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A PRESSURIZED ROVER FOR EARLY LUNAR EXPLORATION

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Abstract

This paper examines the concept of placing a rover on the Moon as one of the first elements in the President's Space Exploration Initiative (SEI). The concept, called Rover First, initially serves as a teleoperated explorer and test bed for hardware development. During subsequent manned visits the vehicle is used to provide astronauts with a shirt-sleeve environment and the radiation protection necessary for extended surface exploration. Between the piloted missions, the rover is controlled from Earth and continues to serve in a dual (teleoperated and piloted) mode throughout permanent base development. A method to implement an early, low-cost program based on proven systems is presented.

Introduction

Planetary rovers were first analyzed and operated over three decades ago. In the 1960's, NASA studied rovers in preparation for Apollo and in the early 1970's, the Lunar Roving Vehicle (LRV) successfully carried Apollo crews from the lander to scientific sites on three separate missions. Also, in the early 1970's, the Soviet Union delivered two Lunokhod rovers to the Moon demonstrating both time-delayed teleoperation and long-term vehicle operations in the harsh lunar environment (LRV and Lunokhod concepts shown in Figure 1). These studies in conjunction with hardware from the Apollo, Skylab and Shuttle programs, enable the Rover First concept.

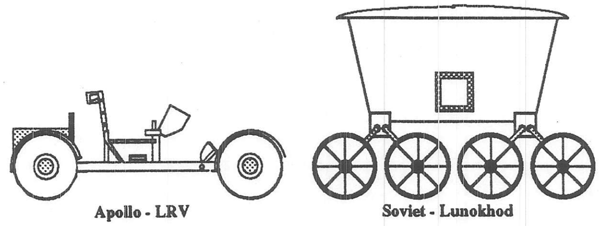

Figure 1. Successful Lunar Rovers

As was evident in the 1960's and remains true for SEI, mobility equals exploration. Teleoperated rovers appear to be the logical first choice for early missions, however for piloted operations, space suit consumables, physical endurance, and radiation protection necessarily limit excursions to a small area around the lander. In contrast, a pressurized vehicle provides extended range with both shirt sleeve operations and radiation protection. Without a pressurized vehicle, human exploration will require extravehicular activity (EVA) which has always been considered a costly and high risk operation. Use of the rover's mobility system provides effective close-in operations reducing the need for frequent EVA.

Preceding the first manned landing on the Moon, a two-man rover called MOLAB (MObile LABoratory) was studied under a NASA contract awarded to Boeing and four major subcontractors. Documented in 37 final reports, the study detailed vehicle performance, design, and reliability in addition to developing plans for manufacturing, procurement, and test. Rover First addresses the challenges and priorities of SEI and uses the MOLAB engineering as a springboard and technical refer-

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Precursors	Early Manned Flights	Base Development/ Permanent Presence
Deploy/retrieve/relocate science stations and navigational aids	Mobility from landing site	Piloted exploration from base
Collect/select and transfer samples	Radiation protection	Teleop. exploration from base or Earth
Detailed resource mapping from the surface	Beacon for piloted/ unpiloted landers	Teleop. servicing or repositioning remote stations
Detailed terrain mapping	Handoff samples or data from remote sites	Crew transporation
	Replace/upgrade experiment packages (on rover or remote stations)	Service and repair surface equipment
	Surface habitation	
	Construction site improvement	

Figure 2. Rover First Contributes to all Mission Phases

ence.

Rover First as a Precursor

Lunar surface exploration missions can be characterized by three phases of development; unmanned precursors, manned sorties, and permanent presence (Figure 2). **Precursors** establish a scientific understanding of the environment and conduct site surveys, **manned sorties** confirm and expand on precursor findings and gain incremental confidence in mission operations and hardware and begin construction of a fixed base and **permanent presence** provides continuous habitation with crew rotation and sustaining logistics

Traditionally, pressurized rovers are considered part of the latter development phase supporting extended exploration from the base. In this role, rovers have been perceived as large, long range vehicles. However, a small rover, as part of the precursor fleet, offer essential surface data necessary for future mission planning. In-situ resource mapping and site characterization can be established and compared by experts on Earth making the manned missions cost-effective and focused. Rover First, as a precursor, can: 1) deploy, retrieve, and relocate science stations and navigation aids, 2) collect, select, and transfer samples, 3) conduct detailed resource mapping from the surface, and 4) perform detailed terrain mapping.

