ICEBREAKER: AN EXPLORATION OF THE LUNAR SOUTH POLE

Paul Tompkins, Ashley Stroupe
The Robotics Institute, Carnegie Mellon University
Pittsburgh, PA

Abstract

The proposed Icebreaker mission intends to conduct a robotic ground investigation of the southern polar region of the Moon. Searching for water ice and performing geological studies of the lunar south pole will provide essential information on the presence and distribution of resources necessary to support human habitation and a base for deep-space missions (such as water, fuel and propellant components, and potential construction materials) as well as for fundamental scientific investigation. Icebreaker proposes an academic, commercial and government partnership, to create economical, multi-dimensional missions.

Introduction

Icebreaker is a proposed mission to explore the south pole of the Moon. Icebreaker's goals are to gather scientific data, to conduct exploratory traversals of the surrounding terrain, to measure the prospects for long-term human presence at the poles, and to gather imagery for public enjoyment.

Icebreaker would continue the work of Lunar Prospector, determining the nature of the hydrogen it detected, be it water ice, solar wind protons, or other. If water is found, Icebreaker data will determine its origin and begin to characterize its distribution. If the hydrogen's source is not water, Icebreaker will collect data to determine its true origin.

In addition, Icebreaker will roam the polar landscape, collecting geologic data and exploring hills, valleys and craters to enhance our scientific knowledge of a region never before explored. If water and other useful resources are found on the poles, humans will likely inhabit them in the future. Easily accessible water ice deposits will be catalogued and the ice distribution will be determined to prepare for in-situ resource utilization. Icebreaker data may allow scientists to derive the location and quantity of minerals and metals for future mining and space construction operations. Icebreaker will also search for potential outpost and landing site locations. Finally, Icebreaker seeks to create commercial and educational opportunities stemming from public interest in a return to the Moon's surface.

Goals

Fundamental Science

Scientists have theorized the presence of water ice at the lunar poles for decades[3,19]. Bistatic radar measurements taken by the Clementine spacecraft yielded inconclusive results regarding the presence of water ice[12,16]. Earth-based radar measurements of the lunar poles also do not yield a signature typical of concentrated water ice[17]. However, the neutron spectrometer aboard Lunar Prospector detected high concentrations of hydrogen isolated at the extreme latitudes of the poles, pointing strongly to large deposits of ice[4].

The source of this hydrogen has been in much debate by lunar scientists. Such hydrogen could be due to the presence of water or to an accumulation of solar wind hydrogen. Many have theorized that water from cometary impacts could have gathered over millenia in the low-energy environment of permanently shadowed regions at the poles[3,19]. The rate of atomic hydrogen dissipation and solar wind characteristics have brought more weight behind the belief that water ice can be found in abundance in this region. The Icebreaker investigation will help to confirm or deny this hypothesis.

If Icebreaker determines that water ice is responsible for the polar hydrogen signal, then additional studies will commence to determine ice distribution throughout the permanent dark, its near-surface stratigraphy beneath the lunar regolith, and its isotopic composition. Ice may be concentrated in sheets or thinly distributed throughout regolith. Knowledge of its distribution and stratigraphy could lead to theories on the mechanism for water accumulation. Concentrations of ice might be separated by layers of soil, possibly indicative of impact history or gardening. Finally, water in comets is known to be relatively higher in deuterium concentration than solar wind hydrogen. An isotopic analysis of ice could determine whether its source is comet ice, through a process of FeO reduction with solar wind hydrogen, or lunar interior degassing[3,19].

The initial search may detect large amounts of atomic hydrogen, but no water ice. In that case, we must gather hydrogen distribution and concentration data which could be used to support or counter the hypothesis of solar wind accumulation as its source. This ability to test the validity of hypothesis alternatives is key to the success of the Icebreaker mission.

A second scientific goal of the Icebreaker mission is to characterize the geology of the south polar region. The South Pole Aitken basin is one of the most actively researched for lunar geology. Though primarily a lunar far side feature, the basin encompasses the south pole and territory to a few degrees north of the pole on the near side. The largest known impact crater in the solar system, at 2600 km in diameter, Aitken has led scientists to theorize that the impact uplifted material from the upper mantle. Clementine and Lunar Prospector data have promoted scientists to identify the South Pole Aitken region as representing one of three distinct lunar crustal "terrane" classes[5]. Others credit the dramatic geologic differences between the lunar near side and far side to the South Pole Aitken impact[13].

The goal of Icebreaker is to refine remote sensing measurements by taking ground truth data. South Pole Aitken studies may emphasize the search for deposits to determine composition of the upper lunar mantle and lower crust. A study of the mineral content at the south pole may simultaneously aid in characterizing substantial regions of the lunar far side. Explorations of basin-internal craters may attempt to characterize the geology resulting from the impact and the subsequent crater evolution. The robot may find rocks metamorphosed by the high-energy impact event, as well as evidence of lava flow or crustal and mantle upwelling.

