Mars Rovers, Past and Future[1)]

Brian K. Muirhead
Chief Engineer, Mars Science Laboratory
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
818-393-1013
brian.k.muirhead@jpl.nasa.gov

Abstract- This paper discusses the history of planetary rovers, including research vehicles, from the initial concepts in the early 1960's to the present. General characteristics and their evolution are discussed including mission drivers, technology limitations, controls approach, mobility and overall performance.

Special emphasis is given to the next generation mission of rovers, the Mars Science Laboratory rover. This vehicle is being designed for a 2009 launch with the capability to operate over 80% of the surface of Mars for a full Martian year (687 days). It is designed to visit numerous sites, with a science payload capable of making measurements that will enable understanding the past or present habitability of Mars.

TABLE OF CONTENTS

1. IN THE BEGINNING

Exploration of planetary surfaces by rovers has been researched at JPL since the early 1960's. In 1963, JPL contracted with General Motors to produce the Surveyor Lunar Rover Vehicle (SLRV) (Figure 1). This unit was a prototype for a rover which would land on the moon as part of the Surveyor unmanned spacecraft program. The purpose of the vehicle was to survey landing sites for subsequent Apollo missions. This machine was never flown because the Surveyor landers showed the moon to be mechanically firm enough for astronauts and their equipment to operate.

[1] The work described in this paper (#1024) was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Copyright: 0-7803-8155-6/04/$17.00©2004 IEEE.

Figure 1. General Motors Concept for Surveyor Lunar Rover (1963)

The control methodology planned for these lunar rovers was a "move and wait" strategy which involved human operators on earth "joy sticking" the unit in near real time. An image is sent from the rover to the command station; the human operator selects a steering angle, triggers a command to

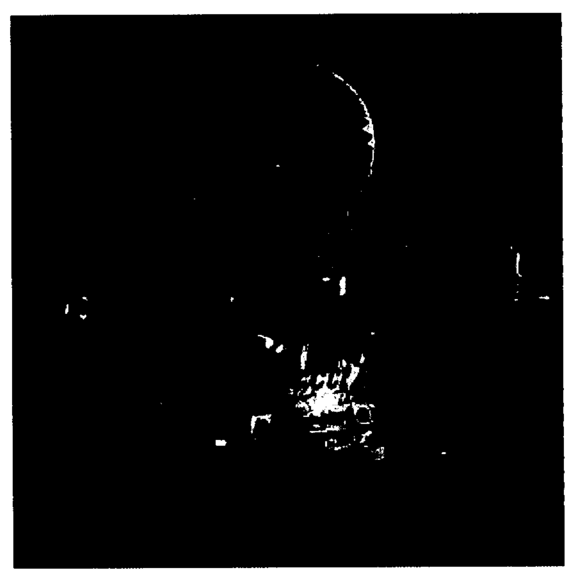

Figure 2. First Rover in Space, Lunokhod, 1971

move forward one wheel circumference (about 1.5 meters), and the cycle repeats. This technique was possible because of the short round-trip light time from the moon (<3 sec.). Extensive testing of this control approach was conducted at JPL in the 60's and early 70's.

On November 17, 1970, the Soviet Luna 17 spacecraft landed the first roving remote-controlled robot, Lunokhod (Figure 2), on the Moon. It had a mass of about 900 kg and was designed to operate for 90 days. It was controlled by a 5-person team using the "move and wait" technique. It toured the Sea of Rains for 11 months and was heralded as one of the greatest successes of the Soviet space program.

The Apollo lunar rover (Figure 3) was first flown in 1971 on Apollo 15 and again on Apollo's 16, 17. The vehicle mass was 205 kg and could carry over 500 kg of passengers and payload. It was developed in just 17 months from contract start to delivery. The interplanetary land speed record of 10.6 mph set by Gene Cernan on Apollo 17 still stands.