The precursor rover is fully equipped to conduct low-speed, daylight, teleoperated missions. It also contains the core systems capable of supporting piloted operations. However, in order to inhabit and operate the vehicle, the crew must bring the necessary consumables.

Human expansion is a stated SEI goal and pressur-

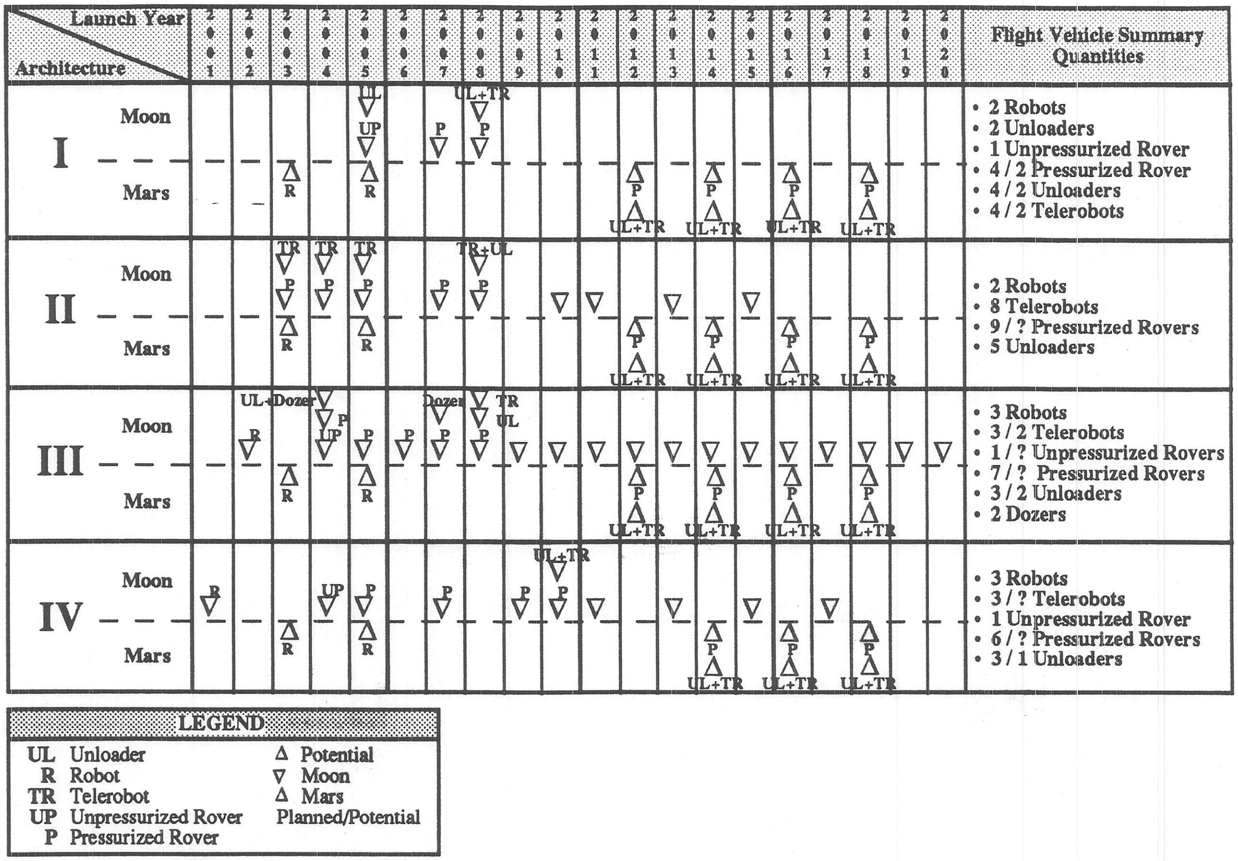


Figure 3. Rovers Role in the Synthesis Report Architectures

ized rovers played a role in each of the four architectures produced by the "Synthesis Group" in America at the Threshold; Architecture II, Science Emphasis for the Moon and Mars identifies 9 pressurized rovers (see Figure 3). Rover First offers significant cost avoidance by incorporating the individual precursors into a long-life multipurpose platform. Also, by arriving a couple years ahead of the crew, it serves as an important testbed for SEI hardware allowing the experience to be included into the hardware development for the manned missions.

