MIT: MoRETA

Citation: Miller, D (2009). MoRETA: *CDIO Knowledge Library*, Cambridge, Mass: CDIO Global Initiative, www.cdio.org

1. Project Overview (1 page)[1]

1.1. Overall goal or purpose

The MoRETA project was established in order to develop and validate a modular rover design capable of conducting a wide range of high impact science operations in a variety of extreme terrains under both direct and remote human guidance in order to maximize the scientific return per cost of future Lunar and Martian rovers.

1.2. Societal context and relevance

The success of the Mars Exploration Rovers (MER) during their missions has demonstrated the importance these rovers have in the exploration of planetary surfaces. Future rovers bound for Martian and Lunar surfaces will need to be more autonomous, capable of assisting astronauts, and able to perform multiple tasks in order to truly return the highest value for the mission. Furthermore, the most interesting scientific samples are located in areas of extreme terrains. For example, meteorite impacts and erosion expose layered bedrock on steep slopes which contain material holding clues to Martian geological, hydrological, and biological history such as those seen in the inner wall of "Endurance Crater". These terrains result in a need for a more mobile and versatile rover as such extreme terrains pose a high risk to the current rovers.

1.3. Integration (e.g., where project fits in a course, program, or curriculum)

MoRETA ran as a three-semester capstone project as part of the MIT Aero-Astro course 16.83x.

1.4. Description (e.g., complexity, duration, group size and number, budget)

The MoRETA project spanned three semesters with nearly 70 students participating in the first semester. Due to the structure of the class, enrollment drops each semester; the second and third semesters had 65 and 23 students respectively. The materials budget for the project was approximately $30,000.

1.5. Learning activities and tasks (brief summary)

High level tasks for the MoRETA Project organized by semester:
Semester 1 (12 Units): Informal Review, Engineering Analysis, Subsystem Requirements Finalized, Systems Requirement Review (SRR), First Iteration of Conceptual Designs, Informal Review, Engineering Analysis, Second Iteration of Conceptual Designs, Conceptual Design Review (CoDR), CoDR Design Document, Informal Review, Preliminary Design Finalized, Leg Prototyped , PDR Design Document, Preliminary Design Review (PDR), Prototype Styrofoam Model of Rover Finished.

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[1] Owing to a number of unique factors, it is extremely unlikely that this specific project (MoRETA) can be replicated. The results of the MoRETA project (*i.e.*, the student work product) is presented here as an guideline for what is involved in the execution of an ambitious, complex 3-semester capstone course.

Semester 2 (12 Units): Informal Review, Engineering Analysis, Second Prototyped Leg Finished, Flight Chassis Finished, Informal Review, Critical Design Review (CDR), Engineering Analysis, Informal Review, Flight Leg Finished, Bench Review (BR), One Full Hip-Leg Module Finished.

Semester 3 (6 Units): Rover Fully Assembled and Wired, Unloaded Leg Testing, Wheel Prototyped, Acceptance Review (AR), Hip-Wheel Design Finalized, Mechanical Light Weighting Finished, Preliminary Joystick Control Integrated with Rover, Flight Wheels Finished, Locomotion Module Begins Sending Gaits, MoRETA GUI Finished, Loaded Leg Testing, Final Design Document Finished.

2. Learning Objectives (1 page)

2.1. Technical objectives (e.g., basic math, science and engineering knowledge, skills, processes and procedures)

- Develop technical specification from detailed customer requirements
- Design and build a complex space-based system
- Analyze the performance of a complex space-based system
- Develop and implement a rigorous testing procedure

2.2. CDIO outcomes (e.g., personal and professional skills and attributes teamwork, communication, conceiving, designing, implementing and operating skills)

2.3.4 Tradeoffs, Judgement and Balance in Resolution
2.4.7 Time and Resource Management
3.1.1 Forming Effective Teams
3.2.6 Oral Presentation and Interpersonal Communications
4.3.1 Setting System Goals and Requirements
4.3.2 Defining Function, Concept and Architecture
4.4.4 Disciplinary Design
4.5.2 Hardware Manufacturing Process
4.5.5 Test, Verification, Validation and Certification

3. Student Instructions

3.1. Project description (e.g., brief description of project purpose and context)

Over the course of three semesters, develop and validate a modular rover design capable of conducting a wide range of high impact science operations in a variety of extreme terrains under both direct and remote human guidance.

MoRETA is comprised of three main subsystems: Mechanical, Avionics and Autonomy, which in turn are broken into subgroups responsible for the specific design of a component on the rover. Each subsystem has had one or more representatives in the systems and integration team during the duration of the project. This team is responsible for the project meeting all high-level requirements and timelines. The Mechanical subsystem is broken into chassis, wheel, leg and foot. The Avionics subsystem is broken into power, orientation, leg & wheel module, and Single Board Computer. The Autonomy subsystem is broken into locomotion, foot placement planning, user interface, and vision/mapping.

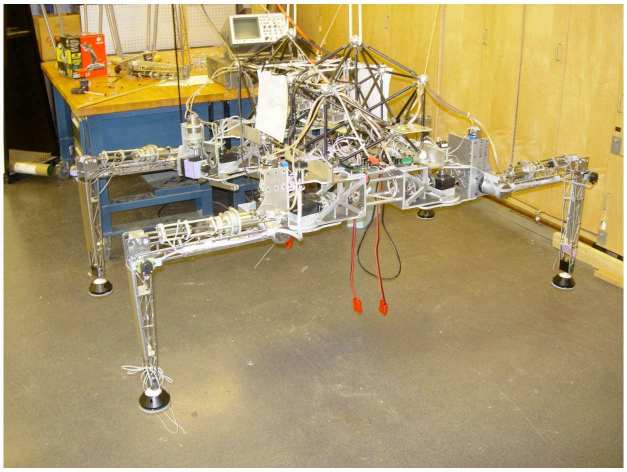


Figure 1: MoRETA Without Wheels Attached

MoRETA is equipped with its own autonomous processing unit, a suite of sensors and actuators accompanied by avionics microprocesssors, a mechanical chassis, wheels, legs and a variety of other components. The overal rover and its conceptual design are shown in Figures 2 and 3 respectively. The entire rover weighs 75 kg as of the spring of 2007, and measures 100 cm in the X-direction, 85 cm in the Y-direction and 85 cm in the Z direction when the rover is in wheeled mobility. Each leg is comprised of two sections which measure 45 cm long giving a maximum leg length of around 80 cm. The wheels themselves measure 22 cm in diameter. The rover is capable of traveling at a maximum speed of 5 cm/sec while in legged configuration and 100 cm/sec while in wheeled configuration. MoRETA is powered via ten 8 amp-hour Lithium Poylmer Cells.

