Systems Engineering for the Design and Fabrication of a Screw-Propelled Automated Martian Regolith Collector Robot

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Abstract

The Screw-Propelled Automated Martian Regolith Collector Robot Version 2.0 system was designed by a team of students from Washington University in St. Louis through the implementation of an iterative and increasingly detailed design process directed by a systems engineering management plan. The team made decisions based on Key Performance Attributes and a set of functions allocated from NASA specifications. The team derived the robot's physical architecture from these functions and principal fabrication was completed by the team. The completed system was entered in the sixth annual Robotic Mining Competition at Kennedy Space Center in May 2015 where the team was ranked 10th out of 46 teams.

Keywords

Systems Engineering; Systems Architecture; Robotic Mining, Screw-Propelled Automated Regolith Collector

System Architecture

Design Philosophy

1) Introduction

In the spring of 2015 the Washington University in St. Louis Robotic Mining Club (WuRMC) adapted a full systems engineering program for the implementation of their Screw-Propelled Automated Regolith Collector (SPARC) Robot. Systems engineering is an interdisciplinary process that allows for the hierarchical reduction in ambiguities of an infinite solution space in order to realize the best possible solution to a complex problem (Blanchard, 2011). It is a heuristic driven application of an overarching program which controls the transition of capability to an operational and suitable system. The WuRMC applied this systems engineering approach across the entire project life cycle from ideation to design to fabrication, integration, and testing.

FIG. 1 WURMC’S SCREW-PROPELLED AUTOMATED REGOLITH COLLECTOR
In this paper the system is defined as the SPARC V-2.0, its components, attributes, interfaces, and their interaction with the environment (Fig. 1) (Blanchard, 2011). These four elements comprise the foundation of systems engineering. The system’s environment is defined as the operational setting of the Sixth Annual NASA Robotic Mining Competition, which was held in May 2015 at the Kennedy Space Center (KSC, 2014).

Through an iterative design process the team was able to specify requirements, allocate functions, derive a physical architecture, and perform several trade studies for the selection of the best fit subsystems. WuRMC adapted a system architecture with specific application and organization of the system engineering process and tools following the specifications in the NASA’s Systems Engineering Processes and Requirements Handbook version 2012 (NASA, 2012).

The system architecture of SPARC V-2.0 is represented by the V-diagram in Fig. 2. Along the leading diagonal is the System Design Process which includes the Stakeholder Expectation Definition, the Technical Requirements Definition, the Logical Decomposition, and Design Solution steps. These steps represent an iterative and increasingly detailed design process starting with the customer (NASA) needs and ending with a mature mining robot design. The following diagonal represents the Product Realization Process and includes the Product Implementation, Product Integration, Product Verification and Validation, and Product Transition steps. These steps represent an increasingly more complex integration of components until the complete system is capable of executing the intended capabilities. The center section in Fig. 2 describes the Technical Management Process which calls out the various planning and management lines that were monitored.

![Fig. 2 WuRMC's SYSTEMS ENGINEERING PROCESS](image)

2) Stake Holder’s Expectation Definition

The first step of any systems engineering process is to clearly articulate the desires of the customer. This step is crucial to the success of the system because ultimately it is the satisfaction of the customer that dictates the success of the project. The customer in this interaction is the NASA Mining Robotics Competition Entity (KSC, 2014). This process begins with a need statement.

The expressed need is for a remote controlled or autonomous robot that is capable of transporting itself across a simulated Martian chaotic terrain of loose regolith, craters and boulders collecting regolith at depth and transporting and ultimately depositing the regolith into collection bins (KSC, 2014). The purpose of this competition was to engage university students in addressing and solving some of the challenges that would be encountered by the future planetary pioneers.

The next step for both the systems engineer and the customer is to expand upon the needs statement with a list of requirements. These requirements, when fulfilled, should meet the intended needs of the customer, and should be detailed and specific enough so that they can be included later in the System Design Process. The ability of the system to meet design requirements was tested in the Product Verification stage. For this competition the customer’s requirements were detailed in the competition’s 2015 Rules and Rubrics document (KSC, 2014), and state of the art planetary mining technologies were researched (Boucher, 1999; Boucher, 2004; Dissly, 2004; Feng, 2009; McKay, 1992; Stoker, 2004; Taylor, 2004).