Why Rover First

Early Science and Site Reconnaissance

In its teleoperated mode, the rover can collect and inspect samples from a wide area, often going into regions that would represent high risk to the astronauts or inefficient use of their limited time. Selected specimens are electronically tagged for time and location then stored onboard for hand-off to the arriving crews Vehicle instrumentation provides detailed data for terrain and resource mapping. The vehicle is also capable of surveying potential landing sites minimizing risks for future manned flights. Early rover excursions can accomplish SEI objectives by positioning navigational aids to assist in surface and landing operations.

More than Science

To enable an early mission, Rover First is designed around proven systems at the terminals of the power, data and fluid buses. This approach allows substitution, bypass and upgrade of the systems and long term exposure to lunar environment for developmental testing of hardware. A pressurized rover serves as an ideal testbed because it contains virtually all the systems required for manned and unmanned exploration and unlike a fixed site, the rover meets the arriving crews allowing access for maintenance, replacement or return of the hardware. Because the rover flies early, lessons from the testbed can be applied to the development of both fixed site systems and other mobile surface vehicles.

Teleoperations

The average driving speed of the remotely controlled rover is approximately 0.3 km/hr. This rate is slower than walking and gives the operator adequate control within the Earth/Moon time delay. Furthermore, this rate allows a traverse over rough terrain with solar arrays deployed, requires less power, avoids complicated thermal control system, and causes less wear on vehicle systems.

Proven Technologies

Five vehicles have been operated on the lunar surface; three were manned and operated on the Apollo 15, 16, and 17 missions and the Soviets sent two teleoperated vehicles. All rovers were successful in establishing a workable technology for mobility systems and teleoperations. The accomplishments of the LRV's and Lunokhod are significant and represent the tip of a large investment in design, development, test and evaluation. Cost, schedule, and technology are embedded in the product. Therefore, by using the hardware from the previous rovers along with Apollo, Skylab, Shuttle and related terrestrial programs millions of dollars can be saved and aggressive schedules can be realistically implemented. The concept of Rover First is to use proven technology and existing hardware for a low cost, early return to the Moon.

Global Coverage

The near side of the Moon is directly accessible and, with a communications relay, teleoperations on the far side is possible. This arrangement allows the remote exploration of sites not easily accessed by landers. When the crew arrives, the rover provides surface transportation from safe and economical landing sites. This dual-mode operation combines the strengths of teleoperations and manned sorties providing safe and economical exploration. Figure 4 shows the expected range of coverage which can be expected when traveling at speeds from .3 to 1 km/hr.

Rover Meets Crew

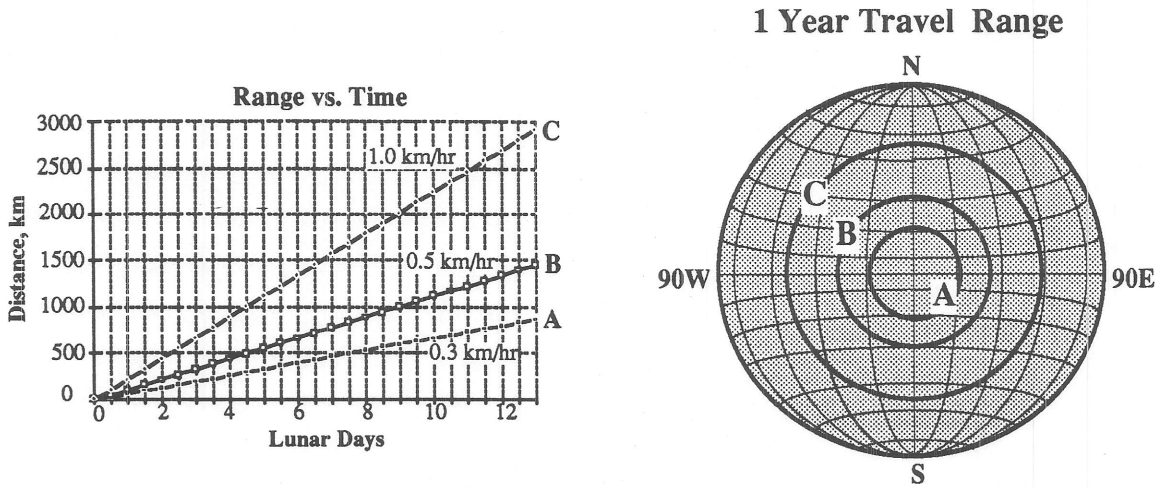
When the crew lands, the rover will be there. The prepositioned rover assists in landing by serving as a beacon for safe, precise, and economical landings. It also brings samples and data from a wide area, and provides shirt-sleeve access to important mission sites. This relationship between rover and lander makes for a more efficient and effective overall architecture.