Additional scientific studies could also be achieved with the Icebreaker mission. The robot could measure the surface temperature at numerous positions within a crater, both in sunlight and permanent dark. Correlated with the positions at which ice was found, scientists may obtain a measure of temperature requirements to support ice accumulation. Sunlit surface temperatures provide data for the effect of reflected radiative energy transfer on other parts of the crater.

Preparation for Human Exploration

Water is essential to the sustenance of human life on the Moon. Mining water from the poles would enable the production of drinking water and oxygen, reducing a habitat's dependence on fully recyclable life support concepts. Aside from improving the prospects for long-term life support on the Moon, finding lunar water ice could create an industry devoted to the in-situ production of cryogenic rocket propellant for Earth-Moon and deep-space orbital transfer. Ice distribution and stratigraphy data from Icebreaker would assist scientists and engineers in designing extraction and purification techniques for in-situ resource utilization. The development of a space flight staging area on the Moon would open space transportation avenues not otherwise available, including faster deep-space trajectories and the ability to carry far heavier payloads to the planets.

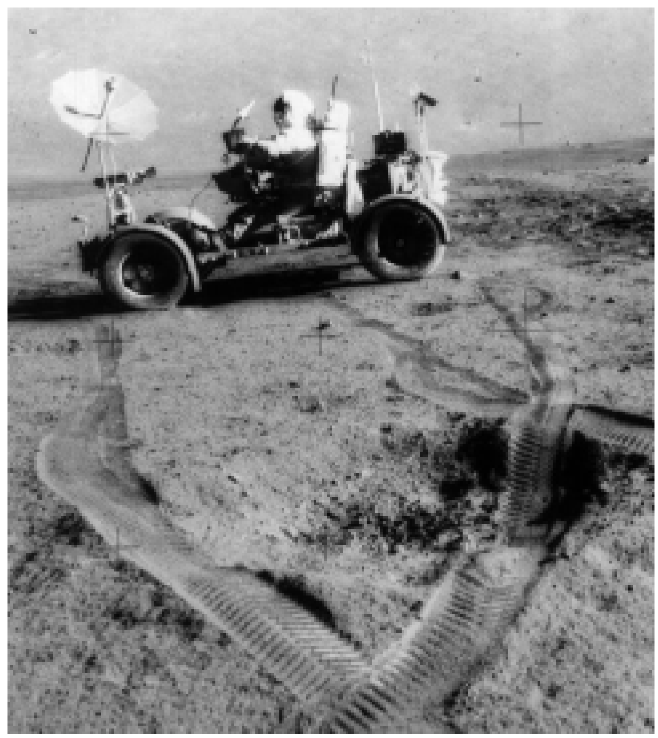

Fig. 1: The human-driven Apollo Lunar Roving Vehicle in typical Lunar terrain. Note that permanent tracks are left behind and clearly visible.

Aside from the possibility of harboring water, the lunar poles exhibit qualities which could be advantageous for early human settlement. Unlike equatorial regions of the moon which experience extreme diurnal variations in surface temperature as the sun rises and sets (254 K ± 140 K), the pole temperatures vary more slowly and less dramatically (220 K ± 10 K)[6]. As on Earth, each pole experiences a summer, during which the sun climbs highest in the sky, and a winter, when the sun remains largely below the horizon. While the Earth's spin axis is tilted 23.5° with respect to the ecliptic plane, the Moon's is tilted a mere 1.5°. Consequently, elevated regions surrounded by extensive lowlands on the poles (e.g. Aitken basin) may enable surface sun exposure far into the winter. Early topographic measurements of the south polar region of the Moon indicate regions that are illuminated by the sun during the winter months[2]. Establishing an outpost in a region with nearly continuous sun exposure would drastically reduce its dependence on power storage or nuclear power production.

Icebreaker would enable the first direct measurements of polar surface temperature and the production of local maps of terrain and sun exposure. Knowledge of solar power availability and the polar thermal environment would aid in the designation of human outpost sites and in setting requirements for lunar habitat modules.

Commercial

The extensive media coverage of the Mars Pathfinder mission reflects a public desire for connection with space exploration. Even more than Pathfinder, Icebreaker will embody the concept of robotic explorer, with long-distance treks across unknown territories over several months. People will watch to find out what lies behind the next hill or in the dark of permanent shadow. Television and internet coverage of the mission, judging by the popularity of Pathfinder, could be an enormously successful commercial venture. Such an enterprise could comprise coverage rights, television and internet advertisements, and spacecraft- and launch vehicle-mounted advertising logos. A return to the Moon's surface could also stimulate the public's interest in television documentaries which describe the design, construction and flight of Icebreaker. For any television or internet broadcast or printed publication, high-resolution, full-color images would be the focus of public attention. Unlike the pictures taken during the Apollo missions, Icebreaker pictures will illustrate a world of extreme light and shadow, with mountains and pronounced crater rims at the horizons. As a backdrop for the stark lunar terrain, the Earth would always be visible from the rover. Such a collection of imagery would be in high public demand.