The WuRMC team divided the competition requirements into three categories: static requirements, active requirements, and logistical requirements. The static requirements represent the innate on-robot structural attributes such as mass and volume restrictions. The motor requirements explain the operational needs and...
actionable capabilities of the robot, and include data volume, power usage, startup and shutdown procedures, and completion operations. The logistical requirements refer to requirements that do not directly apply to the robot functions, but are required by the competition such as task timing and safety protocols.

3) Technical Requirements Definition

Once the customer and system engineer have agreed on the design requirements, the system engineer turns these requirements into a more detailed set of specifications that the participating team engineers can include in the design. This is done in a top down fashion with form following function. The primary function that the team’s robot seeks to accomplish is to robotically mine planetary regolith. In order to accomplish this, three principal actions are required, which can be described as "the three d’s": Dig, Drive, and Dump. This colloquial summary can be allocated into a series of technical functions. These functions are traverse (drive); excavate (dig), deposit (dump), and the latent functions (Fig. 3). Latent functions are actions the robot must be capable of carrying out in order to accomplish all other functions, but they do not tie directly to a single function. Each of these functions flows down into more detailed sub-functions under each heading. These functions represent the capabilities of the system, that is what the system will be able to accomplish once it is functional.

4) Decision Analysis

The decision making process is of paramount importance to any engineering project. The team decided as a group on their Key Performance Attributes (KPA). These attributes describe the system performance, what the team values in the system, and drive how trade-off decisions for the design phase were made. The KPAs were prioritized to allow efficient decision making, and are displayed in a Kiviat Chart (Fig. 4). Kiviat Charts are a quick way to assess how well a system meets its desired attributes. The goal is to maximize the area within the Kiviat. If the system as a whole scores is less than 12, or any one KPA score is less than 2, the system will be deemed unacceptable. The preferred score would be 18, with not more than one KPA below 3. The team’s final system assessment Kiviat can be found in section 2.4.5 in the Performance Summary. The team selected the following attributes as the system’s KPAs:

1. **Functionality**: A measure of how well the system actually operates in response to commands and the environment.
2. **Excavation**: Maximization of the amount of regolith mined and returned to the dump site.
3. **Producibility**: A measure of the proposed design’s ability to be fabricated given the team member’s skills and timeline.
4. **Innovation**: Approaches to the design problems that are considered new and creative.
5. **Automation**: A measure of how well the robot operates without any human operation.

Within the scope of this system, decisions were driven by the prioritized KPAs. These decisions were made in iterative phases of increasing detail so that other subsystems could stay up to date with the whole design as the
system matured. Many of these decisions were made through the application of trade-off studies and are detailed in section 2.3 describing the Design Selection.

![Diagram of Key Performance Attributes](image)

**FIG. 4 IDEAL KIVIAT ASSESSMENT OF KPA’S**

**Project Life Cycle**

The team’s project life cycle followed the systems engineering v-diagram dividing the design process into conceptual, preliminary, and critical phases. Each of these phases became increasingly more detailed and had unique exit requirements. The conceptual design phase consisted of open brain storming periods where all ideas were considered. This process included the entire team and from the variety of ideas, a general concept was agreed on. Based on the target KPAs and function capability, the team decided to design a reciprocal-excavation, screw-propelled mining robot (Boucher, 2004). These two primary systems were chosen to give the best chance of functionality maximizing the regolith return, and still resulting in an innovative design.

