Systems Engineering the Curiosity Rover: A Retrospective

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Abstract - *This paper will discuss systems engineering challenges in development of the Mars Science Laboratory Curiosity Rover. As of the writing of this paper, Curiosity has been successfully exploring the surface of Mars for months, but during development it was not always clear it would be a success. MSL is by design three spacecraft in one: The cruise system to get from Earth to Mars; the entry descent and landing system; and the Rover to perform the intended scientific exploration. Each of these has it own unique challenges and is intertwined given the integrated nature of the design. The rover's complex science payload, sampling system and overall scale resulted in many technical challenges. This paper will present a few examples of the systems engineering challenges overcome during the development of the Curiosity rover.*

Keywords: Mars, Rovers, Systems Engineering, Robotics.

1 Introduction

The Mars Science Laboratory (MSL) project was in formulation before the Mars Exploration Rovers (MER) landed on Mars in January of 2004. Figure 1 provides a timeline for the MSL project. MSL was originally planned as a six-year development effort with a launch in late 2009. However multiple technical challenges led to an extension of the development phase of the project and a delay of the launch date to the next Earth-Mars launch opportunity in November 2011. The rover, named "Curiosity", successfully launched on November 26th, 2011 and touched down at the equatorial landing site of Gale Crater on August 5th, 2012. See NASA's Mars Exploration website for additional information on MSL and other Mars missions [1].

The next section provides an overview of the mission and spacecraft systems as background. This is followed by a discussion of several SE challenges in development of the rover.

Figure 1. MSL Project Timeline

2 Mission Overview

The MSL mission consisted of four distinct phases: 1) Launch 2) Interplanetary cruise and Mars approach, 3) Entry, Descent and Landing (EDL), and 4) Surface/Science operations. It took approximately eight months for MSL to travel over 300 million miles and arrive at Mars. The entry, descent and landing (EDL) system went directly from interplanetary cruise to insertion into the Martian atmosphere. During EDL, the system decelerates from over 13000mph to 0 in less than 7 minutes using an aeroshell for atmospheric deceleration, a parachute, and a rocket powered "skycrane" descent system to lower the rover to touchdown [2]. An advantage of this system is that that the rover lands directly on its wheels and only a few post-landing mechanism deployments are required. Given the complexity of the rover, a month long characterization or commissioning phase was required to checkout the health and basic functionality of the science instruments and mechanisms like the robotic arm and sampling system. Curiosity then began the purpose of her journey, which is to gather data that aids in understanding the potential of habitable environments on Mars [3].

The MSL spacecraft configuration was inherited from the Mars Pathfinder and MER design. At the heart of the system is the rover with its science payload to be delivered to the surface of Mars. Figure 2 shows the rover "self-portrait" taken on Mars in February 2013.

Figure 2. Curiosity self-portrait image

The rover has a mass of approximately 900 kgs and is about five times as massive as the MER rovers. The avionics includes redundant power distribution and computer elements with a RAD750 processor and 4Gbytes of flash data storage. The rover is powered by a radioisotope thermoelectric generator (RTG) that produces approximately 110W of continuous electrical power. Rechargeable li-ion batteries provide approximately 1600Whr of usable energy storage each day. The energy budget allows the rover to be awake about six hours of each Martian day and it sleeps the rest of the time to recharge batteries. (The Martian solar day, or sol, is ~39 minutes longer than an Earth day.) An active thermal control system includes a continuously-operating pumped fluid loop to control temperature of the hardware inside the rover while the Martian ambient temperature fluctuates between approximately -80C and 0C every sol. Warm-up heaters are required on exterior actuators and cameras to ensure they are above a minimum operational temperature of approximately -50C before use. The rover communication system includes a low data-rate direct-to/from-Earth X-Band transceiver as well as a high data-rate UHF-band transceiver for communication with Mars orbiters for data relay with Earth. The six-wheel "rocker-bogie" mobility system includes steering on the four corner wheels similar to previous rovers.

The science payload includes environmental monitoring, remote sensing, in-situ contact science as well as analytic instruments requiring pre-processed Martian samples. The environmental instruments include a sensor package to monitor pressure, wind, temperature and ultraviolet (UV) radiation (REMS). The Radiation Assessment Detector (RAD) is an instrument to monitor the radiation environment on the surface of Mars. The Dynamic Albedo of Neutrons (DAN) is an instrument to detect near-surface hydrogen (water) .