Icebreaker could also generate opportunities in the entertainment market. Icebreaker video, in conjunction with rover motion data recorded during its polar trek, could be incorporated into a highly immersive motion-based simulation ride. Participants would feel as if they were driving on the lunar pole. Offered at theme parks and science museums, a lunar exploration simulator could hold public interest long after the completion of the Icebreaker mission.

Mission Overview

The Icebreaker mission seeks to land in the South Pole Aitken Basin region of the Moon. Earth-based radar-derived topographic maps indicate that the south polar region contains more permanently dark areas than the north[8], perhaps conflicting with Lunar Prospector data which measured a higher concentration of hydrogen in the north[4]. Combined with the geologic goals of the mission, Icebreaker proposes to target the lunar south pole. To ensure the greatest amount of sun for solar energy collection, Icebreaker will launch just before summer begins in the southern hemisphere.

A reusable, single-stage-to-orbit launch vehicle will propel the Icebreaker spacecraft into low-Earth orbit. A solid rocket motor will inject Icebreaker into trans-lunar orbit, a trajectory which will intercept the Moon five days later. Once near the Moon, the remaining space hardware, a lander and its rover payload, will inject into a lunar polar orbit. Following several orbital revolutions, the lander will begin its descent to the lunar surface. Guided automatically, the lander will touch down at a pre-selected location. The target landing site will be an area lighted by the sun and in view of the Earth to permit solar power production and communications with the Earth. After touchdown, operators will work to drive the rover down the lander's ramps to begin surface operations.

To take advantage of the predominantly sunlit regions, a South Pole Aitken mission would land a rover in the basin. The landing site would be within a region of nearly continual light, and would be chosen for its proximity to interesting features and topographic suitability for landing. Extended periods of light during southern hemisphere summer would allow a solar powered rover to traverse tens or hundreds of kilometers. The mission would be nomadic in character, beginning with modest exploration near the landing site, and followed by more ambitious treks across the surface. Geologic measurements would be taken throughout the course of the treks. Areas of suspected permanent dark would be explicitly sought out and explored when accessible. The final Icebreaker sorties would involve entry into a crater, involving more difficult but perhaps more rewarding terrain for the discovery of ice.

The primary advantage of a South Pole Aitken trek mission is the presence of continuous sunlight for solar power generation. Having a substantial, reliable safe-haven from the cold and dark will allow the rover to extend the reach of scientific exploration well beyond the landing site. Without monthly lunar night periods, rover operations could go nearly continuously over several months. Free from the restrictions of rough crater rim terrain, the South Pole Aitken trek would enable a geological exploration far beyond the landing site.

Despite its positive aspects, the South Pole Aitken trek would largely be restricted to crater-external terrain. At such extreme latitudes, ridges and hills may be adequate to create cold traps sufficiently large to harbor water ice. However, craters are the principal topographic features which create permanent shadow, and hence which are suspected to hold ice. The walls and rims of craters are extremely rugged and steep, particularly at the outer perimeter, severely limiting the ability of a robot or other vehicle to safely navigate them. The resolution of current lunar topographic data is not sufficient to locate and plan a safe entry ahead of time, even if such paths exist. The Icebreaker mission could seek opportunistic sorties into craters by taking images which allow operators to locate traversable entries and exits.

The difficulty of solar power generation and Earth communications contact that plague any lunar polar mission are accentuated within a crater. Crater walls reduce the duration of sunlight exposure over the course of a lunar day, and further constrain elevation angles at which direct Earth communications are possible. Additionally, if the rover is to operate in a crater over several months, the rover may be required to repeatedly switch into a hibernation mode for up to 10 days at a time in the extreme cold of lunar night. By identifying less rugged escape paths between the crater floor and the surrounding area, the rover can avoid the worst of these difficulties.

Rover

General Description

Icebreaker features a rover which carries a cryogenic drill and a science instrument package. The rover will be approximately 100 kg, with a footprint of 1 m by 1.5 m. The rover is primarily teleoperated from Earth, but capable of limited autonomy for obstacle avoidance and for automated recovery in the event of communication loss. Unlike the rocky landscape of Mars as seen from Sojourner, the Moon's surface is less cluttered, allowing for faster, longer distance robotic excursions. The rover is capable of driving for tens or hundreds of kilometers, at speeds up to 0.5 m/s across the rugged terrain around and inside lunar craters. Converted solar energy supplies power, and its thermal design allows the rover to survive in direct sun as well as for long periods in the frigid cold of permanent dark. The body of the rover will contain the electronics and science instruments, and a single-deployed mast will contain the sensors, cryogenic drill and communications.

