Lost in Space: A Case Study in Engineering Problem-Solving

Part I: Exploration--Opportunity or Albatross?

by
Albert Titus
Department of Electrical Engineering
Rochester Institute of Technology

Patricia Smith dug a twenty out of her pocket to pay the cab driver and then hurried inside the restaurant. She was already late meeting a few friends for dinner. When she got inside Chez Bistro, she saw that only Kaleen was there. Everyone else was late.

"I thought I was late!" said Patricia to Kaleen.

"You are, but everyone else is later," Kaleen responded with a smile.

Patricia and Kaleen had been friends since Patricia had moved to Washington DC, although their backgrounds could not have been more different. Patricia was a high-level official at NASA, while Kaleen was a well-known sculptor. Patricia ordered a drink as they waited for the rest of the gang to show up. The conversation turned, as do all discussions in DC, to politics.

"Any more failures at NASA?" asked Kaleen, referring to the recent Mars mission failures. "Any more opportunities for sending a few hundred million dollars crashing onto some worthless planet?"

Patricia did not flinch: "Aren't you curious to know if there is life out there? The prevalence of life in the universe is one of the most profound, and as yet, unanswered philosophical questions."

"I may be interested in knowing that, but I'd rather solve some problems here on Earth first. Let's get rid of homelessness, AIDS, cancer, poverty, famine first. Then let's look for little green men," Kaleen responded.

"I don't dispute that those problems are important," retorted Patricia, "but exploring space could bring new technology and new solutions to bear on the problems we have on Earth. The knowledge we gain could solve countless problems. And if we are able to find suitable locations for life in the universe, we could colonize these planets or use them to bring needed resources back to Earth as our own resources disappear."

Kaleen shook her head. "That sounds very iffy to me. Spending a lot of money on the long shot that there would be some return that is beneficial to humans, especially since the returns may not come for many, many years."

"But don't you have a sense of adventure? For centuries human beings have risked their lives and dedicated resources to venture into the unknown and explore the environment around them. Their motivation has been driven by a variety of economic, political and other reasons," Patricia responded. "Space is the 'final frontier'."

"Exploration is just a way of running away from our problems. We can't even justify it as a national defense issue since the cold war is over. It seems clear to me that imperatives other than profit, military exploitation, or nationalism will have to compel human beings to explore the extraterrestrial environment."

Just then Pete and Bill finally showed up, abruptly ending the unfinished debate.

Part I Questions:

1. Is space exploration a good use of money and resources?
2. By what means can extra-terrestrial exploration of space be conducted?
3. What are the limits and constraints for ground-based exploration?
4. What are the limits or constraints for space-based exploration?
5. How can the question of the extra-terrestrial existence of life be addressed?
6. How can life be detected?
7. What planetary characteristics would provide good candidates for life?

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Part II: Why Go to Mars?

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Albert Titus
Department of Electrical Engineering
Rochester Institute of Technology

Outside of the Earth-Moon system, Mars, the fourth planet from the Sun, is the most hospitable body in the solar system for humans. The seventh largest planet in the solar system is at a distance of 4.7 x 10^7 miles from earth. It has a diameter of about 4,250 miles and it has a mass of approximately 6.4219 x 10^{23} kg. Mars' orbit is significantly elliptical, which causes a temperature variation of about 30° C. at the subsolar point between aphelion and perihelion. This has a major influence on Mars' climate. While the average temperature on Mars is about 218 K (-55° C., -67° F.), Martian surface temperatures range widely from as little as 140 K (-133° C., -207° F.) at the winter pole to almost 300 K (27° C., 80° F.) on the day side during summer.

The interior of Mars is known only by inference from data about the surface and the bulk statistics of the planet. The most likely scenario is a dense core about 1,000 miles in radius, a molten rocky mantle somewhat denser than the Earth's, and a thin crust. Data from the Mars Global Surveyor indicates that Mars' crust is about 50 miles thick in the southern hemisphere but only about 22 miles thick in the north. Mars' relatively low density compared to the other terrestrial planets indicates that its core probably contains a relatively large fraction of sulfur in addition to iron (iron and iron sulfide).

Mars has a very thin atmosphere composed mostly of the tiny amount of remaining carbon dioxide (95.3 percent) plus nitrogen (2.7 percent), argon (1.6 percent) and traces of oxygen (0.15 percent) and water (0.03 percent). The average pressure on the surface of Mars is only about 7 millibars (less than 1 percent of Earth's), but it varies greatly with altitude from almost 9 millibars in the deepest basins to about 1 millibar at the top of Olympus Mons. Mars' thin atmosphere produces a greenhouse effect that is only enough to raise the surface temperature by 5 K; much less than what we see on Venus and Earth. However, the atmosphere is thick enough to support very strong winds and vast dust storms that on occasion engulf the entire planet for months.