1) **Schedule**

The team stayed on schedule through the preliminary design phase. However, the critical design phase, which involved several detailed trade studies ended up taking much longer than was anticipated. The team ended up prototyping and began preliminary fabrication while still completing the critical design reviews. This was not ideal, since usually the completion of the critical design review preceded the beginning of fabrication. The team also ran into unanticipated issues such as procurement of the rotating screws (drive pontoons) from Australian tailings mining company ‘Residue Solutions’. However, the basic frame design was mature enough that subsystems fabrication could begin in late January of 2015. The delay on pontoon specifications and complexities in the final set of critical design trade studies caused a delay in the team's Critical Design Review. However, additional time reserve was built into the schedule for this kind of unforeseen situation; thus the internal due dates were set well before the external due dates allowing the team to meet the competition deadlines.

The major internal deadline of 13 April 2015 got the team motivated and back on track with completion of the robot. However, this left the team about a month behind the final phases of the originally planned schedule. Therefore, system integration, testing, training, travel logistics, and verification were completed simultaneously by dividing tasks among different team members, and the team was able to compete at the end of May 2015 to meet the NASA competition deadline.

2) **Major Reviews**

Each of the three design phases had an exit requirement of a design review. These were conducted at varying levels of detail as was required by the level of design. As described previously, the conceptual design review included the entire team. Members submitted their conceptual level designs, sketches and ideas and the team discussed the merits, draw-backs and potential of each idea. Once each major subsystem was whittled down to one or two concepts, the conceptual level review was completed. Decisions were documented and the groups
were assigned to investigate the remaining major design decisions. Major trade-offs were completed which are discussed in section 2.4.1 on Trade-Off Assessments.

The Preliminary Design Review (PDR) was a structured and formal design review and the WuRMC team had an actual organization (Residue Solutions) to interact with. In the conceptual design review, the WuRMC team decided to go with the unique and innovative screw propulsion system they had pioneered a year before in 2014 competition. The team’s principal company sponsor, Residue Solutions, utilizes screw propulsion for major mining, mineral processing, and land reclamation equipment. For the PDR the WuRMC team sent design documentation and basic robot specifications to be reviewed by the Residue Solutions engineering team. The Residue Solutions team sent back comments and questions regarding the screw flight angles and spacing. The WuRMC team responded to the comments and questions, and the pontoon external design was finalized with the help of Residue Solutions. This review also required a near final estimate of weight, size and speed to be selected. The objective of the PDR was to get external feedback on the team’s in-process design, the finalization of one major subsystem, the traverse system, and the vetting of these systems specifications in order for the pontoon hardware to begin production. The selected design specifications are given in section 2.3 on Design Selection.

The Critical Design Review (CDR) was more rigorous and included a detailed report on the system design and constituted the team’s proposed final design. This documentation was sent to Residue Solutions, who acted as a stand in for the competition entity, and the team’s faculty professor. Ideally this CDR would have been completed before principal fabrication began, but due to challenges described above the design were not finalized until late March of 2015. Once the comments on CDR documentation from the Residue Solutions were received and addressed, the team officially closed the Critical Design Phase. The objectives of the CDR were to have at least two experienced engineers from two different entities examine the team’s final design and provide comments to the team. The review of these comments and the implementation of any final alterations or adjustments constituted the exit requirements of the CDR.

**Team Management**

1) Work Flow

The WuRMC team designed their Work Breakdown Structure (WBS) to reflect the project execution and team’s needs (Fig. 5). The elected team leadership was placed into upper management positions while team members with experience in technical fields were put into positions where their direct experience would be most useful. New team members were assigned to specific projects or sub-teams. In 2014, the team arrived at competition behind schedule and with robot one inch too wide. In 2015, the team operated with several levels of management reserve built into both the design and team operation. Three team members were assigned the specific duties of managing power, data, and mass and volume budgets, and were responsible for ensuring that at no point the design would exceed any of the limiting specifications. The management team allotted reserve time in the schedule in order to allow the inevitable schedule creep, and made sure to raise enough funds to ensure a margin of safety for last-minute procurements.