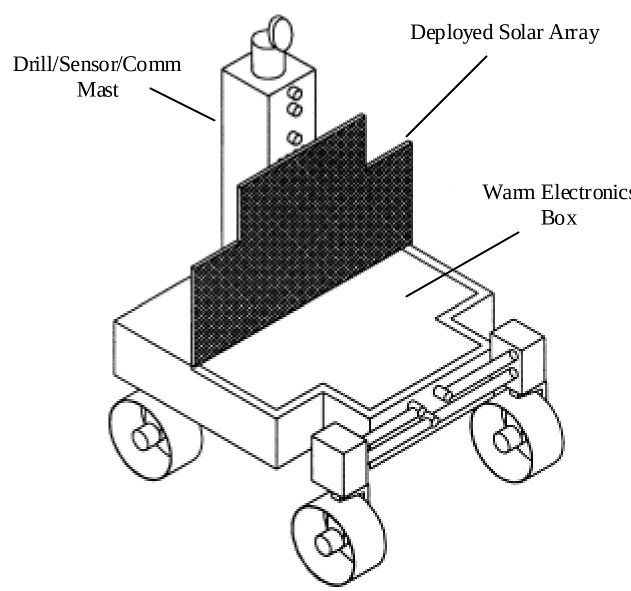

Fig. 2: The Icebreaker rover, rear view.

Suspension, Steering & Locomotion

The rover will have four independently driven wheels. The front pair of wheels are independently steered, while the rear pair of wheels sit on a parallel-link, rocking-axle suspension which keeps the wheels oriented vertically relative to the rover body. The suspension and steering design achieves good steering performance and high positioning accuracy, without sacrificing reliability by including additional actuators[1]. If an extremely tight turn is required, the robot can perform a skid-steer point turn. In addition, the parallel link suspension maintains good wheel contact with the ground as the rover crosses obstacles while still providing a stiff connection to the body for drilling.

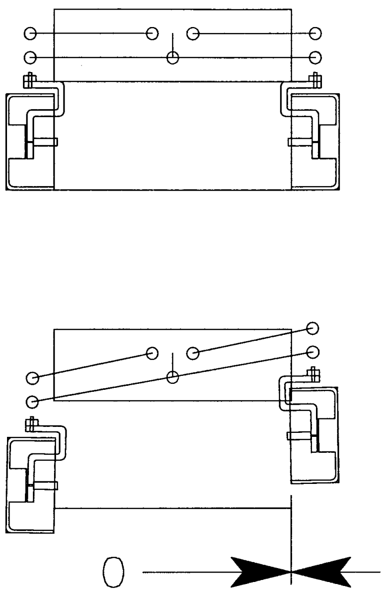

Fig. 3: Rover rear suspension, demonstrating vertical wheel orientation regardless of minor terrain variations

Power

The rover incorporates a vertically-mounted solar array, to optimize power collection at polar sun elevation angles. The rover is estimated to require approximately 80 Watts (on average), with a maximum of 160 Watts. In order to achieve these power levels, solar energy will be collected via a solar array of approximately 1 m^2 area and stored in rechargeable batteries. A 50% safety margin for a 9-hour sortie into permanent dark requires 1092 Wh of storage capacity, accomplished with 20 kg of silver-zinc batteries. Both the solar arrays and batteries will require adaptation to the extreme thermal environment in which the Icebreaker mission will operate. Solar cells and batteries can lose efficiency at high temperatures, and can be permanently damaged through thermal cycling. Developments to reduce the size and mass of battery cells would greatly increase the operational lifetime of the science rover.

Sorties into the permanent dark require the use of battery power for long-distance driving, communications and sporadic drilling. The rover's dependence on solar power will force return trips to illuminated areas for battery recharge. On the other hand, the use of a nuclear power source (Radio-Thermal Generator, or RTG) would alleviate the need for battery recharging, far increasing the capability of the rover. An RTG would enable the robot to spend months in a crater without the need for a special hibernation mode, further increasing the chances of finding ice and deriving detailed crater data. However, public opinion of the danger of such power sources may prevent Icebreaker from incorporating such a device.

Thermal

To date, no space system has been targeted for such a wide range in extreme temperatures as seen at the lunar poles. While in sunlight, the science rover will be subjected to direct solar radiation, requiring a means to reject heat to maintain thermal stability. The rover will regularly drive into regions of permanent dark, where surface temperatures are estimated to be as cold as 40 K. Traditional approaches for protecting components from low temperatures can prove fatal to the components in the sun and vice-versa. For such thermal extremes, the rover must be able to reconfigure itself to alternatively trap heat within its core, or reject heat to space.

The rover thermal properties will be dominated by the deployment state of the solar panel (the array will be deployed to cool and charge, and stowed to conserve heat). Components of the science rover must be organized within a "warm electronics box" such that the effects of thermal production of each component can be modeled and passively controlled. The insulation of the components and surface reflectance properties must also be considered. The type of insulation chosen must be able to prevent each component from exceeding its temperature range in both extreme cold and extreme heat. To eliminate the ground conduction path to the rover, its wheel design will incorporate fiberglass

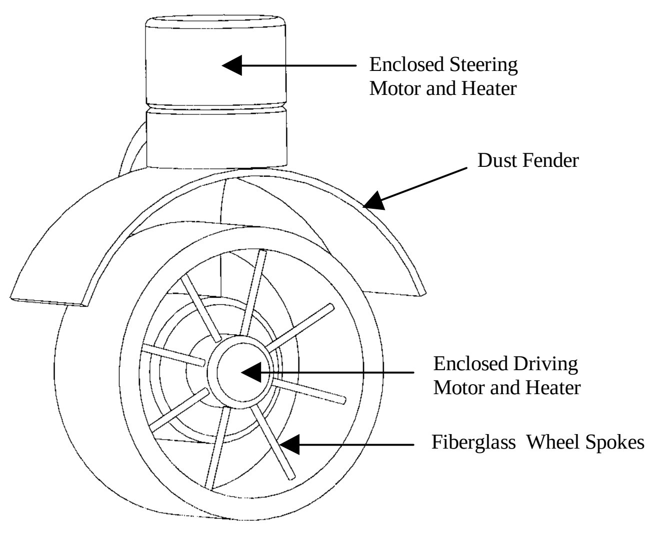

Fig. 4: Wheel configuration with thermal components

spokes.