Mars has permanent ice caps at both poles composed mostly of solid carbon dioxide ("dry ice"). The ice caps exhibit a layered structure with alternating layers of ice with varying concentrations of dark dust. In the northern summer the carbon dioxide completely sublimes, leaving a residual layer of water ice. It is not known if a similar layer of water ice exists below the southern cap since its carbon dioxide layer never completely disappears. The mechanism responsible for the layering is unknown but may be due to climatic changes related to long-term changes in the inclination of Mars' equator to the plane of its orbit. There may also be water ice hidden below the surface at lower latitudes. The seasonal changes in the extent of the polar caps changes the global atmospheric pressure by about 25 percent as measured at the Viking lander sites.

Part II Questions:

1. What is the escape velocity from Earth?
2. What is the escape velocity from Mars?
3. How long does it take light to travel from Earth to Mars? Compare this to human travel time.
4. What characteristics of Mars make it a viable candidate for supporting life now or at some time in the past?
5. How can specific atmospheric conditions and soil characteristics that could sustain life on Mars be measured?
6. How can we ensure that a launch vehicle will arrive at the desired destination?

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Part III: Going to Mars—The Mars Climate Orbiter Mission

by
Albert Titus
Department of Electrical Engineering
Rochester Institute of Technology

OVERVIEW OF MISSION:

- **Mission**
  "Volatiles and Climate History"
- **Launch**
  The orbiter was launched from Cape Canaveral Air Force Station (CCAFS) Space Launch Complex 17 (SLC-17) on December 11, 1998.
- **Launch Vehicle**
  Boeing Delta II 7425. The upper stage consists of a spin stabilized Star 48 with a Nutation Control System and a yo-yo despin device.
- **Spacecraft Dimensions**
  Main bus: 2.1 meters (6.9 feet) tall, 1.6 meters (5.4 feet) wide and 2 meters (6.4 feet) deep.
  Wingspan of solar array: 5.5 meters (18 feet) tip to tip.
- **Spacecraft Weight**
  629 kg (1,387 pounds) total, consisting of 338 kg (745 pounds) spacecraft and 291 kg (642 pounds) fuel.
- **Science Instruments**
  Mars Colar Imager (MARCI)
  Press Modulator Infrared Radiometer (PMIRR)
- **Spacecraft Power**
  Solar array providing up to 1,000 watts just after launch, 500 watts at Mars.
- **Project Cost**
  $327.6 million total for both orbiter and lander (not including Deep Space 2). $193.1 million for spacecraft development, $91.7 million for launch, and $42.8 million for mission operations.

STATUS:

"The MCO had been on a trajectory toward Mars since its launch on December 11, 1998. All spacecraft systems had been performing nominally until an abrupt loss of mission shortly after the start of the Mars Orbit Insertion burn on September 23, 1999. Throughout spring and summer of 1999, concerns existed at the working level regarding discrepancies observed between navigation solutions. As MCO approached Mars, three orbit determination schemes were employed. Doppler and range solutions were compared to those computed using only Doppler or range data. The Doppler-only solutions consistently indicated a flight path insertion closer to the planet. These discrepancies were not resolved.

On September 8, 1999, the final planned interplanetary Trajectory Correction Maneuver-4 (TCM-4) was computed. This maneuver was expected to adjust the trajectory such that soon after the Mars orbital insertion (MOI) burn, the first periapse altitude (point of closest approach to the planet) would be at a distance of 226km. This would have also resulted in the second periapse altitude becoming 210km, which was desired for the subsequent MCO aerobraking phase. TCM-4 was executed as planned on September 15, 1999.

Mars orbit insertion was planned on September 23, 1999. During the weeklong timeframe between TCM-4 and MOI, orbit determination processing by the operations navigation team indicated that the first periapse distance had decreased to the range of 150-170km.

During the 24 hours preceding MOI, MCO began to feel the strong effects of Mar's gravitational field and tracking data were collected to measure this and incorporate it into the orbit determination process. Approximately one hour prior to MOI, processing of this more accurate tracking data was completed. Based on these data, the first periapse altitude was calculated to be as low as 110km. The minimum periapse altitude considered survivable by MCO is 80km.

The MOI engine start occurred at 09:00:46 (UTC) on September 23, 1999. All systems performed nominally until Mars's occultation loss of signal at 09:04:52 (UTC), which occurred 49 seconds earlier than predicted. Signal was not reacquired following the 21 minute predicted occultation interval. Exhaustive attempts to reacquire the signal continued through September 25, 1999, but were unsuccessful.

On September 27, 1999, the operations navigation team consulted with the spacecraft engineers to discuss navigation discrepancies regarding velocity change (DV) modeling issues. On September 29, 1999, it was discovered that the small forces DV's reported by the spacecraft engineers for use in orbit determination solutions was[sic] low by a factor of 4.45."

—Taken from: Mars Climate Orbiter Mishap Investigation Board Phase I Report, NASA, November 10,1999.