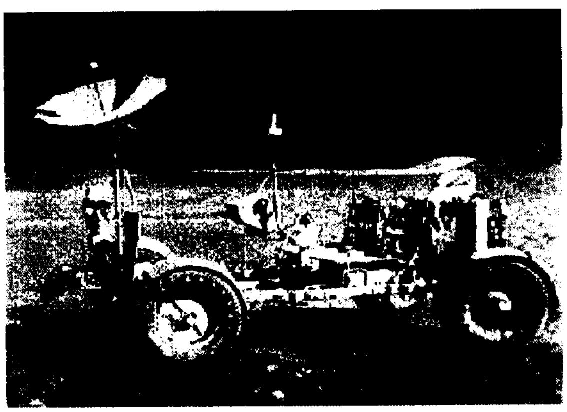

Figure 3, Apollo Rover (1971)

2. Early Mars Rovers

Mars exploration came to the forefront of planetary research in the mid-70's with the success of the Mariner 1971 mission and the development of the Viking mission. Because the round-trip time delay can range from 7-30 minutes, the "move and wait" strategy would not work for Mars. From 1975 through 1980 JPL and the Rensselaer Polytechnic Institute (RPI) focused on developing the technology needed for a vehicle to detect and avoid hazards using on-board sensing and processing. Human operators on Earth would be in a "supervisory" role, choosing goal locations and activity sequences.

These first significant efforts to create an autonomous mobile vehicle showed how difficult it was to build a competent autonomous robot. Using off-board processing, by some of the most powerful mainframe computers then

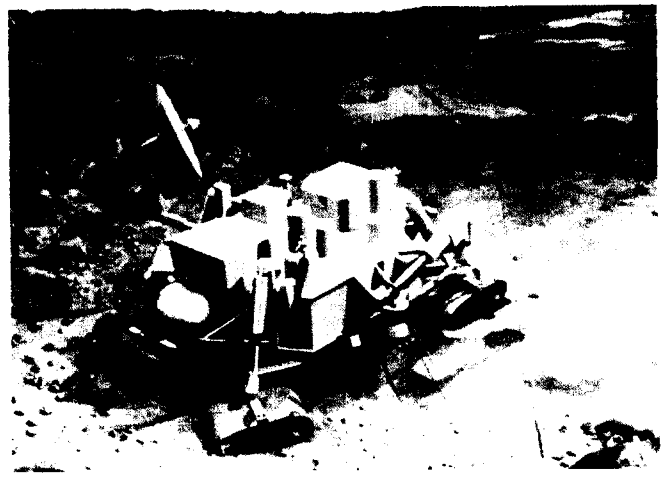

Figure 4, Viking on Loop Wheels (1979)

available, the robot could barely navigate as fast as it would under Earth-based "move and wait" control.

While the U.S. was investigating various designs and autonomy, such as the Viking on wheels (Figure 4), the Soviet Mars rover, Marsokhod (Figure 5) was being designed for high mobility. It featured a very small "bellypan" area to eliminate concerns about high-centering, but at a high cost in energy efficiency and slippage. Batteries were placed in the wheels to help achieve a low center of gravity. An "inchworm" mode, to change distance between axles when climbing in very soft material, was also included.

Given the difficulties of implementing high autonomy, a technique called Computer Aided Remote Driving (CARD) was developed in the early 1980's. This technique permitted larger distances to be traversed with reasonable safety with a single round-trip communication cycle.

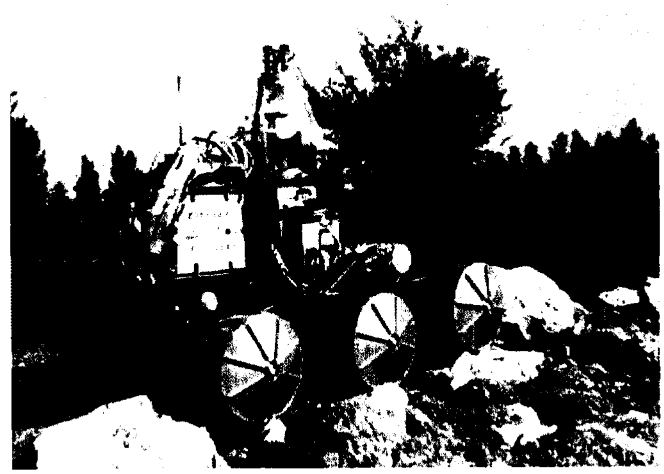

Figure 5, Marsokhod (1980's)

CARD is based on:

- Stereo pairs of images of the terrain are captured and transmitted to Earth
- Human operators view these images on a 3-D display and position a 3-D icon overlay on the images at waypoints along a "hazard-free" path
- Coordinates of those waypoints are transmitted up to the vehicle for execution

Due to deep space communications limitations, ground planning turnaround time, and the need for validation of uplink commands, no more than about one or two command cycles per sol day is practical for a Mars Rover.