Sources of additional heat, either electric or Radioisotope Heater Units (RHUs) will be required for surviving the coldest regions for extended periods. The current design positions RHUs in the wheels to heat wheel motors in the dark. Should an isotope power source (RTG) be employed, it may also have the benefit of contributing to the solution of the thermal design.

An initial lumped parameter analysis indicates that, given the proposed solar panel deployment capability, the rover body steady state temperature can be maintained between 272 K and 292 K in shade and sun respectively. The instrument mast, far from the warmth of the body electronics, will vary between 188 K and 277 K.

Additional Environmental Hardening

One of the greatest challenges in the Icebreaker design will be protecting the science rover against the lunar environment at the poles. Aside from protection from the extreme thermal environment, all components must be hardened to withstand the constant bombardment by solar wind radiation, and software must be robust to occasional data errors from high-energy solar and cosmic radiation. Apollo astronauts found that the fine, electrostatically charged lunar dust readily accumulated on the surface of the Lunar Roving Vehicle and on spacesuits[6]. Lunar dust is theorized to levitate in clouds to over 10 meters at the terminator between sunlit and shaded regions of the Moon. The science rover, alternately searching permanently shadowed regions for water and recharging in the sun, must pass through and spend extended periods of time in the dusty terminus region. This dust may hamper the performance of solar arrays and optical sensors, and could significantly increase the rover's tendency to absorb radiated thermal energy. The Icebreaker science rover must therefore employ techniques for the prevention of dust accumulation as well as dust removal.

Guidance, Navigation & Control

The primary method of rover control and navigation will be Earth-based waypoint teleoperation. The teleoperator will be aided by on-board obstacle avoidance, images, and local maps. The local maps will be generated autonomously on Earth-based computers, using odometry and ground and horizon landmarks as reference points. While traveling in the dark, strobe lighting will be used to illuminate the landscape. The sensors used for navigation are:

- Forward and aft IR laser light stripers with IR imagers, for locating obstacles and characterizing terrain
- Forward and aft CMOS active pixel sensor (APS) cameras, for visual data in sun or shadow (in conjunction with strobe light). APS cameras eliminate the need for a frame-grabber, thereby reducing the complexity of image data collection.
- Forward and aft contact sensors
- Sun sensor, for heading-based navigation and to optimize solar array pointing during battery recharging, and used indirectly to determine the position of the Earth when the Earth sensor is saturated by sunlight
- Earth sensor, to aid in communications antenna pointing while in shadow
- Gyros, accelerometers and wheel encoders, for position and orientation estimation

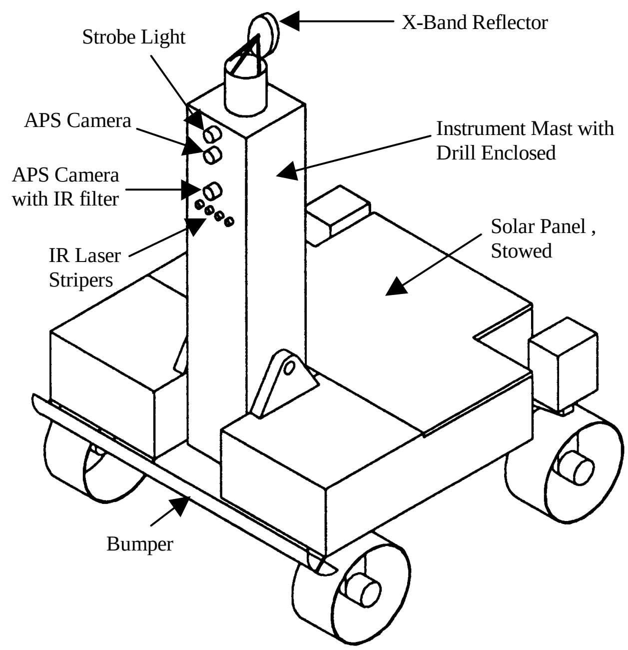

Fig. 5: Rover sensor configuration

Unlike the Sojourner rover on Mars, Icebreaker will be close enough to Earth to allow real-time operations with control delays of between 5 and 10 seconds. Consequently, the Icebreaker rover will be controlled by human operators on Earth. Icebreaker will traverse an unprecedented distance across the lunar surface, perhaps a total of 100 km. Driving such long distances will require a robot that can travel at least 0.3

to 0.5 m/s. Icebreaker will employ STRIPE[7], a teleoperation technique developed at Carnegie Mellon, proving its suitability for lunar robotics and global-distance applications.