![FIG. 5 WuRMC'S WORK BREAKDOWN STRUCTURE (WBS)](image-url)
2) Cost Budget

The team had a very successful fundraising campaign and raised a total of $7,400 from various sources including Washington University in St. Louis, corporate sponsorships, and research grants. The team also secured significant donations in parts and equipment, the most notable of which was the donation of a 2-D Laser Scanning LiDAR system from SICK incorporated with a $7,000 off-the-shelf value. The team’s principal sponsor also donated the drive pontoons, valued at $1,500 in materials. These contributions drove down the technical costs of the team significantly, and allowed excess money to be allocated for the entire team’s transportation needs to the competition site. The team created an estimated budget based on year 2014’s procurements, and carefully monitored the year 2015’s spending.

System Design & Fabrication

Concept of Operations

1) Operation Control Diagram

The flow of operations is summarized in the OV-1 operational control document (Fig. 6). There are two phases of operation: remote control (yellow) and autonomous (orange). For the remote control human-in-the-loop operation there is a necessary telemetry feedback loop. Humans send commands via the wireless blue tooth connection to the onboard rover transmitter/receiver, a panda wireless-N USB adapter. Data travels from the receiver and is relayed to the onboard computation center, a Raspberry Pi. The Raspberry Pi relays control commands to the Arduino Uno microcontroller which communicates by PWM and series signals to the slave Sabertooth 2x6 and Talon SR motor controllers. The Sabertooth and Talon motor controllers control the drive and dig motors respectively. The team receives telemetry from the Raspberry Pi in the form of camera feed and power data.

During autonomous operational control, the wireless communication, camera feed, and human command station are completely removed from the system. The LiDAR system collects a 3-dimensional point cloud in which the robot locates itself. Then the Raspberry Pi uses this information to make decisions about navigation and execute the predetermined excavation routine. Once the robot collects a full dump receptacle of regolith, it autonomously traverses and deposits the regolith in the competition collection site. This process continues until the competition run time has expired. During this whole operation the robot streams its camera feed to the command station to allow the humans to monitor the robot’s progress. If at any time the robot performs off-nominally, the team has the ability to get into the system and return to human-in-loop control operations.

![FIG. 6 SPARC 2.0 OPERATIONAL CONTROL DOCUMENT](image_url)
Logical Decomposition

1) Systems Hierarchy

The SPARC V-2.0 system was designed through an iterative, top-down approach. The team worked through a series of increasingly detailed design phases and made decisions based on the KPAs. The team allocated a set of functions which the system was capable of completing and from these functions derived the robot's physical architecture. The principal fabrication work was completed by two sub-teams: a Mechanical sub-team and an Electrical sub-team. The Mechanical sub-team machined all the aluminum frame parts, connectors, and housings, while the Electrical sub-team programmed and wired all the electronics.

2) Physical Architecture

The SPARC V-2.0 robot's physical architecture is derived from the system functions (Fig. 7). The physical components are grouped into four sub-systems: the Traverse, Excavation, Deposition, and Latent sub-systems. These sub-systems comprise all physical components of the robot. The Traverse sub-system comprises of the drive pontoons, the drive motors, the batteries (located within each pontoon), and the traverse motor controllers. It also comprises the general on-board computing, wireless communication, and mapping sensor. The Excavation sub-system includes the excavation receptacle and excavation motor system, while the Deposition sub-system consists of the regolith receptacle and deposition mechanism (Boucher, 2004). The remaining components fall into the Latent sub-system. These include the general frame, power distribution, and safety and support electronics. Structural components are discussed in detail in section 2.2.3.1.

3) Interfaces

The connection points between all the components are important sources of potential failure and must be monitored closely. The internal connections are represented using interface control documents. The system's interaction with the environment is another important level of interaction and is already represented with the OV-1 operation control document.