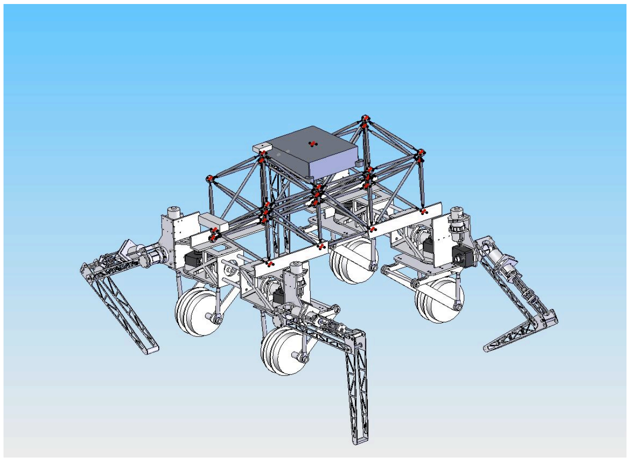
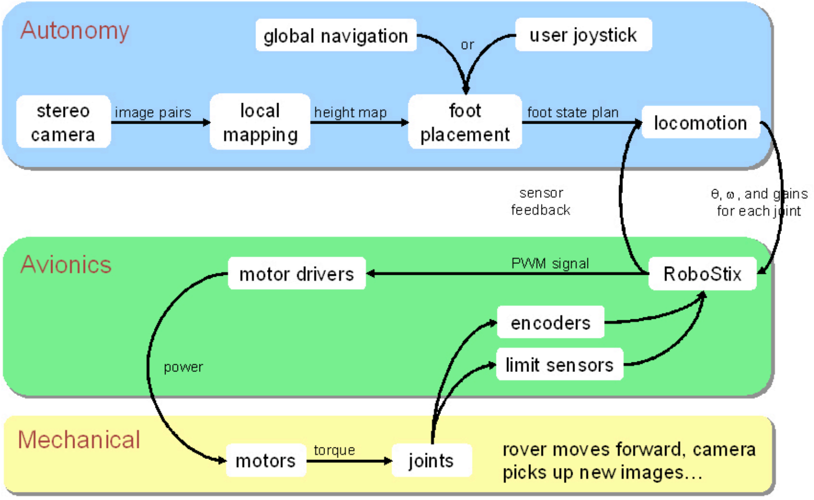


Figure 2: Conceptual Design of the Full MoRETA Rover

MoRETA is capable of autonomously directing itself by means of its onboard autonomy software coupled with robust avionics boards which allow the autonomy commands to be reliably implemented by the mechanical systems. In order to complete its operations, the high level concepts of operation followed:

- The rover captures images using a camera with two lenses spaced apart from one another in order to obtain a stereo-image.
- These image frames are then sent through local mapping algorithms which in turn produce an orthographic map
- The foot placement planning software uses the orthographic maps to create a state plan of steps for the rover to follow. The planning software is capable of receiving direct user input as to the direction for the rover to move to create the state plan or uses a high level global plan that is inputted by a remote user.
- From this state plan a locomotion module determines and sends joint angles and toques to the individual microprocessors located above all four wheels.
- The microprocessors then drive the motors through motor driver chips which move the desired appendage.
- As the rover moves forward, sensors on the wheels, feet and legs feedback their actual angles, rate of movement, location to the microprocessors and locomotion module.
- Simultaneously, the stereo-imaging camera is acquiring more pictures for future movement.

This entire process is illustrated in the high level concept of operations in Figure 3.



3.2. Learning objectives

- Develop technical specification from detailed customer requirements
- Design and build a complex space-based system
- Analyze the performance of a complex space-based system
- Develop and implement a rigorous testing procedure

3.3. Learning activities including specific procedures, tasks, etc.

Three-Term Schedule

Semester 1: February through May

February
22 Informal Review
27 Engineering Analysis
27 Subsystem Requirements Finalized

March
3 Systems Requirement Review (SRR)
15 First Iteration of Conceptual Designs
17 Informal Review
April
3 Engineering Analysis
5 Second Iteration of Conceptual Designs
7 Conceptual Design Review (CoDR)
14 CoDR Design Document
26 Informal Review
May
12 Preliminary Design Finalized
15 Leg Prototyped
15 PDR Design Document
17 Preliminary Design Review (PDR)
17 Prototype Styrofoam Model of Rover Finished

Semester 2 — September through December

September
- 19 Informal Review
- 28 Engineering Analysis
  - 28 Second Prototyped Leg Finished
  - 28 Flight Chassis Finished

October
  - 17 Informal Review
  - 31 Critical Design Review (CDR)

November
- 20 Engineering Analysis
- 28 Informal Review
- 28 Flight Leg Finished

December
- 12 Bench Review (BR)
- 12 One Full Hip-Leg Module Finished

Semester 3– February through May

February
- 15 Rover Fully Assembled and Wired
- 22 Unloaded Leg Testing
- 27 Wheel Prototyped

March
  - 22 Acceptance Review (AR)
  - 22 Hip-Wheel Design Finalized

April
  - 19 Mechanical Light Weighting Finished
  - 30 Preliminary Joystick Control Integrated with Rover

May
  - 1 Flight Wheels Finished
  - 3 Locomotion Module Begins Sending Gaits
- 8 MoRETA GUI Finished
- 10 Loaded Leg Testing
- 17 Final Design Document Finished

3.4. Assessment criteria and standards

The grade is composed of both individual performance and team performance. In addition, since is a Communication Intensive (CI) course, a significant portion of the grade comes from the student's ability to complete both written and oral communication. Also, because the class depends heavily on team work, note that attendance to class is expected and will form part of your final grade. Figure 4 shows how the grade of each student will be composed.

Figure 4-. 16.83 Spring 2008 Grading Scheme

Assignment	Individual %	Team %
Presentation – TARR (technical)		5
Presentation - CoDR (technical)		5
Presentation - PDR (technical)		5
Presentation - CI	5	
Mentor	25	
Peer	5	
Attendance	5	
Short Presentations	5	
Portfolio - Technical	15	
Portfolio - CI	10	
Design Document - Technical		10
Design Document - CI		5
Total	**70**	**30**

Because a fundamental principle of academic integrity is that you must fairly represent the source of the intellectual work that you submit for credit, it is important that individual contributions to the team effort be properly identified. The student's initials in the subheading of the sections that s/he contributed will be sufficient.

3.5. Equipment, tools, supplies and/or materials

Fully-equipped metal fabrication shop for precision machining. Materials are determined by students as part of design process and obtained as needed. Overall materials budget for MoRETA was approximate $30,000.