The STRIPE teleoperation scheme allows an operator to select waypoints on a 2-D image retrieved from the robot's forward-looking camera. These waypoints are converted to points in 3-D, and are sent back to the robot as intermediate goals for driving. Field tests on Earth have shown this scheme allows accurate, high-speed, teleoperated driving under high network latency and with slow image update rates.

The Icebreaker science rover must incorporate some level of autonomy to enable high-level control for driving and to enhance its reliability. Though operators will select waypoints for driving, the rover will plan its path between points to achieve its goal. This involves autonomous local mapping, planning and updates in real time[18]. For the majority of situations, operators will be able to visually detect obstacles which could disrupt driving, thereby selecting waypoints on a path to avoid them. However, with the understanding that an operator's sensory inputs are limited in teleoperation, Icebreaker incorporates forward- and aft-looking laser light striping sensors to enable the independent detection of obstacles. The SMARTY algorithm, developed at Carnegie Mellon, is run on an Earth-based computer to produce an obstacle map given data from laser stripers. This obstacle map is superimposed on the teleoperator's camera image to assist with obstacle detection. SMARTY will additionally make steering recommendations for an operator. As an additional safeguard, Icebreaker will incorporate a fully autonomous obstacle avoidance process. If an operator selects a path which takes the rover toward an obstacle, the rover will detect them before collision, and will intercede to prevent further rover progress.

Driving progress will depend on direct line-of-sight communications with Earth. The Earth will always be at low elevation angles, increasing the likelihood of communications blockage by local terrain features. Depending on the distance of the terrain feature, from a boulder within meters, to a crater wall kilometers away, the communications signal will degrade at different rates. Operators would be able to detect gradual degradations in signal strength, and make adjustments accordingly. Rapid loss of communications will prevent an operator response. In such a case, the rover will first attempt communications via the low-gain antenna. If this is unsuccessful after a timeout of several minutes, the rover will begin an autonomous backtrack to the last position in which link communications could be verified. The RALPH algorithm[14] allows a vehicle to autonomously follow parallel features such as the wheel tracks created by the rover (see Figure 1). This system has been tested for road following at high speeds, and could easily be adapted for lunar rover use.

Finally, Icebreaker would incorporate autonomous self-monitoring functions, either on-board or as part of its ground support software. This functionality will aid operators in determining the cause of anomalistic behavior, and speed their response in fixing or compensating for root problems.

Maps and Localization

One of the greatest challenges of robot navigation in new environments is localization. Creating accurate maps and accurately locating the robot within the map is still an active area of robotics research. Traditional approaches would build maps based on sensor data and use odometry and/or nearby landmarks to localize the robot within the map.

Icebreaker would augment the standard approach with data from downward-looking imagery and from the Deep Space Network. The Mars 1998 lander design incorporated an imager which recorded images at successively lower altitudes while on its final descent[9]. Such imagery could be employed in conjunction with estimates of bearing to topographic features found at the horizon from the robot's perspective, to localize the robot near the landing site. Another scheme might use the ranging capabilities of DSN and the fixed position of the lander to accurately determine the position of the rover on the lunar surface.

Communications

In order to achieve near real-time teleoperation as a primary control mode, the communication system must quickly transfer sufficient data (estimated to be 150 kbps for downlink) to and from Earth. The rover will require an additional communications link between itself and the lander for flight and post-landing check-out.

Using X-Band, a medium gain antenna could provide the primary communications at high data rates and low power consumption. An omnidirectional antenna will act as a backup for the medium gain antenna in case of pointing loss, and for initial acquisition procedures.

Icebreaker may alternatively incorporate "reflectarray" technology developed at NASA[11]. These small, lightweight antennas are electronically steered, improving overall pointing performance, reducing the number of actuators deployed with the system, and improving the communications bandwidth by decreasing the beamwidth required for robust data transfer.

Science Payload

In order to meet the scientific goals of the mission, Icebreaker will incorporate scientific instruments from the following list:

- Cryogenic drill: A drill capable of drilling to depths of 1 meter is essential in enabling sub-surface ground truth measurements. Such a drill would collect samples of at least 1.5 cc, and would keep them thermally isolated for immediate analysis. An alternative approach would direct instrument boresights down-hole to provide in-situ measurements while drilling.
- Optical spectrometer: A long-distance optical spectrometer, operating in the UV, IR, and Visible ranges can provide information on the molecular composition of rocks. IR spectroscopy can also detect the presence of water ice. Laser-induced breakdown may be an option for elemental analysis.
- APXS spectrometer: This is a short-distance spectrometer that can provide elemental chemistry of rocks. This spectrometer is complementary to the optical spectrometer, detecting elements that are not clearly identifiable through optical means. The APXS is not capable of detecting hydrogen.
- Neutral mass spectrometer: This is a short-distance spectrometer than can provide both elemental and molecular composition of vaporized light-weight materials, such as water, carbon dioxide, and other common gasses.
- Neutron spectrometer: Similar to the instrument deployed on Lunar Prospector, data taken from this instrument could provide a ground comparison of hydrogen data to similar data taken from orbit. In conjunction with other instruments which detect water, the neutron spectrometer could provide a connection between local ice measurements and global data acquired from orbit.
- Ground Penetrating Radar: A ground-penetrating radar can provide information of sub-surface features to identify interesting sampling sites. GPR may enable a determination of the presence of ice prior to drilling, and could provide wide area measurements between drill sites. Coupled with ground truth measurements from drilling, GPR could locate the boundaries between lunar dust, ice and other sub-surface materials. NASA is currently developing extremely lightweight GPR units designed for use on planetary rovers.
- Radiometer: Radiometric data could be used to build temperature profiles, which are of interest within craters and cold-trap regions.
- Color Imager: A high-resolution color imager that can be pointed can provide feature information, as well as video sequences.
- Laser range finder: An actuated laser range finder would allow the creation of high resolution local maps for topographic scene analysis.

Lander

The Icebreaker lander will carry the rover from liftoff to landing near the lunar south pole. Incorporating a bipropellant propulsion system, the lander will execute mid-course correction maneuvers, reorientations and spin changes during the coast from the Earth to the Moon, will inject into lunar orbit, and will take the rover safely to the surface of the Moon.

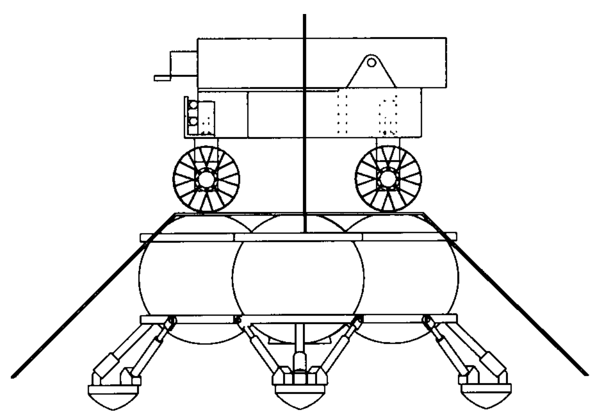

Fig. 6: Lander and stowed rover, with egress ramps deployed, side view

During coast, the lander may be flown in a spin stabilized mode. During final descent, the lander will make use of inertial measurement units and Doppler radar in a three-axis stabilized autonomous descent mode. The lander has its own solar panels, batteries and an independent communications system for on-orbit and post-landing operations.

Launch

The Rotary Rocket Roton[15] is designated the primary launch vehicle option for Icebreaker. The world's first Single Stage to Orbit (SSTO), reusable launch vehicle, the Roton is flown by two human crew members. Its projected payload capability is 3180 kg to 300 km low Earth orbit, which is sufficient to land a rover in the 100 kg class on the lunar surface. The Roton takes off vertically, powered by a rotary engine using liquid oxygen and kerosene. After delivering its payload, the Roton descends using a nose-mounted rotor system deployed in space. The rotor blades provide stability during reentry. A water-cooled skin maintains the spacecraft temperature to limits comparable to supersonic aircraft. Once in the atmosphere, tip-mounted jet thrusters aid the rotors in gliding the Roton to a safe, vertical landing. One added benefit is that the Roton is capable of landing with its full payload, safeguarding against pre-payload separation mishaps.

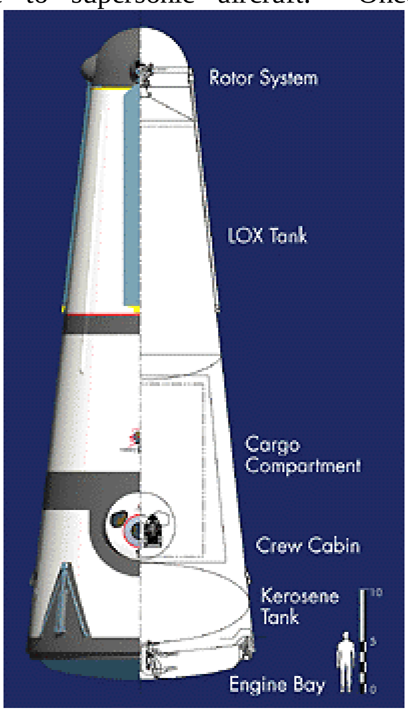

Fig. 7: Rotary Rocket Roton Launch Vehicle

The Roton's primary draw for Icebreaker stems from Rotary Rocket's $7-10 million early flight option. Atmospheric flight tests begin in 1999. The Roton will demonstrate its first orbital flight in summer 2000, with commercial flights beginning in 2001. Though currently in its development stages, the Roton will have flight heritage at the time of the Icebreaker liftoff.