The Remote Sensing Mast (RSM) with an azimuth/elevation gimbal is used for the pointing of the remote science instruments. This includes the stereo monochromatic Navigation Cameras (NAVCAMs) and the stereo color science cameras (MASTCAMs). Also mounted on the mast is the laser induced breakdown spectrometer and telescopic imager (CHEMCAM)

For in-situ investigation, a 5-degree of freedom robotic arm enables precision placement of three tools and two instruments on rock and soil targets. This includes a rotary percussive drill that can gather material from up to 6.5cm inside rocks. There is also a sample scoop and processing system that can sieve drill and scoop material, and provide measured portions to the two analytic science instruments [4]. The Dust Removal Tool (DRT) is a small rotary brush to remove dust from rock surfaces. The two instruments include the Microscopic hand lens Imager (MAHLI), which is a close-up color camera with focus mechanism and LEDs for illumination. The Alpha-particle X-ray Spectrometer (APXS) is a spectrometer for determination of elemental composition of surface material.

The two analytic science instruments include the Chemistry & Mineralogy (CheMin), an X-ray diffraction instrument for determination of sample mineralogy. The Sample Analysis at Mars (SAM) is an instrument suite including a gas chromatograph, mass spectrometer and tunable laser spectrometer for chemical analysis of surface material as well as atmospheric samples.

Operating the rover requires the science and engineering teams to work closely together each day to plan the next sol's operations based on the outcome of the previous sol's activities. The daily surface mission activities fall into four basic types:

- Remote sensing – Use of cameras and CHEMCAM to do reconnaissance of the area around the rover
- Driving – Use of mobility system for long traverses towards area of interest or final approach and positioning at target for in-situ investigation
- Contact Science – Use of Robotic arm and its instruments for in-situ investigation on target

- Sample Science - Use of sampling system to acquire samples and subsequent analytic instrument analysis

The specific rover activities on any sol are controlled by multiple sequences of commands generated by the operations team. A master command sequence controls overall timing and calls other command sequences to execute planned science and engineering activities. The rover was designed to have a variety of automatic and autonomous behaviors to simplify operation and provide fault protection. This included high-level software functions, such as autonomous navigation, that minimize the number of commands the operations team needed to generate to achieve the desired goal. The flight software also included activity constraint management and resource arbitration. For instance, the rover contains 33 electric motors but has only 8 motor controllers, which are multiplexed between the motors limiting what actuations can be done in parallel. A key SE activity was development of a behavior relationship matrix to identify conflicts between activities and how they should be addressed by flight software.

Two flight software behaviors that provide health-critical infrastructure for surface functionality are the vehicle wakeup and shutdown behavior and the communication behavior. The communication behavior is an automatic table driven approach to defining and executing communication windows with Earth as well as Mars orbiting assets. This table is updated periodically during the mission so that the daily tactical operations team does not have the work associated with generating command sequences for communications. As noted previously, the power system only allows for approximately six hours of computer wake time so the rover will typically shutdown and wakeup up several times during a sol depending on the science activities. The wakeup/shutdown behavior coordinates all cleanup activities to ensure a graceful shutdown. It also schedules the next wakeup based on the master command sequence or the next communication window, which ever is earlier.

Unlike typical spacecraft that maintain a stable, power and communication-safe state in the event of errors detected on board, Curiosity's power source (like other Mars rovers) does not allow a single state that simultaneously is both power-safe and also provides communication to earth. Instead the rover must alternate between a state where the rover is awake and communicable and a state where the rover is essentially off and recharging its batteries. Therefore, built into the flight software were fault protection behaviors to ensure the power/thermal safety of the vehicle as well as ensure the ground does not lose communication with the vehicle over the course of a small number of Mars days. For instance, the rover will automatically shutdown if the batteries have been discharged to a low level.