Extended Crew Stay Time

Before the crew leaves the Earth, the rover will be positioned at the landing site and its health determined. Knowing that shelter and transportation are waiting, missions are planned around having rover resources serve as redundant systems thus avoiding the burden on the lander. This avoids the recurring penalties of cost, mass, and volume and affords extended crew stay time by using the rover.

Radiation Protection

Providing radiation protection to astronauts is not only a NASA requirement, but a legal responsibility. Because the Moon lacks a magnetic field and atmosphere, the crew runs the risk of being exposed to excessive radiation. Before the permanent base is established, Solar Proton Events (SPE) will be the greatest concern. Experts say that there is a half-hour to two-hour warning before astronauts need to find shelter. Therefore, the maximum exploration radius without shelter is two hours, meaning that if the lander has shelter, unprotected excursions will be controlled by the warning time or, at best 16km (see Figure 5). This does not meet science objectives and places unreasonable constraints on landing requirements. Rover First works as part of the exploration infrastructure providing mobile radiation protection for the arriving crews. Under a NASA contract to study rover radiation protection, a concept using the strategic positioning of on-board equipment provided acceptable levels of protection with a small mass penalty for resizing tankage. This



Driving Conditions
• 16 hrs/day (two shifts) • 14 days / lunar day • Lunar Days only (13/yr)

A	873 km/yr	1,746 km/2 yrs
B	1,456 km/yr	1,902 km/2 yrs
C	2,912 km/yr	5,824 km/2 yrs

Figure 4. Traverse Capability at Varying Speeds

means that pressurized rovers provide the only safe means of satisfying SEI objectives and Rover First offers a critical resource without consuming payload on each manned landing.

Multiple Site Rendezvous

Because the rover is mobile, a single vehicle can meet arriving crews at different landing sites. Since each manned mission requires a rover for exploration, a single vehicle that remains on the surface, not only saves money, but frees up lander payload mass, volume and off-loading complexity.

On-Going Utility

Rover First is not a dead-ended mission. It performs as a teleoperated precursor and continues in alternating teleoperated and piloted modes during manned sorties and permanent base development and operation. By this approach, the vehicle is a resource and not a mission. It provides a platform for evolving objectives over a long period and accordingly, offers low life-cycle costs.

No Lander Landing

Rover First will land on its wheels. The Apollo Lunar Module (LM) demonstrated that very soft landings are achievable. Figure 6 shows LM-type landing loads to be less demanding than those driving for a rover. Therefore, by attaching a propulsive descent package to the rover and using its suspension in conjunction with lightweight crushables, a

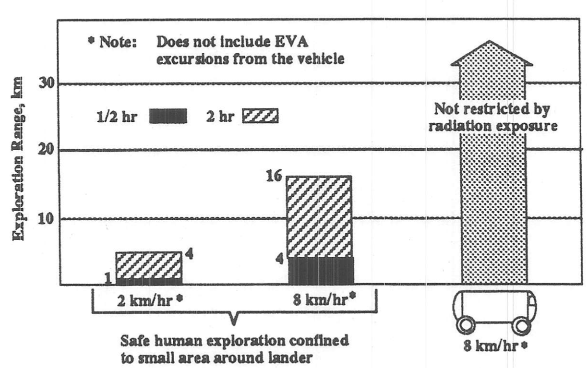


Figure 5. Radiation Traverse Parameters

Assumptions:

- 0.25m (10 in) suspension jounce
- 0.38 m (15 in) obstacle at 8 km/hr design criteria
- Uniform deceleration and damping