3.6. Safety and risk mitigation procedures

None beyond standard shop safety procedures (eye protection, training, supervision, etc.)

3.7. Deliverables (e.g., products, oral and written reports, and/or reflective journals)

The six major design reviews served as the driving force for the project milestones. The six major design reviews and their dates were:

- Systems Requirement Review (SRR) – March
- Conceptual Design Review (CoDR) – April
- Preliminary Design Review (PDR) – May
- Critical Design Review (CDR) – October
- Bench Review (BR) – December
- Acceptance Review (AR) – March

The individual subteams, with the guidance of the systems team and the mentors, set their milestones. Each formal design review had an overarching goal that was to be achieved by that design review. Based on these objectives , milestones typically consisted of incremental improvements towards the design review goal.

The target of the SRR was to have all the requirements finalized and documented. This led to multiple milestones that revolved around what each subteam would do in order to ensure that all of the requirements were achieved at the end of the three-semester project.

The goal of the CoDR was to present a conceptual design of the rover. This led to many milestones revolving around early designs and many possibilities for a final design of the rover.

The objective of the PDR was to present the preliminary design of the rover based upon a downselect of the conceptual designs of the CoDR. Milestones leading up to the PDR involved producing and testing prototypes to support design decisions.

The object of the CDR was to have the design finalized and prototypes produced. This led to milestones focused on producing physical hardware and software and then running tests on them, in order to prove that the CDR rover design was the best design for the rover.

The goal of the BR was to have the physical hardware of the rover produced and the rover assembled and ready for full system integration and testing; this lead to similar milestones revolving around manufacturing, testing, redesigning and manufacturing second and third generations of various hardware and software components.

Lastly, the main object of the AR was to have the rover completely finished and all requirements fulfilled,; this in turn led to the final milestones revolving around finishing up all testing and debugging of the system as a whole.

4. Instructor Guide

4.1. Commentary on conducting the project keyed to the Student Instructions
Attachment: MoRETA Final Design Doc.doc (181 pages)

4.2. Team Organization and Management suggestions (e.g., number of groups and group size, initial organization, and ongoing management)

70 Undergraduates divided into sub-teams. Team organization, management, sub-team assignments guided by staff but ultimately decided by students.

4.3. Assessment

4.3.1. Criteria (e.g., to judge the quality of student products, processes, or performances relative to the learning outcomes and activities)

4.3.2. Methods and materials (e.g., rubrics for oral/written reflection methods, peer/team self-evaluation, assignments, lab reports, and standard quizzes embedded in the learning activities)

Students are evaluated on their contributions to each design review as well as written design documents

5. Resources

5.1. Budget (e.g., recurring and non-recurring expenses)

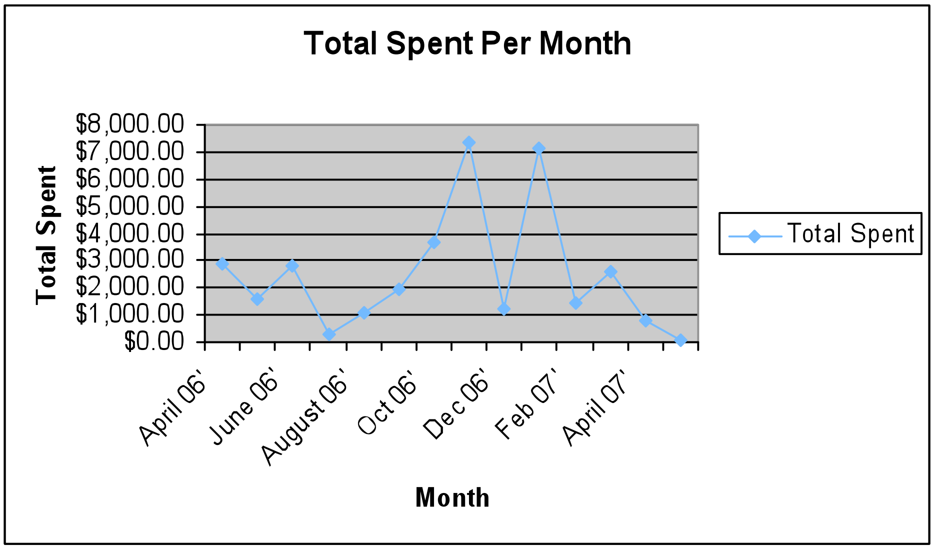


Figure 6: Total Expenses per Month

5.2. Equipment and tools

Fully-equipped machine shop (mill, lathe, etc.) along with normal hand tools.

5.3. Materials and supplies (e.g., reusable and consumable including hazardous materials)

Determined by students as part of project; in-kind donations solicited whenever possible

5.4. Staffing (e.g., describe particular skills and scope of commitment)

2 professors, 3 graduate teaching assistants, 4 technical instructors (during lab hours, 2 electrical, 2 mechanical).

5.5. Spaces (e.g., minimum feasible space requirements per student or per student team, whether space is dedicated or used only during student activity, and use of space for design, build, operate, and storage)

Project (bench-top) workspace for 30 students. 6 workbenches during lab hours; 3 cu. yds. storage.

5.6. Other resources (e.g., computer hardware and software)

6. Safety and Risk Mitigation

6.1. Operational safety

6.2. Governing policies and regulations (e.g., governmental and institutional)

7. Other information, for example:

7.1. Possible variations in the project

The outline of this course is repeated with a different target project every cycle. The most recent iteration of this course (2008-9) designed and built a thruster useful for high-Δv satellites.

7.2. Supplementary multi-media and other resources

See Appendices A & B, Operational Specifications and Original Customer Specifications.

7.3. Sample student products from previous iterations of the project

Appendix A

Operational Specifications:

Described in this section is a set of operational specifications, exploring the limits of the rover's operating ability, *at the time of writing*, May 2007.

