Leveraging Heritage on the Mars 2020 Project

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Abstract— **NASA's Mars 2020 mission is charged with responding to the highest priority objectives of the 2011 planetary sciences decadal survey, conducting extensive in-situ science on the surface of the Red Planet, and carrying important cross-agency human precursor technologies. The mission concept was predicated on and enabled by leveraging the Curiosity rover engineering design, successful Sky Crane landing systems, and other elements from the Mars Science Laboratory project into a new mission with new payload elements. High-heritage paradigms are unusual for flagship science missions and can be difficult to execute as the realities of spacecraft development intervene. However the project has had good success to-date from concept through formulation and into early implementation. This paper will describe the general approaches developed and used by the Mars 2020 Project team at NASA's Jet Propulsion Laboratory (JPL)..**

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1. MISSION CONCEPT DEVELOPMENT

In the spring of 2012, a Mars Program Planning Group (MPPG) was formed to evaluate mission concepts and make recommendations on the next phase of NASA's Mars Program. The MPPG was focused on selecting affordable missions consistent with constrained future funding.

The primary objective for the next major Mars surface mission was to respond to the scientific priorities detailed in the National Research Council's Planetary Science Decadal Survey, entitled "Vision and Voyages for Planetary Science in the Decade 2013-2022". Specifically, the mission was to make progress toward the return of a Mars sample to Earth, while continuing with the broader program exploration mandate.

Two Rover mission concepts were initially identified and traded, these concepts were called Rover A and Rover B (Figure 1).

Both mission concepts were significantly smaller and less capable than the Mars Science Laboratory (MSL) Curiosity vehicle, which had launched in 2011 and was headed for a landing on Mars in early August, 2012. Both concepts relied on recovering the airbag landing systems used on the 2004 Spirit and Opportunity Mars Exploration Rover (MER) missions.

The Rover A concept was intended to maximize the MER design heritage. As such, it was extremely constrained in mass and volume, requiring extensive payload optimization and scope management. It's unclear whether this concept could have met the Decadal Survey objectives at all.

Rover B provided additional mass and volume for sampling and instrument systems by scaling up the MER rover and delivery systems. But it too was constrained in mass and volume. Both missions were essentially single-string systems. Both had solar array power systems and passive thermal architectures that limited mission duration and landing latitudes.

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Figure 1. MPPG Report Rover-A and Rover-B

Rover A

- MER-based system w/ guided entry addition
- Build on successful MER design heritage.

Advantages

- Heritage MER mechanical structures and EDL systems
- High EDL heritage
- Feed forward applicability to small surface missions
- Low recurring costs
- Low launch vehicle costs (Falcon 9 v1.1)

Challenges

- Very limited payload/volume margin

Rover B

- Scaled MER-based system w/ guided entry addition
- Build on successful MER architectural heritage.

Advantages

- Robust to inheritance assumptions (new systems)
- Feed forward applicability to small/mid surface missions
- Low recurring costs
- Low launch vehicle costs (Falcon 9 v1.1)

Challenges

- Requires new airbag & touchdown system development

As the MPPG study progressed, a third mission concept emerged, based heavily on the MSL Curiosity Rover and sky-crane landing system. This concept was called Rover-C.

Rover C

- Solar MSL-based system
- Build on successful MSL design heritage.

Advantages

- Robust to payload growth
- Substantial HEO/STP payload opportunity
- Best mobility range/life/mission return
- Substantial redundancy
- High EDL heritage
- Feed forward applicability to large MSR / MAV missions

Challenges

- High launch vehicle costs (Atlas)

Figure 2. MPPG Report Rover-C

2. Mars 2020 Mission Definition

In the summer and fall of 2012, the MPPG concluded and published its report, including the Rover-A, B, and C concepts. MSL successfully landed on August 5th, 2012. And in December of 2012, John Grunsfeld, the NASA Science Mission Directorate Associate Administrator, announced the establishment of the Mars 2020 Project. The project would be based on the Rover-C / MSL system.