3 Systems Engineering

SE is defined here as the engineering efforts necessary to develop a multi-element system that works synergistically together to meet specified objectives; in this case a Mars science rover mission. A discussion of SE at JPL can be found in [5]. Systems Engineers execute multiple functions over the course of the project and this paper will discuss just a few of the interesting challenges and present learning opportunities. Verification and Validation is a significant part of the SE effort but is not discussed in here. Information on Verification and Validation of the MSL surface system can be found in [6].

In retrospect, it is easy to say that one of MSL's biggest SE challenges was understanding and managing complexity. During development, complexity being built into the design was often not fully recognized. Ways to understand and measure complexity are necessary to ensure technical decisions are made with appropriate consideration. The following sections describe MSL SE activities in select areas to provide examples of some of the SE challenges faced during development.

3.1 System Architecture

The MSL surface system technical architecture is similar to that of the MER rovers with several key changes driven by the MSL mission-specific requirements, which included:

- A prime mission life of one Mars year (approximate 2 Earth years)
- Capability to operate in environments from +/-45 degrees Mars latitude, which include large seasonal temperature variation at higher latitudes
- Providing subsurface sample acquisition system and sample distribution capability
- Supporting the selected science payload including two analytic instruments requiring Mars samples

These requirements drove several key architectural features including:

- Use of redundancy in avionics to ensure mission life
- Use of a radioisotope thermoelectric generator (RTG) as opposed to solar power to ensure mission life.
- Use of a continuously operating pumped fluid loop for thermal control given wide variation in thermal environments (this system also took advantage of waste heat from RTG.)
- Use of brushless motors for mechanisms to ensure actuator life (the MER and Mars Pathfinder rovers used brushed motors.)

Two examples of challenges in the area of system architecture are presented in the following sections.

3.1.1 Avionics Redundancy

The architecture for avionics redundancy evolved over the course of the project. All of JPL's long life missions employed redundant avionic architectures to ensure survival over the required lifetime. It was only the recent relatively short mission life (less than one year) Mars surface missions in which single string avionics were viewed as acceptable risk. MSL's initial design concept was based on a single-string architecture. During later design maturation steps, trade studies were done which resulted in a change to a dual-string (redundant) architecture. Note that the experience base of many of the surface SEs on MSL was a single-string avionic design used on previous rover missions. MSL also started with a nearly completely new avionics platform, whose development required generating new complex FPGA designs. The above factors led to weak redundancy architectural tenants to guide SE.

Technical factors of volume, mass and power as well as cost and schedule to build avionics led to decisions that put asymmetries in the design. For example, the Rover Power Avionics Modules (RPAMs) were intended to be redundant boxes that cross-strapped power distribution as well as redundant analog and temperature telemetry across the system. As the number of spare power switches and telemetry channels eroded, adding additional cards to the RPAMs was considered. However the easily measured mass, volume, power, and cost implication of additional cards led to decision to instead make asymmetric connections amongst the existing cards. This asymmetry was justified by the use case where either string could be used for access to this telemetry and that in the event of a failure the loss of a non-redundant channel, the software or the ops team could find semi-graceful workarounds in flight base on inference from other channels and models. While feasible in principle, this asymmetric pattern was difficult to understand and led to confusion and testability shortcomings. It became very difficult to be able to say with certainty that loss of a redundant RPAM would be recoverable. This is an example of how the complexity of such a pattern was not appreciated at the time the design decision was made. Adhering to common patterns of symmetry and simplicity is fundamental to good architecture. Redundancy asymmetries can lead to difficulty in understanding the design and interfacing it to other parts of the system. The RPAM connectivity was re-evaluated given the time afforded by the launch delay and a variety of changes were made to reduce asymmetries and the associated complexity.

3.1.2 Actuator Heaters

The MSL architecture included a RTG power source, however the net energy available compared to the payload and mechanism needs resulted in limited awake time each sol similar to the solar powered MER missions. Power efficiency across all elements of the system was very important to maximizing energy remaining for science. A mission requirement was to be able to land at higher latitudes with their much colder environments. This combined with large mass of the actuators on Curiosity, meant warm-up heating would be very energetically expensive. As a result, there was a large technology investment made in developing cold temperature capable actuators (operating temperatures below -100C) early in the project. However, due to the great technical challenge involved, this program did not reach maturity and relatively late in development, the project had to move from using unheated dry-lube actuators to using more traditional wet-lube actuators with warm-up thin-film strip heaters mounted on the actuator housings.