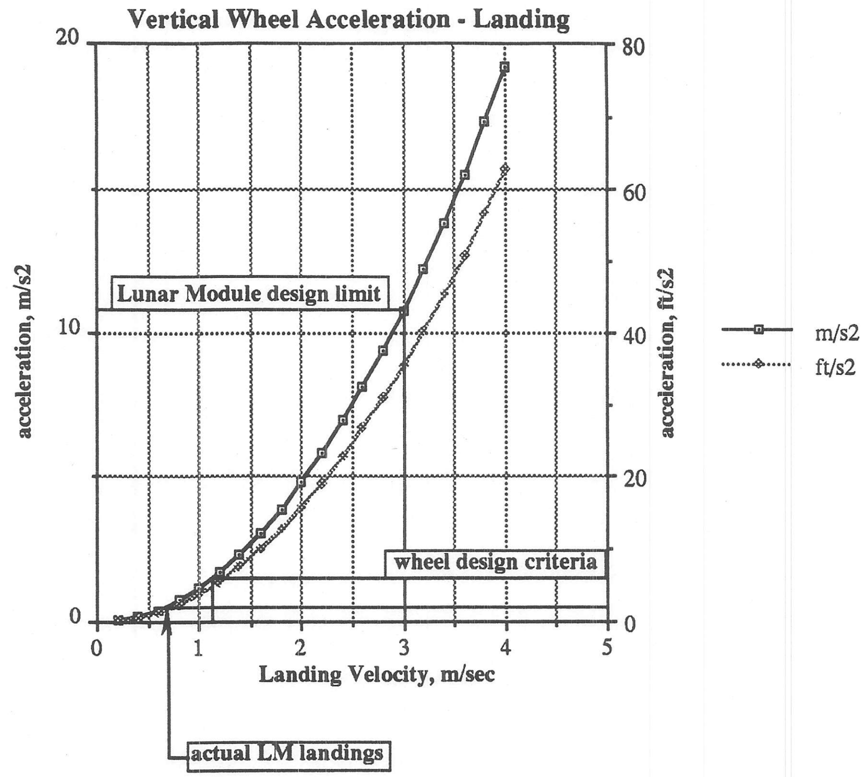


Figure 6. Wheeled Landings Compared to LM

conventional landing stage is avoided.

No Complicated Rover Deployment

Not only does a no lander landing eliminate the landing stage but it avoids the complexity and equipment required for off-loading. Landers are concerned with control during descent and touch-down which usually translates into rather rigid requirements for payload center of gravity. Like Apollo, most concepts have the payload positioned on top of the lander. Consequently, access and equipment for off-loading must be provided by the lander, taking away from payload.

Preselected Samples

Unlike EVA, teleoperation allows remote inspection of samples by many experts without a concern for using consumables. Samples from many sites are collected and delivered to the arriving crew. Forearmed with the telemetry data, the astronauts further assess and select specimens for return to Earth.

Design Approach

Functional Integration

The Rover First process does not adhere to conventional systems engineering practices. A low risk approach to achieve early mission objectives forced selection of proven systems and the integration of hardware designed for other programs. In order to provide guidance to the selection of systems, functional diagrams detailing the characteristics and inter-relationship amongst subsystems were developed. These relationships were determined according to the operating requirements during different phases of exploration and development. Therefore, the result was a vehicle conceived for piloted operations but initially configured for delivery and teleoperations.

Integration analysis established the rover parameters and allocated the "design-to" resources across the subsystems. For example, a 700w solar array/ battery system was selected for teleoperation, balancing the demand for mobility, communication, guidance, navigation, and control within a workable operations scenario and mass and volume constraints. For piloted missions, a Shuttle fuel cell was selected because it is low-cost, proven, provides the required 8 kW, and produces water for the crew, the thermal control system, EVA, and radiation protection. Furthermore, the fuel cell reactants are resupplied by the users, relieving the vehicle of long term cryogenic storage.

Vehicle Configuration

Compatibility with existing delivery systems determined the external envelope for the rover and limited the landed mass to less than 4.3 mt. The delivery configuration was sized to fit within both the Shuttle cargo bay and Titan IV shroud and a 2.6m diameter cylinder was selected as the low-weight solution providing internal equipment packaging and austere accommodations for a crew of two for 14 days.

The overall pressure vessel length is 4.1 m and is comprised of a cylinder and two elliptical end bulkheads. Side-by-side seating provides a commander's station and science station with forward visibility. A manipulator arm with interchangeable end-effectors is within view and available for teleoperated and piloted missions. A Shuttle hatch for crew ingress and egress is located in the aft bulkhead.