Recognizing the limitations of CARD, and with the new technology possibilities of the late-1980's, the JPL rover research program again sought to develop "long-range," autonomous navigation. Advances in microelectronics made it possible to incorporate on-board processing that was greater than anything used off-board in the 70's. The test vehicle, called Robby (for its likeness to another famous robot, Figure 6) demonstrated a 100 meter autonomous traverse in about 4 hours, in the 1990, which approximately matched the requirements for a Mars Rover Sample Return (MRSR) mission then being considered. However, mission plans for MRSR concluded that such a mission could cost $10 billion or more, which was not considered feasible in NASA's budget environment at the time.

Figure 6, Robby 1990

3. Birth of Microrovers

With the demise of the large rover MRSR mission, planning then turned toward landing multiple small instrument packages to perform in-situ analysis. Microrovers, with a mass of around 10 Kg or less, had been first proposed in late 1986. These small rovers were consistent with this new paradigm. The range of the initial microrovers was thought to be very small so CARD was considered as the best control approach

Development and proof of mobility and control have always been a complementary and competitive relationship. To understand and evaluate this relationship, the research environment has progressed through many generations of testbed vehicles. For the microrovers, a group of vehicles has been developed, the first being called Rocky. This family (Figures 7 & 8) is named after its chassis design (invented by Don Bickler of JPL) incorporating wheel bogey assemblies on rocker arms called a rocker-bogey suspension. This unsprung suspension provides exceptional mobility, allowing the vehicle to traverse rocky terrain and climb rocks larger than its wheel diameter very efficiently and safely.

Figure 7, Rocky 3 (1990)

Given the extremely low volume of transmitted data available from Mars, it was desired to have a more capable system than just calling Earth for help at the sign of trouble.

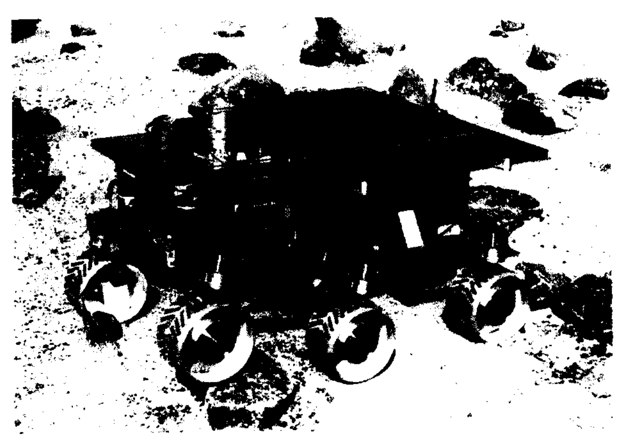

Figure 8, Rocky 8 (2000)

Behavior control was developed (initially at MIT) to offer the ability to respond to anomalies, to circumvent simple hazards, and to ensure vehicle safety using reactive behavior primitives loosely patterned after the observed behavior of insects.

Using the concept of behaviors, a hybrid approach was developed wherein path waypoints are designated on a CARD-like 3-D display and the actions of the vehicle are managed via behavior control. This "waypoint designation with behavior control" approach was developed as part of the Mars Science Microrover (MSM) activity that demonstrated, using a Rocky testbed vehicle, an end-to-end microrover mission scenario in mid-1992.

4. SOJOURNER AND THE MARS EXPLORATION ROVERS

The success of the Mars Science Microrover program led to the adoption of a plan to incorporate a microrover, with roughly the same size and control approach as Rocky, into the Mars Pathfinder mission. Initially, there was a major dispute over whether such a rover should be tethered or free ranging. Power and communications were facilitated by the tether but terrain access and the risk of being hung up by obstacles argued against the tether. The project team eventually came down on the side of the tetherless approach.

Sojourner (Figure 9) weighed in at about 11.6 kg with another 4 kg of supporting equipment (e.g., transponder) on the lander. She employed hazard avoidance sensors based on small CCD imagers and laser stripe projectors, which allowed a wide range of plausible terrain hazards to be detected prior to a possible fatal engagement with the vehicle.

Figure 9, Sojourner (1996)

Sojourner operated very well on Mars (in fact better than it ever did on Earth). The CARD control and behaviors worked well together to provide access of its single science instrument, an Alpha-Proton-X-ray spectrometer, to numerous rock and regolith sites. The behavior control kept Sojourner out of trouble when ground operators directed her to places they couldn't quite see and when her gyro drift became excessive and dead reckoning became the only driving control approach.