This change required many more power switches for the new heaters that contributed to the RPAM issue discussed previously. This also greatly increased the work the thermal subsystem needed to do. The existing actuator housings were made to save mass and therefore had complicated geometry making strip heater design complex. Modeling of the heater performance was critical to understanding energy utilization to analyze overall mission performance as well as for use in operations. The complexity of this effort was not appreciated at the time the architecture was changed. The resulting increase in energy also contributed to restricting the landing site latitude from the initial +/-45 degrees to +/-25 degrees to remove the extreme winter environments that could be encountered at the higher latitudes.

3.2 Requirement development & management

MSL requirements were a complex web of documentation with differing approaches. This spanned from the traditional functional requirements levied on each system and subsystem, the environmental requirements managed by the mission assurance office, interface control documents between different system elements, institutional policy documents, as well as stand alone requirement documents covering, for example, planetary protection. While these were based on established institution practice, there was not an architecture that pulled them together in a cohesive manner for MSL. It became difficult to maintain cognizance over the full requirements set given the diversity of approaches and turn over of staff which sometimes led to changes in requirements management. The consequences were often felt late in development when divergent requirements were discovered during test resulting in late design changes.

Flight software requirements were a challenge given the complicated and diverse system behaviors that are embodied in software. Functional Design Documents (FDD) for each functional area (e.g. thermal control, imaging, fault protection, etc.) provided a detailed description of desired behavior in nominal and off-nominal conditions, command and telemetry associated with function, as well as functional requirements on software. Over 40 FDDs that represent thousands of pages of SE design documentation were developed and maintained through the project lifecycle. Compared to past projects, this was an area MSL did very well in, with the software design well documented and controlled. Without this strong FDD requirements approach, keeping track of and verifying the complex software on MSL would have been a much more challenging task.

In hindsight, the MSL requirements process could have been improved in several ways:

- More upfront effort to understand and architect the breadth of requirements processes and products across the project and a clear flow of parent requirements to target subsystems.
- More formal training and detailed documentation on the project specific approach. Although most SEs involved had previous experience in requirements development and management, inevitably their experiences were different. Better training material would have also helped over the entire project lifecycle given staff turnover.
- More attention to verifiability of high-level functional requirements. SEs with limited V&V experience did not fully appreciate the implication that they would eventually be tasked with verification of requirements and therefore did not always consider verifiability during requirement definition.
- Better documentation of analyses that led to requirements. For instance, mechanism life requirements were based on mission use cases but those analyses were not formally documented in all instances. When time came to verify these requirements, their basis was not understood and needed to be re-analyzed to ensure they were still consistent.

3.3 System Modeling & Analysis

System modeling and analysis forms the basis of trade studies as well as understanding margin in a given design. Many models were used to support MSL SE activities, but a formal model based system engineering approach (e.g. use of SYSML) was not employed by MSL.

An important mission level model to develop is one that addresses system performance in terms of the scientific objectives of the surface mission. This model is necessary to make informed decisions on the potential impact to science objectives due to changes to spacecraft and instrument design throughout the project lifecycle. But building and maintaining such a model can be extremely challenging to do for a mission of discovery like MSL where science performance is not measured in a quantitative way and the specific landing site would not be selected until close to launch. As a compromise solution, the project elected to build a relatively simple model based on the two most quantifiable aspects of the mission – number of samples acquired and analyzed and total distance travelled which represented diversity of samples.

The functional requirements from the Mars program specified that the rover should have a capability to drive 20km and a sampling system capable of acquiring 74 solid samples. These were viewed as requirements driving the life of the mobility system and sampling system independently. Given MSL is a mission of discovery, there was not a program requirement on how these capabilities should be used in the mission; that is, there was not a requirement on how far the rover had to drive and how many samples had to be acquired during the prime mission. Therefore, the project working with the science teams developed a representative surface reference mission that resulted in a requirement of 28 samples and 4.5 km of traverse distance at the end of the one Mars year prime mission.