3.1) Structural Components

The SPARC V-2.0 robot's structural interfaces show how the different sub-systems physically interact. The drive motors, controllers, and power source are within the drive pontoons (Fig. 8). The remaining electrical and computing components, power distribution, and communication components are housed in the electronics box. This box and the pontoons are fixed to the robot frame. Also fixed to the frame are the excavation and deposition systems. These two components are structurally fixed to reduce the number of required actuators and reduce the complexity. The same actuators that lower the reciprocating excavation system raise the attached deposition system for regolith delivery. The SPARC V-2.0 is constructed out of t6-6061 aluminum, and measures 1.45 m long, 0.74 m tall, and 0.70 m wide.
3.2) Electrical and Data Components

The electrical and data interfaces are very important to plan for both the design and its implementation. These are detailed in the following wiring diagram, which is also a graphical representation of the electrical and computing interfaces (Fig. 9).

Figure 9 shows the following components:

a) Two 12V Batteries provide electrical power for the robot.

b) Emergency Stop Button allows for emergency battery disconnect.

c) Stinger SGP38 Relay disconnects the batteries when E-Stop is triggered.

d) Eagle Tree eLogger V4 provides power consumption measurement. Each logger measures the power output from one battery.

e) Eagle Tree PowerPanel displays the power consumption of the robot.

f) Blue Sea Systems DualBus Bus Bars provide power distribution throughout the robot.

g) Sabertooth 2x60 Motor Controllers are used to control the drive motors speed.

h) CIM Motors are used to rotate the drive pontoons, and for digging system.

i) Pololu 5V, 5A Step-Down Voltage Regulator lowers the voltage from 12V to 5V in order to power the Raspberry Pi.

j) Pololu 24V Step-Up Voltage Regulator raises the voltage from 12V to 24V in order to power the Sick LMS111 laser.

k) Raspberry Pi acts as primary computing module on the robot.
l) Sick LMS111 laser provides positioning data for autonomous operation.

m) Panda Wireless-N USB Adapter provides networking capability to allow the robot to communicate wirelessly.

n) Arduino Uno relays commands from the Raspberry Pi via USB to other electrical components using digital, PWM, and serial signals.

o) Talon SR Motor Controller provides motor control for the digging motor.

p) The SainSmart 8 Channel Relay Module provides on/off control of the actuators in the digging system.

q) PA 02-24-200 linear actuators are used for the digging system.

**Design Selection**

Once the physical architecture was derived, the next stage of the iterative design cycle - the detailed subsystem design and part selection began. First this was completed at a preliminary level to decide between major design options and then at a critical level to bring the design to completion. These were principally completed in a series of trade-off studies. These trade-off studies were given to small groups of specialized team members who completed investigations that ranged from research to prototyping to modeling. The ultimate decisions of the trade-off studies were driven by the team’s Key Performance Attributes.

1) **Trade-off Assessments**

Here only two of the trade-off studies completed by the team are highlighted. These trade-off studies were done as a part of the design process to make informed decisions. Other trade-off studies that were completed but are not described in this paper included: excavation trade-off (front loader vs. backhoe vs. reciprocating digger), deposit system trade-off, computing hardware trade-off (Raspberry Pi vs. Tablet), sensor mounting trade-off (telescoping vs. pivoting), and a materials trade-off (aluminum vs. composites vs. carbon fiber).

1.1) **Power Supply Selection Trade-off Study**

In order to select an appropriate power supply system, the team completed a trade-off study. After research the team down-selected and sourced three different battery options: a Sealed Lead Acid, a Lithium Iron Phosphate, and a Nickel Metal Hydride battery. Each of the batteries was evaluated in seven categories derived from the KPA values. The categories were prioritized and given relative weights (Fig. 10). This resulted in the selection of the Lithium Iron Phosphate as the battery of choice.