Part III Questions:

1. Insertion into the Mars atmosphere seemed to be at an altitude that was too low for the MCO to survive, less than the 80km. Why would 80km be a minimum altitude for survivability?
2. While en route to Mars, periodic adjustments must be made to the MCO's flightpath. How would this be accomplished?
3. What could be the cause of the discrepancies in the small forces DVs?
4. How could this happen?

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Part IV: Mars Climate Orbiter Mishap Investigation

by
Albert Titus
Department of Electrical Engineering
Rochester Institute of Technology

Patricia Smith sighed and rubbed her eyes as she picked up the Mars Climate Orbiter (MCO) Mishap Investigation Board (MIB) Report. She thought about another cup of coffee, but decided that four were enough for one morning. She glanced at the clock on her desk, the official NASA clock that was given to those who had been at NASA for 10 years. She had been there for 12 years now, but just recently was promoted to the position of Associate Administrator of the Office of Safety and Mission Assurance at NASA. As such, she reported directly to the head of NASA, Denis T. Newman. Denis had initiated the revolution in NASA thinking through the slogan "Faster, Better, Cheaper," and he had requested that Patricia submit to him personally a memo that specified what she thought should be done as a result of the report.

These thoughts whizzed through her mind in a matter of seconds as Patricia focused her gaze back onto the report. She looked at the Executive Summary again:

> This report addresses any aspects of the MCO mishap that may have caused the failure of the mission and potentially could threaten the successful completion of the Mars Polar Lander Mission.
>
> The MCO Mission Investigation Board (MIB) has determined that the root cause for the loss of the MCO spacecraft was the failure to use metric units in the coding of a ground software file, Small Forces, used in trajectory models. Specifically, thruster performance data in English units instead of metric units were used in the software application code titled SM_FORCES (small forces). A file called Angular Momentum Desaturation (AMD) contained the output data from the SM_FORCES software. The data in the AMD file was required to be in metric units per existing software interface documentation, and the trajectory modelers assumed the data were provided in metric units per the requirements.
>
> During the 9-month journey from Earth to Mars, propulsion maneuvers were periodically performed to remove angular momentum buildup in the on-board reaction wheels (flywheels). These Angular Momentum Desaturation (AMD) events occurred 10-14 times more often than was expected by the operations navigation team. This was because the MCO solar array was asymmetrical relative to the spacecraft body as compared to Mars Global Surveyor (MGS) which had symmetrical solar arrays. This asymmetric effect significantly increased the Sun-induced (solar pressure-induced) momentum buildup on the spacecraft. The increased AMD events coupled with the fact that the angular momentum (impulse) data were in English, rather than metric, units, resulted in small errors being introduced in the trajectory estimate over the course of the 9-month journey. At the time of Mars insertion, the spacecraft trajectory was approximately 170 kilometers lower than planned. As a result, MCO either was destroyed in the atmosphere or re-entered heliocentric space after leaving Mars' atmosphere.
>
> The Board recognizes that mistakes occur on spacecraft projects. However, sufficient processes are usually in place on projects to catch these mistakes before they become critical to mission success. Unfortunately for MCO, the root cause was not caught by the processes in-place in the

MCO project.

A summary of the findings are listed below. These are described in more detail in the body of this report.

Root Cause: Failure to use metric units in the coding of a ground software file, Small Forces, used in trajectory models.

Contributing Causes:

1. Undetected mismodeling of spacecraft velocity changes
2. Navigation Team unfamiliar with spacecraft
3. Trajectory correction maneuver number 5 not performed
4. System engineering process did not adequately address transition from development to operations
5. Inadequate communications between project elements
6. Inadequate operations Navigation Team staffing
7. Inadequate training
8. Verification and validation process did not adequately address ground software

Patricia shook her head as she read the root cause for failure. She knew the software engineer who was in charge of that portion of the project, William (Bill) Burns. Patricia and Bill had gone to college together, were hired by NASA at the same time, and were still close friends. She even had Bill write her a letter of recommendation when she applied for the high-level position she now held. Bill was a top-notch programmer. More than once she had visited the Linux utilities website he ran on the side. Thus, she was uncertain about what to do.

Clearly the error in the software was the primary cause of the failure of the MCO. She could recommend to Denis that Bill be fired or demoted as a result. However, she also felt that the "Faster, Better, Cheaper" mantra could be the overarching cause of the problem; the report indicated that there were contributing causes to the failure and one could fault the NASA goal to do things faster and cheaper. Since Patricia reported directly to Denis and it was his philosophy that now drove NASA, a memo that faulted his direction could be problematic.

Patricia sighed again as she clicked on the Word icon to start typing her memo.

Part IV Questions:

1. What should Patricia do in this situation?
2. Should Patricia act differently if Bill Burns was not a close personal friend?
3. Is "Faster, Cheaper, Better" a failure or success? Why?