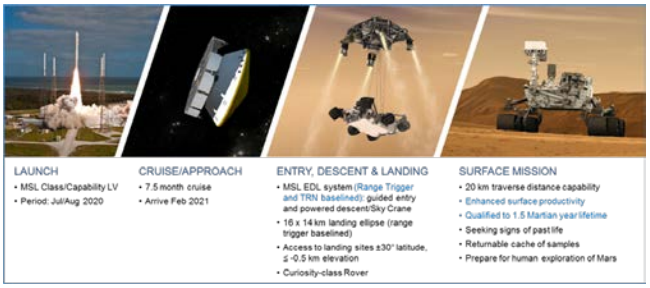

Figure 3. Mars 2020 Mission Overview

A Science Definition Team (SDT) was formed, and the project completed a set of early trades based on the specific science objectives – including a change from solar power back to the heritage Multi Mission Radioisotope Thermoelectric Generator (MMRTG) for electrical power. The payload was selected in July of 2014. Figures 3 and 4 provide an overview of the mission and its payload.

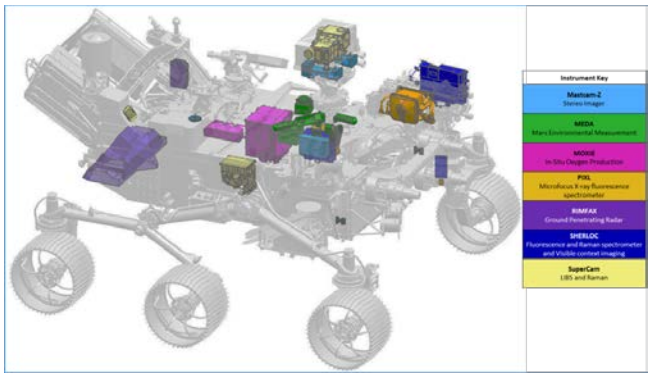

Figure 4. Mars 2020 Instruments

Utilization of the MSL mission capabilities provided significant programmatic advantages:

- Enabled a robust in-situ surface mission
- Supported the large sampling systems necessary to collect and cache samples for potential future return
- Provided opportunities for cross-agency participation, including key human pre-cursor technology demonstrations and augmented landing technologies
- Utilized flight-proven, mostly redundant, designs that enhanced mission reliability
- Supported extended mission durations, and access to rough terrain in a wide range of latitude bands
- Met the program budgetary constraints and supported the 2020 launch schedule

3. Criticality of Heritage

Significant attention is often paid to the new components of a mission, particularly those most closely associated with the mission objectives themselves. On Mars 2020, these elements are primarily the science and technology payloads, and sampling systems. Growth in these 'new' developments can affect the project cost and complexity, and their schedules typically drive the project critical path. However, on Mars 2020, these elements represents only ~5% of the spacecraft by mass, and only ~15% of the total project cost (see cost breakdown Figure 5). The project realized very early on that the most significant and systemic threat to budget and overall mission feasibility, by far, was the breakdown of the assumed MSL heritage.

Figure 5. Mars 2020 Cost Breakdown

Building a system with significant heritage is often more difficult than anticipated. The agency and industry have struggled in the past with high-heritage, legacy concepts that were not sustainable, driving up cost, mission risk, and schedule durations (Ref 1). Consequently, throughout most of the mission formulation phase from 2012 to 2016, the Project made a concerted effort to identify and mitigate threats to the heritage implementation strategy.

4. Heritage Risks Factors and Response

At the start of the mission, the project identified a set of heritage risk factors. These risk factors guided the team toward areas with inheritance risk.

Inheritance Risk Factors
Mission requirements / applications commonality – More mission similarity represents less risk to heritage
Common or bounding payload/instruments systems – Newly selected elements conform to heritage interfaces
Common implementation approach – Same inhouse/out-of-house, vendors, people …
Common or bounding mission assurance requirements – Parts, reliability analyses, qual program, SPF req'ts, etc…
Strength of documentation – Required for accurate and successful rebuild
Electronics parts obsolescence – Parts changes ripple into board, box, subsystem, procedures, ..
Common environmental conditions – Rebuild should be same or enveloped by 1st unit
Reflight technical margins – Large margins minimize threats to optimize (mass, pwr, …)
First mission launch maturity / performance history - Inflight issues, pre-launch Red Flag PFRs, high risk waivers, ….
Reflight change control – Controlling bottoms up scope growth

Table 1. Inheritance Risk Factors

To address these risks, the project created a Heritage Working Group, comprised of implementation and technical expertise from both the Project and the JPL institutional organizations. The working group met weekly for nearly four months. It created a set of key heritage topics, and stepped through these topics to understand the applicability, level of concern, and mitigation strategies. During this period, the group surveyed and interviewed key members of other JPL projects with both positive and negative heritage experiences. This included Phoenix, OCO, SMAP, and InSight projects.