![FIG. 10 POWER SUPPLY SELECTION TRADE-OFF STUDY MATRIX](image)

1.2) **Traverse Design Trade-off Study**

The team ultimately selected rotating screws as the propulsion method for terrain traversing. This was selected after evaluating several traditional drive mechanisms. The screw propulsion outperformed all the other mechanisms in every KPA. In 2014, this drive system proved very capable in the BP-1 regolith, and easily handled maneuvers and obstacles proving its functionality. The screw-propulsion is the most innovative propulsion system in the field.
Screw-propelled vehicles use one or more cylinders fitted with helical flanges to navigate terrains typically characterized by high sinkage (Stein, 2014). Two-cylinder screw-propelled vehicles such as SPARC V-1.0 and V-2.0 are capable of forwarding and backwarding (longitudinal) motion during which the pontoons are rotated inward and outward respectively, and in side-to-side (lateral) motion in which the pontoons are simultaneously rotated in the drive direction (Stein, 2014). During lateral drives, the screws can be treated as long, non-deformable wheels with motion dominated by shear-stresses between the cylinder surface and the soil (Stein, 2014). Ignoring flight-soil interactions, lateral motion is controlled by motion resistance ($R$) and traction ($T$) which are related to normal and shear stresses as $T = \tau \cos \theta$ and $R = \sigma \sin \theta$ where $\tau$ and $\sigma$ are shear and normal stress respectively, and $\theta$ is the angle between the side of the screw and the terrain at the exit point (Fig. 11) (Stein, 2014). In deformable surfaces such as lunar regolith, $\tau$ and $\sigma$ are a function of soil properties including cohesion, internal friction angle, and shear modulus (Wong, 2001). Traction and motion resistance are functions of wheel sinkage. Due to the large area of the screw-terrain interface which reduces surface pressure, screw-propelled vehicles are characterized by relatively low sinkage that minimizes motion resistance and maximizes traction (Stein, 2014).

During longitudinal drives, the vehicle is propelled by interactions between the flanges and surrounding medium with efficiency proportional to the helix angle (Fig. 12) (Stein, 2014). Variations in helix angle affect multiple parameters including ground deformation, drawbar pull and slip, although no single angle optimizes every parameter (Cole, 1961).

The SPARC V-2.0 Mobility Design consisted of two 91.45 cm long, 15.25 cm wide aluminum tubes with oppositely threaded 3.8 cm high continuous aluminum helix grousers each driven by 88:1 geared 12 V 6.35 cm CIM brushed DC motors (Stein, 2014). Motors and batteries were mounted on an axle within the pontoons, which were shielded from dust by PVC endcaps that served the additional purpose of bulldozing material during longitudinal drives. A helix angle of ~25° was selected to balance motor efficiency with slip and drawbar pull (Stein, 2014). The team presented this screw propulsion design at the 14th ASCE International Conference on Engineering and at the 2015 Lunar Planetary Science Conference (Stein, 2014).
1.3) Torque Selection Trade-off Study

The next level of detail was addressed with a complimentary trade-off study to select the optimal torque. The team member completing this trade-off created a model to evaluate various inputs to output relationships which allowed the team to quantitatively select the appropriate level of torque required (Fig. 13). The model computed current, speed, power, and efficiency plotted as a function of torque for a generic CIM motor. The model was developed using motor performance research (FIRSTintern, 2015). As the model stepped from no torque to stall torque, the RPM changed linearly.

The gearing ratios from year 2014 competition were used as an input to determine the torque output from the motors. If the current is known, the unguarded torque of each motor can be derived. Multiplying the torque by the gearing ratio gives the total torque, which is used to derive the revolutions per second. The model allowed the team to understand how changing various factors affected the ultimate drive torque of the robot, and allowed a quantitative decision to be reached.

Management of Fabrication and Testing

The systems engineering process starts at the top and guides the design and implementation phases of the project all the way to product delivery. However in both the design and implementation phase (see v-diagram in Fig. 2), there was an active level of internal monitoring and evaluation that constituted the Technical Management Process. Internal monitoring is the glue which holds the v together in Fig. 2, and was divided up into sub-disciplines and was delegated to different team members to monitor as various phases occurred.

The initial plans were laid out to incorporate management reserves. For example, there was a conscious effort to ensure that the year 2015’s robot would not exceed the volume restrictions which required major last-minute adjustments in year 2014’s competition. There was also management reserve built into the schedule, which allowed for the inevitable schedule creep. One of the most important aspects of keeping a team on track was inter-team communication. This was facilitated through weekly group administrative meetings beyond the weekly work periods, at which sub-systems were evaluated and updates were given. Major decisions and plans were documented and were sent out as electronic tag-ups allowing absent members to stay informed, and ensuring that changes were adequately documented.