The Mars Exploration Rovers (Figure 10) were conceived in 2000 as a rebuild of Mars Pathfinder with a new rover design that integrated all the operational electronics into the mobile vehicle, i.e., no lander base station. This mission evolved into a twin rover mission with an almost completely new design. The first rover named Spirit, will arrive on Jan. 4, 2004, and Opportunity will arrive on Jan. 25, 2004.

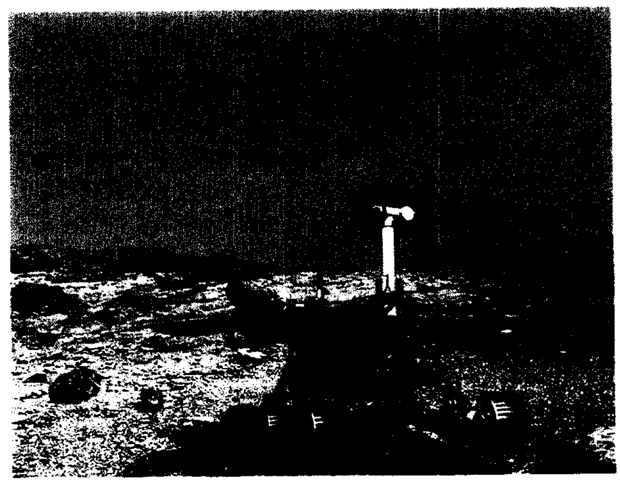

Figure 10, Mars Exploration Rover (2003)

The primary mission objective is to determine the history of climate and water at two sites where conditions may once have been favorable to life.

The mission design features are:

1. Pathfinder-like entry, descent and landing, including airbags, with the addition of terminal horizontal velocity sensing and some correction capability
2. 180 kg mobile field geologist
3. Mars Odyssey science payload
4. Highly integrated/optimized rover design due to the very tight mass and volume constraints of the Delta II rocket and Pathfinder-sized aeroshell and lander

5. MARS SCIENCE LABORATORY ROVER

The Mars Science Laboratory (MSL) mission is proposed as a new generation of Mars explorer leading into the next decade of Mars surface missions. The mission science

