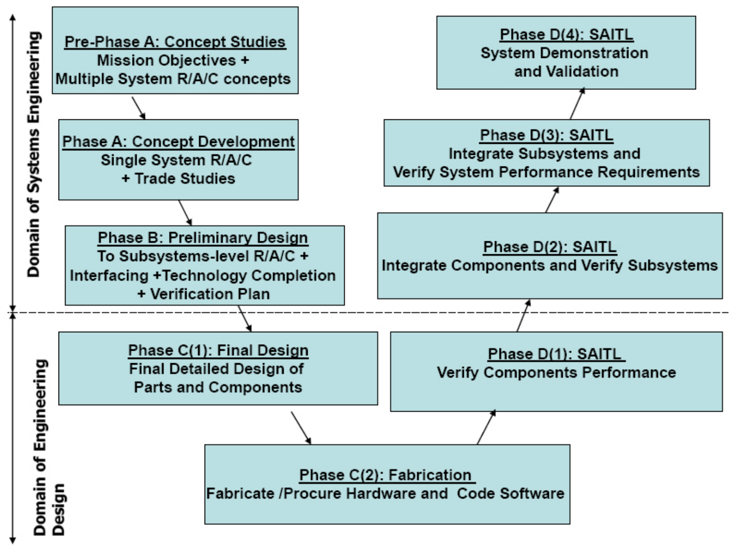

Figure 1: Systems Engineering Vee Chart

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.

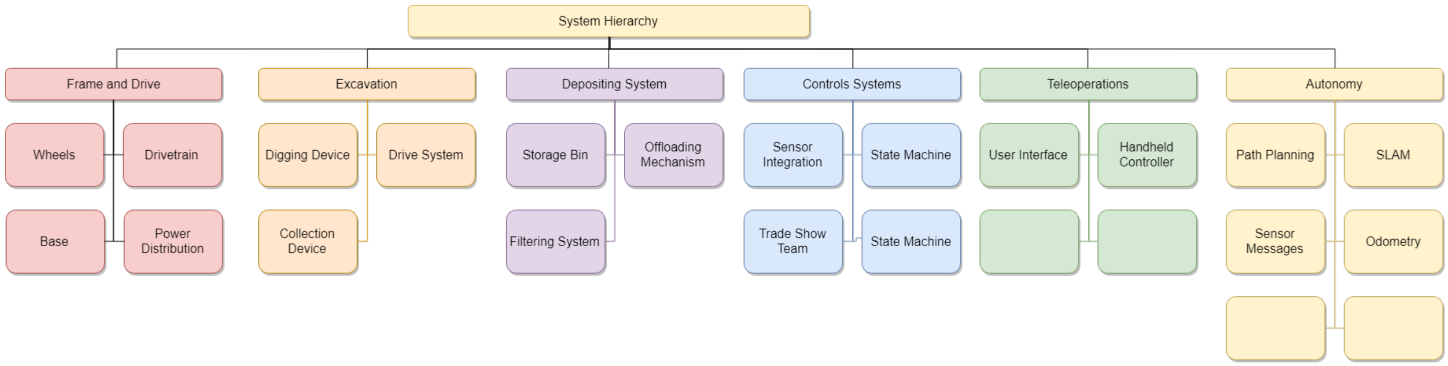

Figure 2: Robot System Hierarchy

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 qfor next round

Table 3: Robot Concept of Operations

2.1.5 System Requirements Review

On September 28, 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

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 Figure X 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.

2.3 System Assembly and Testing

2.4 Project Management

2.4.1 Work Schedule

2.4.2 Cost Budget

2.4.3 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.

2.5 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.