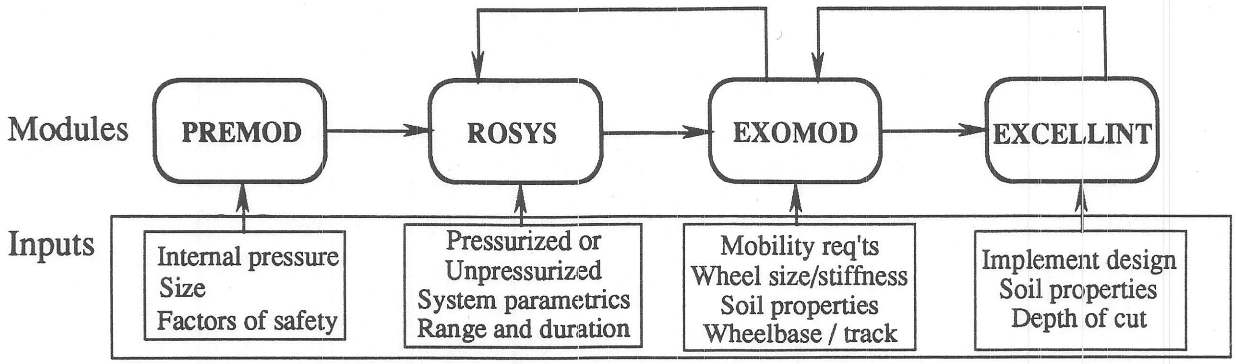
The rover's mobility combined with a manipulator/ mini-airlock enable close inspection of external elements reducing the need for frequent EVA's Therefore, to minimize weight and recognize the reduced dependency on EVA, the crew airlock was omitted. Like Apollo's Lunar Module and Command Module, this means the vehicle is exposed to ambient during the EVA then repressurized after the crew returns.

Six 1.23 m, flexible wire mesh, wheels provide the rover with stability and traction. The wheels are similar to the proven design of the LRV and each is equipped with an electric motor for maximum traction and simplicity. The two front wheels control steering and use a double wishbone suspension while the rear dual wheels are on a trailing arm suspension. For delivery packaging, wheel size and location allows for a simple compression of the suspension springs avoiding complex, single-use folding mechanisms.

Analysis

Computer design and analysis tools have been developed to support definition of Rover First. A set of four integrated tools, shown in Figure 7, was developed in 1991 to assist the design and analysis of the mobility and structural systems for pressurized rovers. The EXtra-terrestrial Off-road MODeler (EXOMOD) was used for determining key design parameters for rover wheels, drive-motors, and mobility dimensions (wheelbase, track, etc.). The PREssurized MODule (PREMOD) sizing algorithm was used in determining the vehicle's pressure structure configuration and mass.

Other critical rover design and analysis issues have dictated the development of extensive simulation capabilities. The first of these involves the use of a crew cab and drive station mockup in driving and viewing simulations. This mockup is currently being configured with controllers (wheel/yoke, joystick, etc.) and a high-resolution visual system. A digital terrain model has been developed and included in the simulator. This terrain model is used as an input for performing dynamic analyses with the Dynamic Analysis and Design System (DADS) program. The dynamic analysis provides key inputs to the simulator, including dynamic response and ride quality. A culmination of the simulations are embodied in computer-generated engineering animations of the rover's traverse on the lunar surface.



Tool \ Use	Mass Estimation	Mobility Performance	Maneuver-ability Performance	Soil Working Forces	Structural Design	Parts Lists
EXOMOD	Historical/ Parametrics	Empirical / Theory	Theory			
EXCELLINT				Empirical / Theory		
PREMOD	Design Based				Classical PV theory	
ROSYS	Detailed Parametrics					Historical Design Data

Figure 7. Computer Analysis Tools for Rover First

Summary

It is important to stress that although Rover First has a self-imposed constraint to use proven systems, there is much work to be done. Spacecraft engineers must be willing to create a new product from these systems. Scavenging requires a special kind of integration to connect disparate pieces into a functioning unified total. It's not a new approach and is the normal way of business for many industries.

There are ways of creating a bus architecture that will accommodate substitution at the terminals allowing early implementation with proven systems without inhibiting future upgrades. The parts exist, how they come together into a whole will be determined by management. There will be an overwhelming temptation to change and upgrade the hardware. In some cases, like avionics, the substitution may be transparent and beneficial. But, too many changes may make a more capable rover but not Rover First.

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