1. **Legged Motion Performance**
    1.1. Ability to stand on all four legs:
    -Stability/structural integrity proven under static conditions

    1.2. Ability to stand on three legs:
    -Stability/structural integrity proven under static conditions

    1.3. Operation from suspended position:
    -Full range of controlled motion proven
    -Autonomous locomotion for a single step proven

    1.4. Operation under self-weight loading:
    -Leg controller PCB overheating issues encountered, due to excessive current draw

2. **Wheeled Motion Performance**
    2.1. Ability to stand on four wheels
    -Not yet proven

    2.2. Wheeled operation
    -Not yet proven

3. **Mapping Performance**
    3.1. Local mapping functionality
    -Proven for visually stimulating terrain
    -Minimum object resolution: 5 cm @ 3.5m
    - Stereo processing rate: 5 fps
    - Refresh rate: 1 / minute

    3.2. Global mapping functionality
    -None

4. **Environment**
    4.1. Operation in extreme temperature
    -Not proven

    4.2. Operation in wet/humid conditions
    -Strongly not recommended

5. **User Interface**
   5.1. Operation from a remote computer
   -Ethernet communication proven
   -Wireless communication via 802.11B

   5.2. Interface with rover's computer:
   -GUI available for input of desired joint angles
   -Joystick interface to stop and restart leg motion in case of emergency (inhibit/un-inhibit operations)

6. **Power**
   6.1. Operation from external DC supply:
   -Proven for supply voltage of 22V
   -Maximum Voltage: 26V
   -Mininum Voltage: 18V

   6.2. Operation from on-board DC batteries:
   -Not yet proven
   -Expected battery life: 30 minutes

7. **Speed:**
   7.1. Measured maximum speeds:
   -Hip yaw: 8.3 RPM
   -Hip pitch: 8.3 RPM
   -Knee: 4.5 RPM
   -Wheel: 10 RPM

   7.2. Estimated maximum speed of integrated system:
   -Legged motion: 0.5 cm / s

Appendix B

Requirements Document

This appendix contains four different requirements documents used throughout the MoRETA Project. The four documents are (1) the Original Customer Requirements Document, (2) the Original Functional Customer Requirements Document, (3) the Final Customer Requirements Document and (4) the Final Functional Customer Requirements.

Appendix B.1: Original Customer Requirements Document

This is the original customer requirements document that was given to us by the MoRETA Staff during the first week of the project. All requirements for the project were derived from this document.

NASA PROJECT TEMPLATE MIT MORETA

- 1.0 Must be capable of high speed, wheeled mobility on relatively smooth terrain and legged mobility on rough and steep terrain.
- 2.0 Must have distributed and modular avionics to allow rapid assembly and check-out.
  - 2.1 Hard interfaces between modules can only carry mechanical loads, bus voltage and ground.
  - 2.2 All command and data handling between modules must be wireless.
- 3.0 Must be able to support different concepts of operations
  - 3.1 Direct commanding by astronaut in the field
  - 3.2 Remote control with zero delay
  - 3.3 Remote control with lunar communications delay
  - 3.4 Remote control with Mars communications delay
- 4.0 The rover will be a mobility platform for demonstrating the MERS model-based mobile executive
  - 4.1 The operator would be able to directly control foot placement if desired
- 5.0 The rover must never be able to get into an inverted position
- 6.0 Navigation using on-board and off-board sensors.
  - 6.1 Must have an independent truth sensor
  - 6.2 Scenarios
    - 6.2.1 A priori accurate map
    - 6.2.2 Low resolution or inaccurate map
    - 6.2.3 No map
- 7.0 Bigger than Sojourner and smaller than MER
- 8.0 Must be able to complete the course shown in Figure 1 without the need to recharge batteries.
  - 8.1 Traverse a flat region five (5) meters in length and three (3) meters in width with increasingly difficult rock coverage and a hard and soft (sand) surface.
  - 8.2 Climb a slope of sand at its angle of repose.
  - 8.3 Take an image of a target on a cliff face
  - 8.4 Return to the start line
  - 8.5 Target definition
    - 8.5.1 Target 1 (must): image a surface feature located somewhere below the top of a two (2) meter high. two (2) meter wide cliff.
    - 8.5.2 Target 2 (should): return a >0.5kg surface rock to the start line
    - 8.5.3 Target 3 (should): return a >0.5kg object, buried in the sand slope, to the start line.
    - 8.5.4 Target 4 (could): acquire a sub-surface ice sample and return it to the start line.

- 9.0 Fixturing for solar arrays: The rover design shall have mechanical and electrical connections to allow attachment of solar array(s) for battery charging. For the purposes of this project, the following will be deemed sufficient to satisfy this requirement:
  - 9.1 *Mechanical*: the rover shall incorporate bolt-holes or brackets (a minimum of two) of sufficient strength to attach at least 20 kg of solar panel, in a position on the rover such that affixing a solar panel at that location will not interfere with rover moving parts.

9.2 *Electrical*: the rover shall have an accessible electrical connector that gives access to the battery system, such that the battery can be recharged from an external electrical supply. (The rover does not need to incorporate the battery charger.)
It is not necessary that the project team design the solar array or analyzes the performance under solar power, and the volume and mass of solar arrays are not counted against the rover size envelope and mass budget. The purpose of this requirement is to make sure that the rover design does not foreclose the option to incorporate a system for solar recharging if a later team decides to design one.

10.0 200-m traverse: To demonstrate autonomous operation, the rover shall be able be able to complete a 200 meter autonomous traverse to a designated target across unpaved terrain, operating in wheeled mode, without recharging. The traverse course has the following characteristics

10.1 The 200 meter traverse may, if desired, be implemented as a traverse of 100 meters to a target, followed by a return to the origin.

10.2 The course may contain slopes of up to 10 degrees in either the travel direction or transverse to the travel direction

10.3 The course may require the rover to detect and navigate around one or more obstacles, but will not require the rover to drive over rocks.

10.4 The definition of "unpaved terrain" means that the rover should be designed with the ability to demonstrate the traverse on either of the following surfaces. (The actual decision on which surface to run the demonstration on will be made depending on time and weather constraints later; the rover should be designed to traverse either.):

10.4.1 Briggs Field
10.4.2 A dry, sandy beach, above the high-tide mark.

The 200-m traverse requirement is separate from the course requirement (8.0); that is to say, the rover does not need to complete both the 200 meter traverse and the rock/hill/cliff course on a single charge.

Appendix B.2: Original Functional Customer Requirements

This is the original functional customer requirements document that was derived by taking the original customer requirements and expanding it to fully include all the requirements needed to successfully build MoRETA to meet the customer requirements.