1) Technical Budgets

The first technical budget required consideration of the mass and volume restrictions. The competition rules required the mass limit to be 80 kg, with penalty points for each kg of the robot’s total unloaded mass. The volume limit was 1.5 m length x 0.75 m width x 0.75 m height. A team member was assigned to monitor both of these metrics through the entire design phase and was responsible for letting the team know if the potential design decisions were in jeopardy due to exceeding of the dimensional and/or weight restrictions. The ultimate decision to build the robot out of aluminum came out of a materials trade-off study where it was determined that aluminum offered the best strength to weight ratio, and was within the team’s fabrication capability.

Volume was also monitored by the configuration manager, who organized the physical layout of the internal electronic components within the electronics box. This was done in a fashion to minimize complexity in wiring to minimize the total volume and thus the weight.
The data budget was the responsibility of the chief programmer. He advised the computing decisions and hardware selection accordingly. The competition rules stated that the average maximum bandwidth use must be less than 5 Mbps average. However it was in the interest of the team to keep the bandwidth as low as possible since every 50 Kbps results in a point deduction. The team used the NASA provided camera, which started the team off at a base data usage of 120 Megabits. In year 2014, the team used an average of 8 bps, but SPARC V-2.0's maximum usage was 32 bps. There was no telemetry feedback to the operating team members; this was a design decision to keep the transmitted bandwidth as low as possible. There was also a data cost due to the use of WiFi and TCP/IP. The code ran on the onboard Raspberry Pi, which counted toward the total number of packets sent. In testing, the team was able to predict the robots data consumption for a typical run.

The team’s electrical lead was responsible for monitoring the projected power production and consumption. The power supply was two 12.8 V, 12 Ah, 153.6 Wh rechargeable Lithium Iron Phosphate batteries. Based on a ten minute run, the SPARC V-2.0 consumed 80 watt hours of energy, which was an estimated 25-30% draw out of the total power source. The batteries contained enough power to perform both competition runs on a single charge.

2) Reliability

One of the most important duties of the technical managers was to ensure that the product was reliable. This meant that the product could safely execute its intended capabilities within the operational environment. Safety was the first priority of the group. Nothing within the team’s scope was worth endangering anyone and themselves. This was handled on two fronts. First the robot itself was designed with safety in mind. The team implemented the required off-the-shelf voltage meter in order to allow the competition entities to monitor the power situation, and intervene or remove personnel from a potentially dangerous situation. The team also considered safety during the design process, and the robot was equipped with a well labeled easily accessible emergency stop button.

The second part of project safety included the actual team operations. The team went through safety training for access to the campus machine shop, encouraged people to work in pairs, and followed common sense safety protocols. The other aspect of reliability is that the system can actually complete the assigned functions completely and satisfactorily and consistently. The team evaluated the system’s performance in both of these categories through implementing system technical assessments for verification and validation

3) Verification

The process of product verification is a measure of how well the system meets the needs and requirements of the customer. This can be best evaluated by examining the initial requirements which were used to inform the design process, and to determine if the product actually met these requirements. As previously stated, the WuRMC derived the requirements from the competition rules and rubrics, and divided them into three categories, static requirements, active requirements, and logistical requirements. Each of these three different categories required a different approach to verification.

The static requirements mostly pertain to the robot’s structural and physical attributes such as mass and volume. These were straightforward to verify and their compliance was guaranteed by taking static measurements of the robot and comparing them to the requirements of the customer. The SPARC V-2.0 met all the prescribed innate static requirements.