In addition, the project reached out to Jeff Gramling, project manager at Goddard Space Flight Center for NASA's Tracking and Data Relay Satellite (TDRS) program. TDRS performs multiple concurrent spacecraft builds, but has also incremented from its second generation to third generation spacecraft over a launch gap of about 10 years. The program was therefore highly applicable the MSL-Mars 2020 issues. The TDRS Goddard team, and its industrial partner, Boeing, provided invaluable insight into their own experiences in this area.

The working group produced a Project Heritage Policies document. The project reviewed the document with key members of the JPL Executive Council to ensure institutional support and concurrence. The policy document became part of the Project Implementation Plan, and was delivered to the project agency sponsors as a lifecycle gate product. It has remained essentially unchanged since early 2013, and the policies have guided the project throughout formulation.

5. MARS 2020 HERITAGE POLICY

Overview

The Mars 2020 Project Heritage Policy identifies the following objectives:

1. Preserve the successful flight heritage of mission critical system elements from MSL thereby reducing mission risk.
2. Reduce projected implementation cost and schedule by avoiding non-recurring design development.
3. Reduce cost and schedule risk / uncertainty by eliminating a vast majority of design driven problems.

The policy document is guided by a set of strategic observations and principles:

- Mars 2020 will require a level of heritage reuse that is fundamentally unmatched in previous flagship JPL missions. The project is breaking new ground.
- The Project will baseline MSL system designs wherever feasible as a starting point. Modifications will be managed by a codified change control process.
- The Project must quickly recognize and realistically plan for modifications where the MSL approach is not feasible, or at risk. Heritage should not be assumed viable in the face of real threats.
- The Project should accept that the designs and systems were properly analyzed and evaluated on MSL as a starting point, but review all artifacts (waivers, problem reports, test results, analyses, etc…) for residual, altered, or unknown risks
- Successful utilization of heritage requires recognition of and maximum adherence to heritage in many domains beyond just the design itself, including the build processes, organization and facilities, key personnel, GSE and V&V programs, environmental requirements, etc...
- Often heritage assumptions breakdown when heritage elements are inserted into systems with new interfaces. For this reason, the project shall endeavor to maximize heritage upward to the highest level of assembly, including preservation of full subsystem designs and entire vehicles wherever possible.
- The Project should extend the applicability of the heritage policies to vendors to the maximum extent possible, understanding that these elements were just as critical as in-house builds.

The following sections provide details on some of the key elements in the Mars 2020 Heritage Policy.

Change Control

The Project augmented the standard JPL change control process to ensure modifications to 'heritage' systems are rigorously understood and visible at the appropriate level of the project.

At the core of the change control process are a set of classifications. All hardware and software components are given a formal classification of 'Heritage', 'Modified', or 'New'. This classification defines the required reviews and change control authority for each element. Nearly all elements of the system were initially classified as 'Heritage', ensuring changes and reclassification were reviewed at the project manager level.

The classification is captured in a Heritage Document (D-71896), which itself is under Project Manager change control, so elements classified as 'Heritage' cannot be changed without Project Management approval. The introduction provides background information, such as previous work, and describes how the paper is organized.

Reviews

Review requirements are tied to the element classification. Elements defined as 'Modified' or 'New' require standard Preliminary Design Reviews (PDRs) and Critical Design Reviews (CDRs) during the development cycle. Elements defined as 'Heritage' are allowed to follow JPL practices of an Inheritance Review (IR) followed by a Manufacturing Readiness Review (MRR) prior to the build.

Due to the unique degree of dependence on these IRs, the Project strengthened the IR criteria and certification form. The form now requires assessment of all residual risk elements associated with the design or the residual hardware.

It also includes penetration into non-design related heritage considerations (facilities, organizations, processes & practices, etc...)

Acquisitions

In support of heritage builds, the project pursued and was granted sole source authorization on heritage components. Exceptions were made where vendor capabilities or obsolete products were an issue.

In addition, the project policy called for 'fixed price' contract types, rather than 'cost plus' to minimize cost risk. Again, exceptions were made where significant restart or other development risks were identified on contracts.

The project prioritized early funding based on obsolescence risk and potential impacts. Active electronic parts were purchased first, followed by critical sky-crane propulsion components. Long-lead parts and material contracts were put in place in other areas such as the aeroshell, when funding was insufficient to let the full contract.