1. Mobility
   1.1. General
      1.1.1. The rover shall be capable of legged and wheeled motion.
         1.1.1.1. The rover shall be capable of forward and backward motion.
         1.1.1.2. The rover shall be capable of side to side motion.
      1.1.2. The rover shall be able to maneuver in limited (dimensions) space (e.g. get back off cliff after climbing).
      1.1.3. The rover shall be equipped with be able to determined its orientation.
      1.1.4. The rover shall never be rendered immobile.
         1.1.4.1. The rover shall never become inverted.
         1.1.4.2. All legs shall be operable under sand.
         1.1.4.3. The rover shall not be vulnerable to anticipated wheel traps and ditches.
         1.1.4.4. The rover shall maintain balance while in legged mode
            1.1.4.4.1. While stationary.
            1.1.4.4.2. While in motion.
      1.1.5. Loads
         1.1.5.1. Each wheel and leg shall be able to support weight of rover and payload and maximum impulse possible on course.
         1.1.5.2. Wheel and leg assembly shall be able to support torques induced on structure (and payload) from turning.
      1.1.6. The rover shall be stable and controllable during all operations.
      1.1.7. The rover shall be able to transition from wheeled mobility to legged mobility.
         1.1.7.1. In any rover orientation.
         1.1.7.2. The rover shall be able to decide when to transition from wheeled to legged mobility.
      1.1.8. The placement of the rover's legs shall be able to be controlled by a human operator.
      1.1.9. The human operator shall also be able to control emergency stopping at any time with one simple command.
      1.1.10. Be able to support closed-loop control with optional open-loop functionality in the case of the driving system.
      1.1.11. Wheel/leg sensors (should this be a subset of the previous).
   1.2. High speed mobility on smooth terrain, where smooth terrain is defined as a surface with incline no more than TBD degrees and obstructions no more than TBD in size and a soil bearing load of no less than TBD.
      1.2.1. The rover shall maintain a course across smooth terrain at no less than TBD m/s.
      1.2.2. The rover shall be able to stop from full speed within obstruction detection range.
      1.2.3. The rover shall have ground clearance of no less than TBD(while wheeled motion).

- 1.3. Legged motion on extreme terrain, where extreme terrain is defined as a surface with incline no less than TBD degrees or obstructions no more than TBD in size or a soil bearing load of no less than TBD.
  - 1.3.1. The rover shall be able to climb up and down the angle of repose on Martian sand in a Martian environment.
  - 1.3.2. The rover shall be able to walk over or around objects no more than TBD in size.
  - 1.3.3. The rover shall be able to walk through extreme terrain as defined by rock distribution given in Golombeck model.
  - 1.3.4. The rover shall have ground clearance of no less than TBD(while in legged motion).
- 1.4. Mobility on Sand
  - 1.4.1. The rover must be capable of moving over sand.

2. Observation/Sensors
   - 2.1. Rover Information
     - 2.1.1. Velocity-Measurement System
       - 2.1.1.1.The rover shall be able to return its current velocity to the operator while using wheels and while using legs (JWB)
       - 2.1.1.2.The avionics shall include sensors to support requirement 2.1.1.1
       - 2.1.1.3.Acceleration when on wheels.
       - 2.1.1.4.Acceleration when on legs.
     - 2.1.2. Location Identification
       - 2.1.2.1.The rover shall be able to return its current location with respect to a local coordinate frame to the operator (JWB)
       - 2.1.2.2.The rover shall be able to return its current global coordinates to the operator (JWB)
       - 2.1.2.3.Rover must know it's location with respect to
         - 2.1.2.3.1. home.
         - 2.1.2.3.2. target
     - 2.1.3. The avionics shall include health Sensors (temperature, battery)
   - 2.2. Environmental Information
     - 2.2.1. The rover shall have an imagining system (JWB)
       - 2.2.1.1.The rover shall have panoramic imaging capabilities (JWB)
         - 2.2.1.1.1. The panoramic imaging system shall be able to image 360 degrees of footage about the rover's current location (JWB)
         - 2.2.1.1.2. The panoramic imaging system shall have wide angle capabilities (JWB)
         - 2.2.1.1.3. The panoramic imaging system shall be able to take color images (JWB)
         - 2.2.1.1.4. The imaging system will allow for digital zoom after images are returned to operator.
         - 2.2.1.1.5. The imaging system shall be able to take a picture of the rover in its current environment (JWB)
       - 2.2.1.2.The rover shall have an imaging system for detecting ground hazards in front of and behind the rover (JWB)
       - 2.2.1.3.The rover shall have an imaging system for detecting objects beneath the rover

2.2.1.4.The rover shall have an imaging system for showing the position and placement of the legs

2.2.1.4.1. The cameras shall be able to take video and still images (JWB)

2.2.1.5.Actuate all imaging systems.

2.2.1.6.Aids for autonomous navigation

2.2.1.6.1. The rover must sense the impedance ahead

2.2.1.6.2. The rover must detect range to target.

2.2.1.6.3. The rover must detect range to obstacles and other geological features.

2.2.1.6.4. The rover must be able to acquire target.

2.2.1.6.5. The rover must be able to have images of sufficient resolution to identify potential targets.

2.2.2. Other Environmental Information

2.2.2.1.The rover must detect the drop off of the horizon

2.2.2.2.The rover must detect when it is on top of cliff.

2.2.2.3.The rover should sense positional change from angled to flat.

2.2.2.4.The rover must be able to detect composition of new ground

2.2.2.5.The rover must be able to detect the weather conditions necessary for making a decision about proceeding with mission.

3. Sample Acquisition/Scientific Data Collection

3.1. Target1: imaging a surface fossil with a digital camera

3.1.1. The camera should be able to take a surface image of an object 2 meters below the rover in the vertical direction.

3.1.2. The camera should be maneuverable in three dimensions, with a range of 2 meters in the vertical direction, 2 meters in the horizontal direction, and 0.5 meters in the direction perpendicular to the surface being imaged, and should have a position accuracy of 0.5 cm

3.1.3. The camera shall be held motionless while the image is taken

3.1.4. The camera must be able to take a high quality color image of a 10 cm by 10 cm surface area from a distance of 15 cm.

3.1.5. The camera should be able to auto-focus on a surface area selected by a human operator

3.1.6. The camera could be able to be focused manually by an astronaut in the field

3.2. Target 2: returning a surface rock

3.2.1. The rover should accurately align capture mechanism with rock, and g back to search if the rock is missed.

3.2.2. The rover should be able to pick up a rock on the surface with a diameter in the range of 3 cm to 15 cm_weighing no more than 0.5 kg

3.2.3. The rover should be able to pick up a rock on the surface with a diameter in the range of 3 cm to 15 cm weighing from 0.5 kg to 1 kg if the exact location of the rock is given to the rover in reference to its current position

3.2.4. The rover should be able to store up to two rock samples in a secure manner and operate functionally with the rock samples.