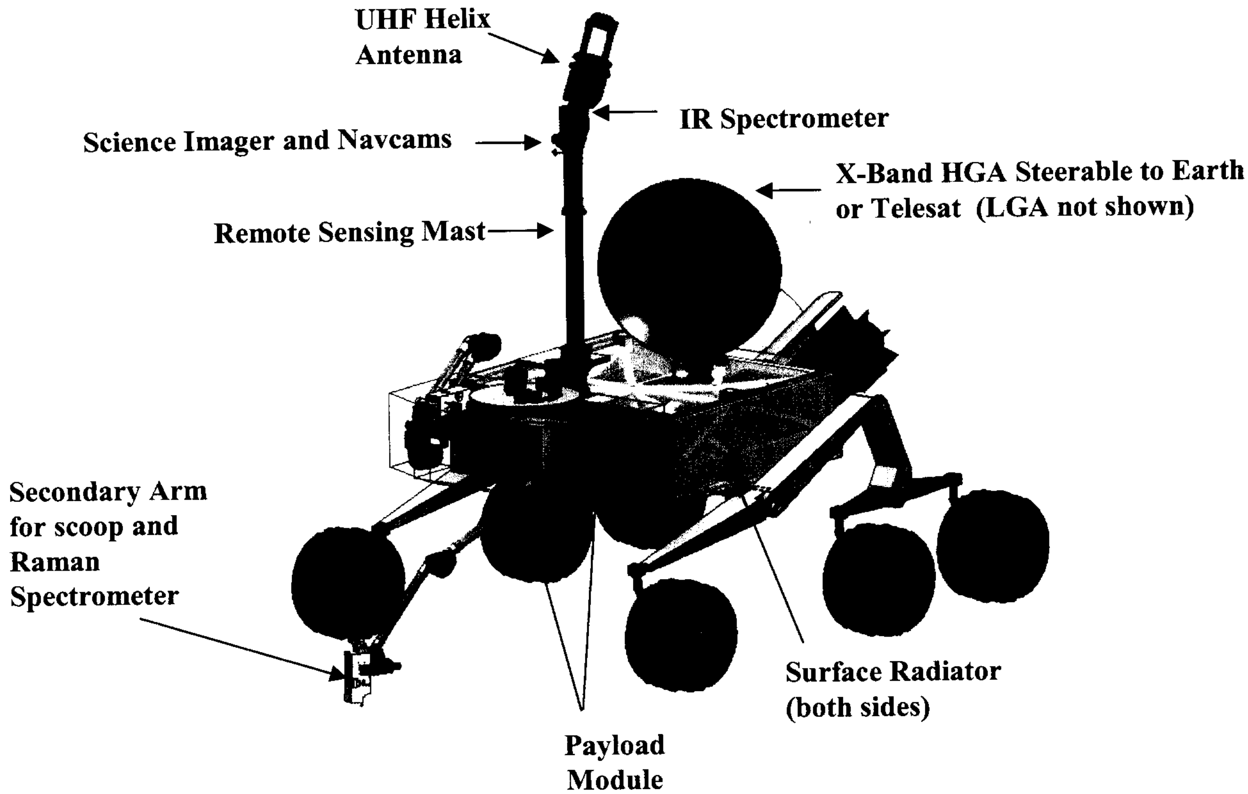

Figure 11, Mars Science Laboratory Rover, 2003

objectives are to understand the "habitability" of Mars - the capacity, past or present, for Mars to sustain life. This objective will be met through multidisciplinary measurements related to biology, climatology, geology and geochemistry. The rover design is shown in Figure 11.

MSL's mission design features:

1. One Mars year of operations
2. Able to access almost 80% of the surface of Mars
3. Precision landing (10x5 km landing ellipse)
4. New entry, descent and landing system including guided entry (Apollo-like), supersonic and subsonic parachute, propulsive terminal descent stage with hazard detection and correction and "rover on a rope" landing
5. 900-1000 kg mobile system with >120 kg of science payload
6. Mission driven by number of sites (~4) and samples (>28)
7. Science decisions requiring human interaction at a rock sample site are greatest driver on mission duration
8. 50 m/sol average driving range based on 5-10 cm/sec average driving speed
9. Hazard detection capability needed is no more than MER-class
10. Large vehicle size allows for simple path planning

Programmatic Approach

The Mars Science Laboratory is currently in Phase A. The Project is planned to be JPL's next major in-house mission, with significant contributions from industry and other NASA centers including Langley, Johnson and Ames.

The major milestones include:

System Requirements Review	12/04
Preliminary Design Review	10/05
Critical Design Review	10/06
I&T Readiness Review	2/03
Flight Readiness Review	9/09
Baseline Launch Day	10/09
Arrival at Mars	5/10
End of Mission	10/12

	Sojourner	MER	MSL	Lunar Rover
Launch Year	1996	2003	2009	1971
Rover Mass (including payload)	10.6* kg	180 kg	900 kg	700 kg
Payload Mass	1 kg	25 kg	120 kg	500 kg
Rover Power	50 Wh/sol	600 Wh/sol	5000 Wh/sol	2800 Wh
Compute power	.25 MIP	20 MIP	>200 MIP	Human
Control scheme	CARD+Behaviors	CARD+Hazard	CARD+Hazard	Human
Rover Life	>90 sols (actual)	90 sols	670 sols	Hours
Rover Range	~0.1 km	~1 km	~6 km	>25 km
Average speed	0.3 cm/s	5 cm/s	5 cm/s	6 mph
Traverse robustness	Low	Moderate	High	Low
Ground clearance	0.1 m	0.25 m	0.75 m	0.3 m
Kinetic energy at landing	10000 (N-m)	10000 (N-m)	450 (N-m)	NA

Figure 12, Rover Comparisons

The total cost of the development phase (excluding launch vehicle, power source and operations) of the project is capped at $870M for pre-Phase A through launch plus 30 days. There is an additional $77M in the Mars Technology Program for technologies focused specifically toward MSL including a Viking derivative throttled engine, phased array radar, mobility, descent stage, guidance and control S/W.

The project plans to execute a significant amount of work in Phase A/B focusing on high-risk developments, including instruments and software, and on procurement of long-lead hardware. By the time of confirmation, the Project will have spent about $100M, which represents a healthy Phase A/B over C/D ratio of ~15%.

6. COMPARISON SUMMARY

The family of extra-terrestrial rovers has evolved in capability and application since their first concepts in the 1960's. Figure 12 compares various performance parameters of the Sojourner, MER, MSL and Apollo rovers. Figure 13 shows the relative sizes of the three Mars rover designs and their obstacle tolerance capabilities.