Ground Communications Network

The NASA Deep Space Network (DSN) has been selected as the baseline ground antenna system for the Icebreaker mission. Its three primary facilities at Goldstone, California, Canberra, Australia, and Madrid, Spain are distributed around the globe for nearly full space coverage at lunar distances. Each DSN site consists of a collection of antennas, 9, 26, 34 and 70 meters in diameter: the smallest, fastest slewing antennas are optimally used for low-Earth orbit applications, and the largest antennas for deep-space communications or high data rate applications. The operators are the most experienced space mission operators in the world, having supported every NASA deep space mission flown.

Fig. 8: Deep Space Network (DSN) 70 meter antenna, Canberra, Australia

Initial link budget calculations indicate that the 34-meter antennas are appropriate for the lunar surface mission baseline[10]. These antennas produce the signal strength required to receive medium and low data rate transmissions from the lunar surface and from orbit. The Icebreaker mission baselines the DSN 34-meter antennas due to their wider availability than 70-meter antennas. The mission includes some particularly critical events which may require the extra data transmission potential and signal margin from the 70-meter dishes, such as lander vehicle descent and initial rover excursion into shadowed regions. In addition, the DSN 70-meter dishes may be requested during an anomaly situation that requires very high signal strength to establish communications, or for high data rate imagery downlink.

In addition to communications services, the DSN provides a highly accurate ranging capability. Measurements taken by DSN antennas include spacecraft line-of-sight range rate, line-of-sight range, and azimuth and elevation. Once enough data has been gathered, estimates of lunar transfer orbit accurate to the level of centimeters and centimeters per second are possible. Also, lander and rover position on the Moon may be estimated within several hundred meters after many hours of ranging.

Carnegie Mellon University Robotics

The Carnegie Mellon University Robotics Institute has a strong basis in developing robotics technology for harsh environments, long life and long distance traverses, resource extraction, and site preparation for construction. Robotic systems such as Dante I and II, Nomad, and Pioneer have been designed for the hazardous environments of volcanoes, Antarctica as preparation for the Moon, and Chernobyl clean-up, respectively. Demonstrating long-distance traverses and long-life systems is an ongoing focus of the Nomad program, in addition to demonstrating automated scientific exploration by identifying and classifying Antarctic meteorites. Large-scale resource extraction (such as coal mining), earth-moving vehicles, and agricultural equipment have also been automated

Icebreaker Partnerships

The Icebreaker team current membership includes LunaCorp, a company devoted to the prospect of lunar exploration and commercial development, and Carnegie Mellon University, which has been developing field-capable robotic systems for over a decade. Our principal programmatic goal is to establish a dedicated team of scientists, both from the lunar and planetary science and from the NASA human exploration communities, to develop a detailed mission plan and science instrument package. In addition, Icebreaker seeks partnership with space industry to build critical vehicles and other components for the mission.

The Icebreaker team also hopes to generate commercial opportunities stemming from public interest in the mission's development, progress and findings. The team is actively exploring business opportunities with advertisers, internet website providers, educational television producers, and the entertainment industry. Commercial membership in the Icebreaker mission may pave the way for future space-related business ventures.

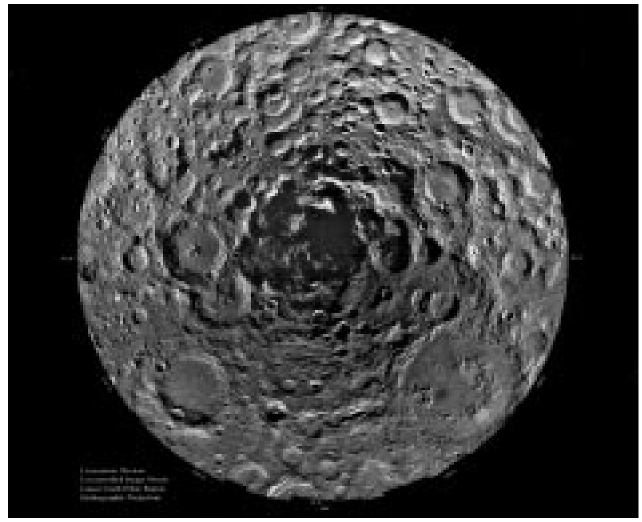

Fig. 9: The south pole of the moon, from Clementine UVVIS data

Conclusions

The Moon is of interest to many different parties including lunar and planetary scientists, developers of systems for human space exploration and colonization, commercial pioneers of space, and the general public. However, with NASA's eyes fixed principally on Mars, the development of missions to explore the Moon may be relegated to teams of partners who each satisfy a need of the composite lunar interest community. Icebreaker may become the first mobile surface system deployed for space exploration designed and built by a university laboratory, showing that successful space systems can be produced in small commercial and academic settings. With funding coming from multiple sources including NASA Code S, Code M, and companies devoted to space industry, entertainment, and education, Icebreaker could demonstrate how fruitful research and discovery can be accomplished while simultaneously promoting space enterprise.

Icebreaker will use newly developed technologies for its task. Icebreaker may lead the way in utilizing single stage to orbit launch technology which will undoubtedly typify commercial space operations of the 21st century. Finally, Icebreaker will utilize burgeoning technologies developed under NASA research and transferred to the commercial and academic sectors to overcome the numerous difficulties in surviving on and exploring the lunar south pole.

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