3.3. Target 3: digging into sand for sample location and collection purposes

3.3.1. The rover should be able to probe, without digging, up to 0.15 meters into loosely packed sand

3.3.2. The rover should be able to carry out probing when under direct human command mode
3.3.3. The rover should return information to the human operator on the resistance offered by the sand, particularly if the probe encounters a solid object
3.3.4. The rover shall be able to dig into loosely packed sand
3.3.5. The location at which the rover will dig shall be input by a human operator
3.3.6. The rover shall be able to remove an object, once located, from the sand
3.3.7. The rover shall align the penetration tool with penetration site.
3.3.8. The rover shall align the penetration tool with ice or sand.
3.4. Target 4: acquiring a sub surface ice sample
3.4.1. The system shall have a camera that shows the view of the drill (downwards under rover)
3.4.2. The rover should be able to drill into an area of rock and return an ice-core sample
3.4.3. This area shall be specified by a human operator
3.4.4. The rover should be able to carry an ice sample in a waterproof storage container.
4. Rover Structure/Modules
4.1. The size of the rover shall be larger than Sojourner smaller than MER
4.1.1. Assembled rover shall fit inside entry shield of dimension .
4.2. The number and type of batteries shall be sufficient to complete all course objectives on a single charge.
4.3. The rover shall feature standard mounts for all avionics and mechanical components.
4.4. The rover body structure must be large enough to fit all avionics components.
4.5. The rover body structure shall be able to resist all stresses anticipated during operation
4.6. Modules
4.6.1. Break-down
4.6.1.1. Drive System
4.6.1.2. External Communications
4.6.1.3. Autonomy (Central Control)
4.6.1.4. Vision (Navigation)
4.6.1.5. Scientific Camera with associated actuator
4.6.1.6. Drill Control
4.6.2. The rover shall feature standardized modular connections for all mechanical and avionics components.
4.6.3. Each module shall have a snap connection.
4.6.4. All connections shall prevent sand from entering the joint.
4.6.5. All connections shall feature standardized electric connections.
4.6.6. Each module shall be able to sustain the anticipated loads of all connecting components.
5. Communications/Feedback
5.1. Be able to support real-time communication of commands.
5.2. Be able to support wireless communication internally and externally.
5.2.1. Each module will be capable of supporting inter-module communications.
6. User Interface/Control
6.1. Mission Specifics
6.1.1. Astronaut
6.1.1.1. The primary operation mode should be direct control. (Autonomy Level 1)

- 6.1.1.2.The controller shall be portable so that the astronaut can easily transport it while traveling across the Lunar or Martian surface.
- 6.1.1.3.The display shall be navigable and controllable by a gloved hand.
- 6.1.1.4.The controller shall be useable in the case when the astronaut can see the rover as well as when the view of the rover is obstructed

6.1.2. Zero Delay

- 6.1.2.1.The primary mode of operation shall be direct control. (Autonomy Level 2)

6.1.3. Earth to Moon

- 6.1.3.1.The primary mode of operation shall allow for direct control or allow a number of operations to be uploaded at one time and carried out in succession (Autonomy Level 1/Autonomy Level 2)

6.1.4. Earth to Mars

- 6.1.4.1.The primary mode of operation shall allow for many operations to be uploaded at one time each day and carried out in succession (Autonomy Level 2)
- 6.1.4.2.The system shall enter a hibernation mode after completing a given set of instructions.

6.2. Direct Control Options

6.2.1. Locomotion control

- 6.2.1.1.The controller display could allow the operator to click on a point in a camera view display and cause the rover to turn or travel in that direction.
- 6.2.1.2.The rover shall be able to travel to a location on the map specified by the operator.
- 6.2.1.3.The operator shall be able to direct the rover to turn left or right a specified number of degrees +/- 2 degrees.
- 6.2.1.4.The operator shall be able to move the rover forward, backward or side to side.
- 6.2.1.5.The operator shall be able to specify the placement of the legs (with respect to the rover)
- 6.2.1.6.The operator shall be able to input a distance for the rover to travel.
- 6.2.1.7.The rover shall have a set-up box that allows input of distance and turning orientation, as well as a “GO” button. (3.0)
  - 6.2.1.7.1. The mobility mode (legged or wheeled) shall be able to be changed (1.0)
- 6.2.1.8.Turning orientation
  - 6.2.1.8.1. Shall be displayed by camera view (3.0)

6.2.2. Could be in 5 degree increments from forward orientation controlled by pointer (3.0)

6.2.3. Drilling for Ice Device

- 6.2.3.1.The operator must be able to align the drill with the desired location

6.3. Display/Monitor Options

6.3.1. Current State of Rover

- 6.3.1.1.Monitor shall show what operation is being carried out
- 6.3.1.2.The monitor shall show the queue of operations
- 6.3.1.3.The velocity of the rover shall be displayed at all times

6.3.2. Cameras

        - 6.3.2.1.The controller display shall allow for the operator to scroll through and view different navigation camera views
    - 6.3.3. Map
        - 6.3.3.1.One of the controller display windows shall show any available map of the terrain.
    - 6.3.4. “Emergency Stop” button
        - 6.3.4.1.Shall always be on the display (3.0)
    - 6.3.5. Mode of leg
        - 6.3.5.1.Shall be displayed on interface (3.0)
    - 6.3.6. The interface shall display the rover’s location relative to its initial mission location (3.0)
    - 6.3.7. The interface shall display orientation
        - 6.3.7.1.From initial location of mission in degrees (3.0)
        - 6.3.7.2.From North in degrees (3.0)
        - 6.3.7.3.Using a single word for which way the rover is pointing (North, Northwest, West, Southwest, South, Southeast, East, Northeast) (3.0)
    - 6.3.8. The interface shall have a display Map (3.0)
    - 6.3.9. The user interface shall show images from the Cliff Imaging Device
    - 6.3.10. The user interface shall know the location and current action of the Sand Probing/Digging Device
        - 6.3.10.1. The display should include the resistance offered by the sand
    - 6.3.11. The user interface shall know the location and current action of the Rock Picking-Up Device
    - 6.3.12. The user interface shall know the location and current action of the Drilling for Ice Device
    - 6.3.13. Self Diagnostic
        - 6.3.13.1. The display shall show the battery life remaining.
        - 6.3.13.2. The display shall show the rate at which the battery is being used
        - 6.3.13.3. The display shall display a warning if interal temperature exceeds safety levels

7. Power
    - 7.1. Be able to power the following systems for entire mission using only the initial energy supply. (e.g. one battery charge).
        - 7.1.1. Communications
        - 7.1.2. Sensors
        - 7.1.3. Processors
        - 7.1.4. Actuators/motors
        - 7.1.5. Data storage
    - 7.2. Operator must know Battery Life and Remaining Rate of Battery
8. Processors
    - 8.1. Be able to support programming by autonomy group
    - 8.2. Be able to support the processing of data in the various modules.
9. Data Storage
    - 9.1. Be able to store images from scientific camera
    - 9.2. Be able to store communication information (e.g. timed commands)
    - 9.3. Be able to store data from navigation