The active requirements were more complex and required a full system operations test. The test involved putting the robot through several steps of the competition run both in selected sub-operations and in full operation. These tests included excavation tests where the team practiced recovering regolith from different depths and traverse tests where the team practiced driving the robot across mocked up terrain and obstacles, and deposition tests where the robot deposited various payloads into a model reception bin. The final set of tests was a series of timed full operation practice runs. These tests took place in a reduced scale test pit. These tests evaluated the robot’s ability to meet the operational functions as defined in Fig. 3. The robot was able to accomplish all intended operational tasks required in the competition in these tests. This was made possible due
to the team’s commitment to delivering an operational robot to the competition, as has been previously articulated in the paper through having set functionality relative to the primary KPA’s.

The final set of verification tests was designed to address the logistical requirements. These requirements concerned competition logistics such as timing and safety protocol. The final round of motor tests was timed, allowing the team to be able to evaluate how the robot performed under competition conditions. The robot regolith collection was slower than was desired, but this allowed the team to address options to boost recovery rate. The robot passed all safety tests in the implemented safety hardware.

4) Validation

The process of product validation usually involves the customer and its assessment of the systems performance. Ideally the initial steps of deriving the needs statement, requirements, functional allocation, and further design flow down should be carried out reasonably well so that the ultimate product is what the customer desires. However this is not always the case, that is why customer’s interaction is very crucial in the early phases of the process. The validation of SPARC V-2.0 occurred at NASA’s Sixth Annual Robotic Mining Competition, held at the Kennedy Space Center from the 18th to 22 May 2015. This competition was NASA’s opportunity to evaluate SPARC V-2.0 in action. The team did their best to design to the customer’s satisfaction, which was the fundamental purpose of adopting a systems engineering process. The team competed against 46 other university teams from across the country. In order to transport the robot to competition, the team disassembled the entire robot and had to re-assemble it onsite. Unfortunately the re-assembly contaminated the pontoons and created motor control issues resulting in some performance problems during the two runs of the robot. Despite these challenges, the team’s final score placed WuRMC in 10th place.

System Summary

Performance Summary

Prior to competition at Kennedy Spae Center, the performance of SPARC V-2.0 was assessed using the data collected during the tests run at Washington University by conducting the Kiviat assessment (Fig 14). This assessment graphically shows how well the system performs in each of the five KPA’s. In order to pass this assessment the robot’s individual KPA value should be greater than two on one to five scale, with a total score greater than 12. The preferred score for SPARC V-2.0 was 18, with not more than one KPA below a 3. The Kiviat assessment ranked Functionality as 4/5, excavation as 3/5, Producibility as 5/5, Innovation as 5/5, and Automation as 3/5. The robot functioned well, but not perfectly. The robot turned out to be very dependable and quite innovative with the employment of screw propelled drive system. Its total KPA score was 20. This score met an acceptable system performance metric. Unfortunately, the robot’s overall performance in the 2015 competition at Kennedy Space Center was less than nominal due to problems resulting from onsite re-assembly, power management, and water contamination in the competition site.

![Key Performance Attributes](image-url)


**Screw-Propelled Automated Martian Regolith Collector Robot**

**Systems Engineering Summary**

In the 2015 NASA Robotic Mining competition, WuRMC team adopted a full systems engineering approach, incorporating an iterative design cycle, KPA and function driven design choices, and a much more extensive verification, validation, and testing regime. As a second year team in 2015, WuRMC was able to build upon the baseline robot from the 2014 competition and incorporate the concept of management reserve into the project. The higher level of planning and attention to details helped the team to address problems and implement the best solution comprehensively. The team demonstrated itself to be capable to address the challenge of planetary regolith mining. There were necessary evolutions of plans, schedules and even designs over time as the team learned or discovered new things, but these were implemented within the procedures, styles, and resources of the systems engineering process. Through the systems engineering process, the team was able to meet the competition’s requirements, designing an innovative robotic excavation platform that could remotely recover planetary materials. In this manner, WuMRC hopes to contribute to NASA and the nation’s vision of a bright future in space exploration.

**ACKNOWLEDGEMENTS**

The last author of this paper is Dr. Ramesh Agarwal who served as the team’s faculty advisor. Fabrication and storage space, and machine shop tools were provided by Washington University in St. Louis.

**REFERENCES**