Surface SE worked across all project offices and science teams to develop surface scenarios that could be used to assess mission performance. In order to understand what could be done within the rover resources, details on the duration/power/data each activity would take was required. The activities then had to be combined in a representative way to show that they would meet the science intent within the capability of the system. The operational approach in how quickly we could command the rover in response to new data also had to be considered. The level of abstraction for this modeling effort was very important. Too shallow and the fidelity would be insufficient to know with any confidence how changes in say, actuator heater power, would impact science return. Too deep and the resources just to develop and maintain the model quickly grew.

Figure 3 provides an assessment of the mission performance space at the time of landing site selection approximately one year before launch. The black line indicated the number of samples versus traverse distance that could be achieved in the one Mars year prime mission; that is if you spend all your days driving you could traverse 20km versus all your days sampling where you acquire and analyze approximately 37 samples. This model showed the reference mission requirement of 4.5km and 28 samples could be achieved. Given that the landing latitude and seasons significantly affected available energy for science, the model was run for a ~25 degree southern latitude which was expected to be the bounding case from a thermal point–of-view. This meant the rover would land in Martian Southern Spring and the graph shows the approximate variation in performance over the four Martian seasons. The model also included a top level margin allocation which assumed that one in every four sols would be required to address the non-determinism of a mission of discovery; that is some activities would need to be repeated to achieve the desired results. Another 150 sols were set aside for science activity not directly tied to sampling or traverse (e.g. contact science).

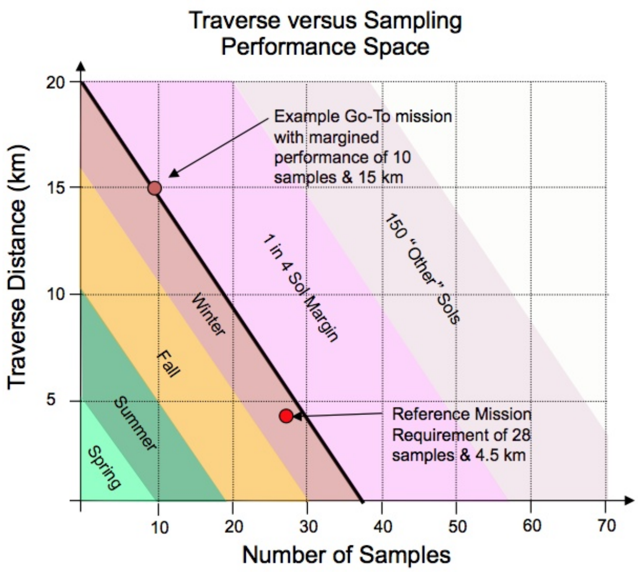

Figure 3. Mission Performance Model

The mission performance model played into a late decision to increase the rover battery capacity. The battery size drove how long the rover could stay awake and do activities before needing the sleep and recharge. Overtime, the inevitable increase in energy needs of engineering subsystems and instruments (both increases in power as well as increases in duration of activities) limited what could be accomplished before having to sleep and recharge. As noted earlier, the mechanism warm-up heaters resulted in a significant increase in energy usage per sol as they were not in initial design.

Early in the development phase, the rover batteries were essentially built-to-print copies of the MER design of ~40Ahr total capacity (Two 20Ahr batteries). It was recognized early that more battery capacity would be beneficial but volume was already becoming an issue inside the rover where the batteries were mounted. The batteries were increased by what could "easily" be accommodated leading to ~56Ahr capacity. To ensure long battery life, state of charge was limited to a minimum of 40% so the useable capacity was ~1000Whr (assuming bus voltage of ~30volts). As energy demands continued to increase, the mission performance model showed that battery capacity was the limiting factor. After the launch delay, the decision was made to fit the largest possible battery in the rover which led to a new ~86Ahr capacity with ~1600Whr of useable capacity. The model showed this to be a very good match to RTG performance and time or activity duration became the driving constraint over battery capacity. A rule of thumb based on these modeling results for future rovers is that usable energy storage capacity should be at least 50% of the total power source integrated energy capacity over a Martian day.

4 Summary

The MSL surface mission is a stunning success and a testament to the hard work and perseverance of the systems engineers who were key to ensuring Curiosity would be able to execute the science mission. The development effort was fraught with challenges many of which were due to system complexity both foreseen and not foreseen. This paper provided examples of a few of the SE challenges that came up during development and how they were addressed.

Acknowledgement

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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