10. Autonomous behavior
10.1. Initialization and plane path traversal
10.1.1. Must evaluate current weather conditions, terrain conditions and must be capable of autonomously deciding whether to proceed with mission or not.
10.1.2. Must be capable of making its own decision on whether to switch to legged mobility or wheeled mobility
10.1.3. Must be able to navigate without the use of a video camera.
10.2. Hill-climbing
10.2.1. Rover must determine if impedance is scalable
10.2.1.1. Based on measured incline
10.2.1.2. Based on images from pre-programmed map from satellite or other source
10.2.2. Rover must slow down and stop accordingly at top of cliff.
10.2.3. Rover must change driving mode to cliff terrain mode.
10.2.4. The rover should determine optimum hill climb rate to economize power consumption. If stuck in a rut, rover should enter powersave mode.
10.3. Imaging on Cliff
10.3.1. The rover shall determine the optimal location along cliff to take picture.
10.3.2. The rover shall determine ow to maneuver to that optimal location.
10.3.3. The rover hall determine focus, zoom, and other image properties for taking the picture.
10.3.4. The rover must decide whether or not to descend down the cliff.
10.4. Recovering Ice or other sample from Underground
10.4.1. Rover must be able to identify target.
10.4.2. Rover should select surface penetration site
10.4.3. Rover should check that there are no obstacles between robot and penetration site, and if there are, plan a path to get around them.
10.4.4. Rover must retrieve sample autonomously
10.5. Returning to home
10.5.1. The rover must be capable of navigating to home base.
11. Martian Terrain
11.1. The rover will be tested on a course that will be constructed by the 16.83x team.
11.2. The test course shall have a flat region that is 5 meters in length and 3 meters in width. (CR 8.1)
11.3. The flat region should approximate the surface conditions of Mars.
11.4. The flat region of the test course shall contain X rocks per square meter
11.5. X percent of the rocks should be between X and X meters in diameter.
11.6. X percent of the rocks should be between X and X meters in diameter
11.7. The rocks shall be distributed so that the smallest rocks shall be between zero and one meters from the start, and the largest rocks shall be between four and five meters from the start. (CR 8.1)
11.8. A rock weighing more than 0.5 kg but less than X kg placed no more than two meters from the start line shall be designated as a retrievable sample of scientific interest ("target 2"). (CR 8.5.2)
11.9. The flat region of the test course should contain an object simulating sub-surface ice that is located X meters below the mean surface level of the course and between four and five meters from the start line. This item shall be designated "target 4". (CR 8.5.4)

11.10. The flat region shall contain a hard surface region and a soft surface region (*define these terms*). (CR 8.1)
11.11. The flat region shall be X meters thick.
11.12. The test course shall contain a slope of sand at its angle of repose. (CR 8.2)
  11.12.1 The sand should approximate the physical characteristics Mars regolith.
    1.12.1.1 Particle size and shape?
    1.12.1.2 Chemical composition?
    1.12.1.3 Coefficient of friction?
    1.12.1.4 What is the angle of repose?
  11.12.2 The top of the sand slope shall be at least 2 meters above the mean surface level of the flat region of the course. (CD 8.5.1)
  11.12.3 An object weighing more than 0.5 kg but less than X kg representing an object of scientific interest shall be buried in the sand slop at least X meters below the surface perpendicular to the angle of repose ("target 3"). (CR 8.5.3) (*bury more than one item in the sand?*)
  11.12.4 The test course shall contain a 2 meter by 2 meter vertical cliff face. The sand slope shall be between the flat region and the vertical cliff face. (CR 8.3)
  11.12.5 The cliff face shall contain a marked region representing a surface feature of scientific interest ("target 1"). (CR 8.5.1)

Appendix B.3: Final Customer Requirements Document

This is the final customer requirements document, which replaced the original customer requirements document after the various descopes.

1.0 Must be capable of high speed, wheeled mobility on relatively smooth terrain and legged mobility on rough and steep terrain.
2.0 Modules must be able to be easily attached and detached.
3.0 Must be able to support different concepts of operations
  3.1 Direct commanding by astronaut in the field
  3.2 Remote control with zero delay
4.0 The rover must never be able to get into an inverted position
5.0 Navigation using on-board and off-board sensors.
  5.1 Must have an independent truth sensor
  5.2 Scenario of no map
6.0 Bigger than Sojourner and smaller than MER
7.0 Must be able to complete the course shown in Figure 1 without the need to recharge batteries.
  7.1 Traverse a flat region five (5) meters in length and three (3) meters in width with increasingly difficult rock coverage and a hard and soft (sand) surface.
8.0 200-m traverse: To demonstrate autonomous operation, the rover shall be able be able to complete a 200 meter autonomous traverse to a designated target across unpaved terrain, operating in wheeled mode, without recharging. The traverse course has the following characteristics
  8.1 The 200 meter traverse may, if desired, be implemented as a traverse of 100 meters to a target, followed by a return to the origin.

- 8.2 The course may contain slopes of up to 10 degrees in either the travel direction or transverse to the travel direction
- 8.3 The course may require the rover to detect and navigate around one or more obstacles, but will not require the rover to drive over rocks.
- 8.4 The definition of "unpaved terrain" means that the rover should be designed with the ability to demonstrate the traverse on either of the following surfaces. (The actual decision on which surface to run the demonstration on will be made depending on time and weather constraints later; the rover should be designed to traverse either.):
  - 8.4.1 Briggs Field
  - 8.4.2 A dry, sandy beach, above the high-tide mark.

The 200-m traverse requirement is separate from the course requirement (7.0); that is to say, the rover does not need to complete both the 200-meter traverse and the rock/hill/cliff course on a single charge.

Appendix B.4: Final Functional Customer Requirements

This is the final functional customer requirements document, which replaced the original functional customer requirements document after the various descopes.

12. Mobility
- 12.1. General
  - 12.1.1. The rover shall be capable of legged and wheeled motion.
    - 12.1.1.1. The rover shall be capable of forward and backward motion.
    - 12.1.1.2. The rover shall be capable of side to side motion.
  - 12.1.2. The rover shall be able to maneuver in limited (dimensions) space (e.g. get back off cliff after climbing).
  - 12.1.3. The rover shall be equipped with be able to determined its orientation.
  - 12.1.4. The rover shall never be rendered immobile.
    - 12.1.4.1. The rover shall never become inverted.
    - 12.1.4.2. All legs shall be operable under sand.
    - 12.1.4.3. The rover shall not be vulnerable to anticipated wheel traps and ditches.
    - 12.1.4.4. The rover shall maintain balance while in legged mode
      - 12.1.4.4.1. While stationary.
      - 12.1.4.4.2. While in motion.
  - 12.1.5. Loads
    - 12.1.5.1. Each wheel and leg shall be able to support weight of rover and payload and maximum impulse possible on course.
    - 12.1.5.2. Wheel and leg assembly shall be able to support torques induced on structure (and payload) from turning.
  - 12.1.6. The rover shall be stable and controllable during all operations.
  - 12.1.7. The rover shall be able to transition from wheeled mobility to legged mobility.
    - 12.1.7.1. In any rover orientation.
    - 12.1.7.2. The rover shall be able to decide when to transition from wheeled to legged mobility.
  - 12.1.8. The placement of the rover's legs shall be able to be controlled by a human operator.