Documentation

Flagship planetary missions rarely lend themselves to significant re-use, and in this sense, Mars 2020 is more of an exception than a rule. One byproduct of this reality is that the institutional documentation systems and practices are less suited to direct documentation inheritance. The project was reminded of this as it attempted to move rapidly into heritage buys and builds. As a result, the project worked with the institution to establish an acceptable streamlined and well controlled process for inheriting documentation released on other projects. The project requires all project personnel to be trained in this area.

In addition, recognizing that small documentation requirements and modifications can drive significant delta costs into heritage systems, the project took steps to 'grandfather' MSL documentation and requirements where applicable. These included the use of MSL environmental requirements when the heritage test levels were still applicable or acceptable.

Verification and Validation

Planetary missions, and particularly Mars surface missions, face naturally unforgiving conditions post-launch. They require high reliability and extensive autonomy during landing and surface operations in indeterminate hostile environments. The project focused considerable attention on verification and validation (V&V) as a result.

Mars 2020 made a policy decision to require all MSL V&V testing to be repeated as a beginning point for the mission. This includes design qualification efforts. However, the project is and will continue to tailor future tests when a deviation is formally accepted in an Inheritance Review or Test Readiness Review.

Table 2. Mars 2020 Heritage Overview

Area	MSL Flight System Component	Heritage Status
CRUISE STAGE		
Power	Cruise Power Assembly	Heritage
Power	Cruise Power Analog Module A/B	Heritage
Power	Cruise Solar Array	Heritage
GNC	Sun Sensor Electronic & Heads A/B	Heritage
GNC	Star Scanner-A/B	Heritage
Mechanical	Cruise Stage Structure / LVA	Heritage
Mechanical	Cruise Stage Harness	Heritage
Propulsion	Cruise Stage Propulsion	Modified - New thruster vendor
Thermal	Cruise Thermal Design / Thermal Hardware	Heritage
Telecom	Cruise Antenna's	Heritage
AEROSHELL		
Mechanical	Backshell	Heritage
Mechanical	Heatshield	Heritage
Payload	MEDLI-2	Modified
Mechanical	Parachute	Heritage
Mechanical	BIP, PSS, PCC	Heritage
Telecom	Parachute UHF Antenna & Closeout Cone	Heritage
DESCENT STAGE		
Power	Descent Power Assembly	Heritage
Power	Descent Power Analog Module A/B	Heritage
Motor Control	Descent Motor Control Assembly	Heritage
Power	Power Thermal Batteries (2)	Heritage
Power	Pyro Thermal Batteries (2)	Heritage
GNC	Descent IMU-A	Heritage
GNC	Descent IMU-B	Heritage
Telecom	Descent Stage X-Band - TWTA	Heritage
Telecom	Descent Stage X-Band (SDST)	Heritage
Telecom	DS Antennas	Heritage
Radar	Radar / Terminal Descent Sensor	Heritage
Thermal	Descent Stage Design / Thermal Hardware	Heritage
Mechanical	Bridle Umbilical Device	Heritage
Mechanical	Descent Stage Structure	Heritage
Mechanical	Descent Stage Harness	Heritage
Propulsion	Descent Stage Propulsion	Heritage

Area	MSL Flight System Component	Heritage Status
ROVER		
Avionics	Rover Compute Element A/B	Heritage
Power	Rover Power Assembly / Shunt Radiators	Heritage
Power	Rover Power Analog Module-A/B	Heritage
Motor Control	Rover Motor Control Assembly	Modified
Power	Rover Pyro Firing Assembly	Heritage
Power	Rover Battery	Heritage
Power	Rover MMRTG	Heritage
Mechanical	Rover Chassis	Modified
Mechanical	Rover Harness	Modified
Avionics	Surface FSW	Modified
Avionics	EDL FSW	Heritage
Mechanical	Mobility	Modified
Thermal	Rover HRS	Modified
Telecom	RVR X-band - SSPA	Heritage
Telecom	RVR X-band (SDST)	Heritage
Telecom	Rover Low Gain and UHF Antennas	Heritage
Telecom	High Gain Antenna System	Heritage
Telecom	UHF Radio -A/B (Electra)	Heritage
GNC	RIMU-A/B (LN200)	Heritage
GNC	TRN VCE & Camera	New
Imaging	NavCams (4)	New
Imaging	HazCams (8)	New
Mechanical	Remote Sensing Mast	Modified
Sampling	Adaptive Caching System	New
Sampling	Robotic Arm Assembly	New
Sampling	Coring Drill	New
Payload	EDL Cameras	New
Payload	SHERLOC	New
Payload	PIXL	New
Payload	MOXIE	New
Payload	MEDA	New
Payload	RIMFAX	New
Payload	MastCam-Z	Modified
Payload	SuperCam	Modified

6. IMPLEMENTATION RESULTS

The project has been successful in implementing the policies discussed in the previous sections. The change control process is now embedded in the project normal practices. Inheritance Reviews have been successful in identifying open issues early, allowing the project to close early on go-forward plans. A majority of the heritage contracts on the project are firm fixed price with the same contractors used on MSL. Payload selection has been managed so that it did not create any systemic heritage issues on the vehicle. And while the project has made some conscious, key changes for both performance and reliability purposes, the project has retained nearly all the heritage originally assumed (see Table 2).