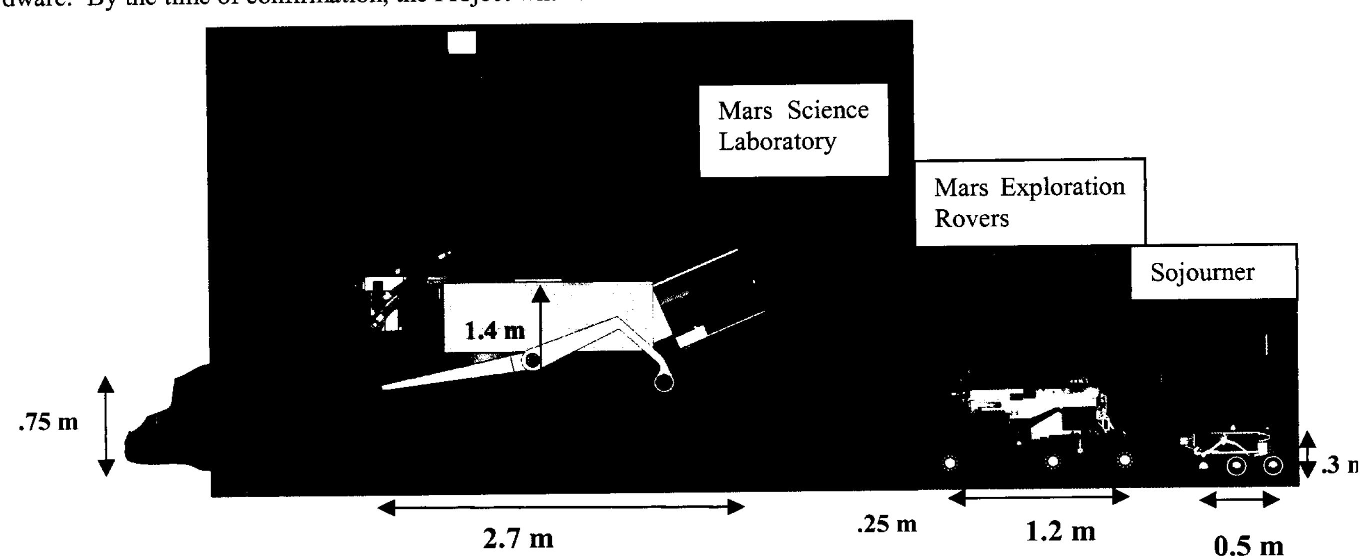

Figure 13, Rover Size Comparison

7. CONCLUSIONS

The mobility that rovers provide is an essential element in the exploration of planetary surfaces, especially Mars. Rover design is always a trade-off between conflicting factors including mobility and control, safety, and scientific return. To date, the design and operation of rovers on Mars has been necessarily conservative due to the large investment, high degree of uncertainty in the environment and short operational life time.

Mars Science Laboratory represents a new generation of long duration, high performance rover that is inherently more robust to the unknowns of the Martian environment. By virtue of its on-board capabilities and large payload it has the potential for significant new scientific discoveries. In addition it enables an evolution toward a more reliable and sophisticated balance between autonomous control, mobility and user/science friendly operations.

ACKNOWLEDGMENTS

The work presented in this paper was carried out by members of the Mars Science Laboratory team at the Jet Propulsion Laboratory and the Langley, Johnson and Ames NASA centers. The author wishes to thank Brian Wilcox for his significant help in providing information and insight into the rich history of planetary rovers.

Brian Muirhead has worked on numerous spacecraft and technology projects, including Galileo, SIR-C, and MSTI-1, since coming to NASA's Jet Propulsion Laboratory in 1978. He was responsible for the design, development, test, and launch of the Mars Pathfinder spacecraft that landed successfully on Mars on July 4, 1997. Following this successful landing he was named Project Manager. In August 1999 he was appointed Manager of the Deep Impact Project whose mission is to attempt the first-ever impact of a comet nucleus to uncover the structure and composition of these 4.5 billion-year-old time capsules dating back to the beginning of the solar system. In November 2002, he became the Chief Engineer of the Mars Science Laboratory mission.

He received his BS in Mechanical Engineering from the University of New Mexico in 1977 and an MS in Aeronautical Engineering from Caltech in 1982. He is the recipient of NASA's Exceptional Achievement Medal for his work on SIR-C and the Exceptional Leadership Medal for his work on Mars Pathfinder. He is the author of "High Velocity Leadership" (Harper Business, 1999) and "The Mars Pathfinder Approach to 'Faster-Better-Cheaper'" (Pritchett and Associates, 1998).