    - 12.1.9. The human operator shall also be able to control emergency stopping at any time with one simple command.
    - 12.1.10. Be able to support closed-loop control with optional open-loop functionality in the case of the driving system.
    - 12.1.11. Wheel/leg sensors (should this be a subset of the previous).
  - 12.2. High speed mobility on smooth terrain, where smooth terrain is defined as a surface with incline no more than 30 degrees and obstructions no more than TBD in size and a soil bearing load of no less than TBD.
    - 12.2.1. The rover shall maintain a course across smooth terrain at no less than TBD m/s.
    - 12.2.2. The rover shall be able to stop from full speed within obstruction detection range.
    - 12.2.3. The rover shall have ground clearance of no less than TBD(while wheeled motion).
  - 12.3. Legged motion on extreme terrain, where extreme terrain is defined as a surface with incline no less than TBD degrees or obstructions no more than TBD in size or a soil bearing load of no less than TBD.
    - 12.3.1. The rover shall be able to walk over or around objects no more than TBD in size.
    - 12.3.2. The rover shall be able to walk through extreme terrain as defined by rock distribution given in Golombeck model.
    - 12.3.3. The rover shall have ground clearance of no less than TBD(while in legged motion).
  - 12.4. Mobility on Sand
    - 12.4.1. The rover must be capable of moving over sand.
- 13. Observation/Sensors
  - 13.1. Rover Information
    - 13.1.1. Velocity-Measurement System
      - 13.1.1.1. The rover shall be able to return its current velocity to the operator while using wheels and while using legs (JWB)
      - 13.1.1.2. The avionics shall include sensors to support requirement 2.1.1.1
      - 13.1.1.3. Acceleration when on wheels.
      - 13.1.1.4. Acceleration when on legs.
    - 13.1.2. The avionics shall include health Sensors (temperature, battery)
  - 13.2. Environmental Information
    - 13.2.1. The rover shall have an imagining system (JWB)
      - 13.2.1.1. The rover shall have panoramic imaging capabilities (JWB)
        - 13.2.1.1.1. The panoramic imaging system shall be able to image 360 degrees of footage about the rover's current location (JWB)
        - 13.2.1.1.2. The panoramic imaging system shall be able to take color images (JWB)
      - 13.2.1.2. The rover shall have an imaging system for detecting ground hazards in front of the rover (JWB)
      - 13.2.1.3. Aids for autonomous navigation
        - 13.2.1.3.1. The rover must sense the impedance ahead
        - 13.2.1.3.2. The rover must detect range to target.
        - 13.2.1.3.3. The rover must detect range to obstacles and other geological features.
    - 13.2.2. Other Environmental Information
      - 13.2.2.1. The rover must detect the drop off of the horizon

        13.2.2.2. The rover must detect when it is on top of cliff.
        13.2.2.3. The rover should sense positional change from angled to flat.

14. Rover Structure/Modules
    14.1. The size of the rover shall be larger than Sojourner smaller than MER
        14.1.1. Assembled rover shall fit inside entry shield of dimension .
    14.2. The number and type of batteries shall be sufficient to complete all course objectives on a single charge.
    14.3. The rover shall feature standard mounts for all avionics and mechanical components.
    14.4. The rover body structure must be large enough to fit all avionics components.
    14.5. The rover body structure shall be able to resist all stresses anticipated during operation
15. Communications/Feedback
    15.1. Be able to support real-time communication of commands.
    15.2. Be able to support wireless communication externally.
        15.2.1. Each module will be capable of supporting inter-module communications.
16. User Interface/Control
    16.1. Mission Specifics
        16.1.1. Astronaut
            16.1.1.1. The primary operation mode should be direct control. (Autonomy Level 1)
            16.1.1.2. The controller shall be portable so that the astronaut can easily transport it while traveling across the Lunar or Martian surface.
            16.1.1.3. The display shall be navigable and controllable by a gloved hand.
        16.1.2. Zero Delay
            16.1.2.1. The primary mode of operation shall be direct control. (Autonomy Level 2)
    16.2. Direct Control Options
        16.2.1. Locomotion control
            16.2.1.1. The operator shall be able to direct the rover to turn left or right a specified number of degrees +/- 2 degrees.
            16.2.1.2. The operator shall be able to move the rover forward, backward or side to side.
            16.2.1.3. The operator shall be able to specify the placement of the legs (with respect to the rover)
                16.2.1.3.1. The mobility mode (legged or wheeled) shall be able to be changed (1.0)
    16.3. Display/Monitor Options
        16.3.1. Current State of Rover
            16.3.1.1. Monitor shall show what operation is being carried out
            16.3.1.2. The monitor shall show the queue of operations
            16.3.1.3. The velocity of the rover shall be displayed at all times
        16.3.2. Map
            16.3.2.1. One of the controller display windows shall show any available map of the terrain.
        16.3.3. "Emergency Stop" button
        16.3.4. Self Diagnostic

        - 16.3.4.1. The display shall show the battery life remaining.
        - 16.3.4.2. The display shall show the rate at which the battery is being used
        - 16.3.4.3. The display shall display a warning if internal temperature exceeds safety levels

17. Power
    - 17.1. Be able to power the following systems for entire mission using only the initial energy supply. (e.g. one battery charge).
        - 17.1.1. Communications
        - 17.1.2. Sensors
        - 17.1.3. Processors
        - 17.1.4. Actuators/motors
        - 17.1.5. Data storage
    - 17.2. Operator must know Battery Life and Remaining Rate of Battery
18. Processors
    - 18.1. Be able to support programming by autonomy group
    - 18.2. Be able to support the processing of data in the various modules.
19. Data Storage
    - 19.1. Be able to store communication information (e.g. timed commands)
    - 19.2. Be able to store data from navigation
20. Autonomous behavior
    - 20.1. Hill-climbing
        - 20.1.1. Rover must determine if impedance is scalable
            - 20.1.1.1. Based on images from pre-programmed map from satellite or other source
        - 20.1.2. Rover must slow down and stop accordingly at top of cliff.