In addition, the careful implementation of a heritage program has provided benefits that have become more measurable over time.

Efficient Formulation Spending. The early project budget profile was below the typical pre-launch investment level required by most project. Only xx% of the project was spent prior to PDR, whereas a more typical number is xx%. However, ~xx% of that investment was used to buy and build flight hardware, an extremely high percentage for such an early phase of the project. This has been enabled by both the massive reduction in non-recurring engineering (NRE), and a large available reserve of residual hardware from MSL. Focusing the early project money on actual hardware was critical in driving down obsolescence risk early on the project.

Expanded Payload Mass / Volume. Exploration of the fundamental as-built heritage capabilities has allowed the project to expand payload mass and volume well beyond that carried on MSL. This is the result of the need to hold margin and contingency during the first build of new systems, that can be released on the rebuild. As a result, Mars 2020 is carrying about 35% more surface payload than MSL at a much lower cost. The combination of the two results in a development cost per kilogram of surface payload that is ~50% that realized on MSL.

Technology Opportunities. The additional mass and volume resources noted above in conjunction with the reduced NRE noted earlier, have opened up opportunities to include new technologies on Mars 2020 that would have been too demanding for MSL. These include the following:

- Human precursor payloads such as MOXIE, which will demonstrate the efficacy of producing high purity oxygen in-situ on Mars for future fuel and human support systems.
- New landing technologies such as Terrain Relative Navigation (TRN) that allows the mission to identify and divert away from landing hazards in real-time.
- Engineering and outreach elements that include ruggedized commercial cameras placed around the vehicle to image the system during the parachute deployment and sky-crane landing activities; as well as a microphone to capture surface mission operational sounds for the first time on Mars.

Stable Budgets. The successful implementation to-date of the MSL heritage on Mars 2020 has resulted in predicable, stable budgets since the original concept. After correcting for accounting changes, and the increase in the selected and directed payloads by the project sponsors, the overall project development costs have been flat. In addition, most independent estimates have matched or migrated toward the project's own estimates – minimizing any programmatic disturbances (descopes, funding augmentations, etc…) during formulation.

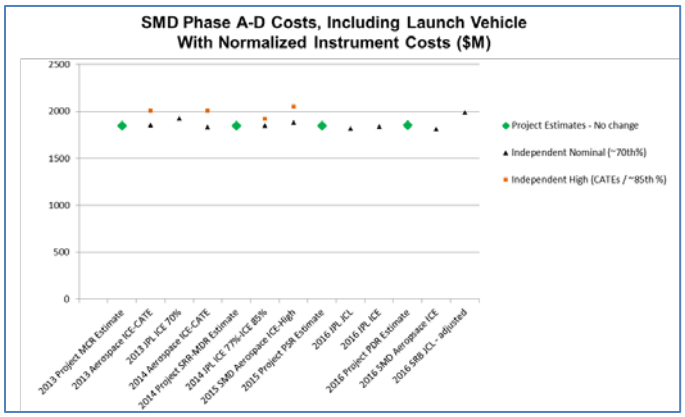

Figure 6. Mars 2020 Cost History

7. SUMMARY

It would be ill-advised to draw pre-mature conclusions about either the programmatic or technical success of the Mars 2020 project. However, the careful application of heritage has enabled the project to establish an acceptable and executable project baseline from concept initialization, through the start of Phase C.

Any well balanced project will include a reasonable ratio of new / modified elements to inherited / reuse designs. Many of the lessons learned on Mars 2020 may be more broadly applicable for other NASA missions.

8. ACKNOWLEDGEMENT

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REFERENCES

[1]Barley, B., Bacsksay, A., Newhouse, M., "Heritage and Advanced Technology Systems Engineering Lessons Learned from NASA Deep Space Missions," AIAA Space 2010 Conference and Exposition, August 2010