SUN-SYNCHRONOUS LUNAR POLAR ROVER AS A FIRST STEP TO RETURN TO THE MOON

Frank Teti(1), William Whittaker(2), Sam Kherat(3), Timothy Barfoot(1), Christian Sallaberger(1)

(1)MDA, Space Missions, Brampton, ON, L6S 4J3, Canada,
Email: {frank.teti, tim.barfoot, christian.sallaberger}@mdacorporation.com

(2)Carnegie Mellon University, Robotics Institute, 5000 Forbes Av., Pittsburgh, PA, 15213, USA,
Email: red@ri.cmu.edu

(3)Caterpillar Inc., Systems & Controls Research, Technical Center, M/S 855, Peoria, IL 61656, USA,
Email: kherat_sam_m@cat.com

ABSTRACT

Lunar discoveries having the greatest impact to human and robotic exploration and habitation will occur near the poles [1]. Specifically, the characterization and utilization of in situ resources such as propellant and life support expendables are of paramount importance to exploration of the Moon, Mars and beyond. We assert that locations near the lunar poles offer significant advantages for initial human and robotic presence and the greatest potential for development in future decades [2]. In this paper we make a case for sending a sun-synchronous exploration rover (see Fig. 1) to the lunar south pole as the first step in human return to the Moon. The key technical challenges associated with this concept are: Magellan route identification from lunar data, long-life locomotion for the lunar environment, and high-speed autonomous guidance, navigation, control. We examine each of these and propose a plan to mature the key technologies toward flight.

1. INTRODUCTION

Lunar discoveries, resources, and habitation having greatest impact to human and robotic exploration will occur near the poles. Pivotal architecture options like refueling and life support for human and robotic explorations of the Moon, Mars, and beyond hinge on availability of resources such as propellant and life support expendables. We assert that locations near the lunar poles offer significant advantages for initial human and robotic presence and vast potential for development in future decades. Sun-synchrony offers near term achievable, affordable, safe, sustained, non-istotope exploration and provides an inspiring means to catapult initiatives such as characterization of polar regions for cold-trap identification, lunar base site selection, and pioneering of Magellan routes. Sun-synchronous exploration follows the sun, avoids night, and circles a pole exploiting continuous solar polar and benign thermal conditions.

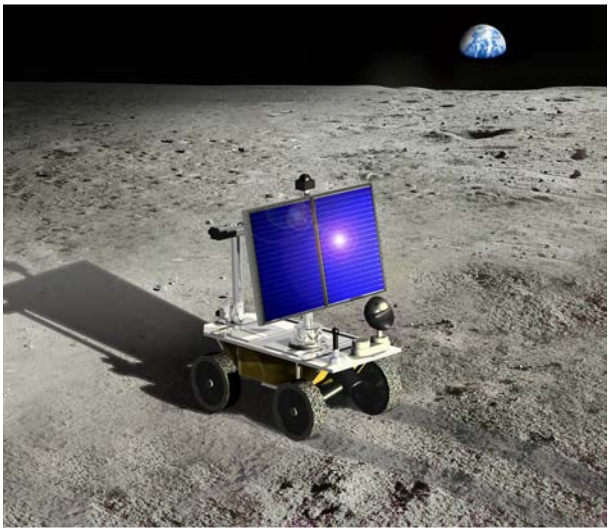

Fig. 1, Artist's rendition of a sun-synchronous lunar polar rover.

The "most valuable real estate in the solar system" was once imagined as a "point of eternal light" on the Moon, but we now know that no such point exists [3][4]. However, many paths of eternal light are real (see Fig. 2). We call these Magellan routes, after the explorer whose expedition completed the first circumnavigation of the Earth in 1522. Sun-synchronous exploration exploits the existence of these routes by following the sun and avoiding darkness, all the while carrying out valuable exploration activities such as resource characterization, cold-trap identification [5], and lunar base site selection [6].

In addition to the benefits of continuous solar power, sun-synchrony offers benign thermal conditions. By appropriately maintaining a vehicle within the terminator between dark and light, a steady thermal envelope may be selected (see Fig. 3). This reduces mass for insulation, heaters and batteries, and avoids the liabilities of cyclic hibernation and isotopes. Reducing mass and power helps to reduce cost. By avoiding the use of isotope-based power systems we may simplify the development process, decrease mission risk, and significantly reduce

Proc. of 'The 8th International Symposium on Artifical Intelligence, Robotics and Automation in Space - iSAIRAS', Munich, Germany.
5-8 September 2005, (ESA SP-603, August 2005)

the cost of flight programs, which require strict adherence to planetary protection protocols.

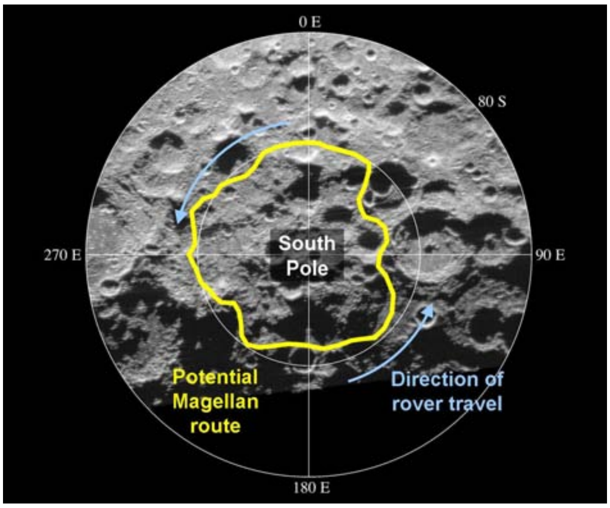

Fig. 2, Traversing lunar Magellan routes provides high exploration yield and abundant power.

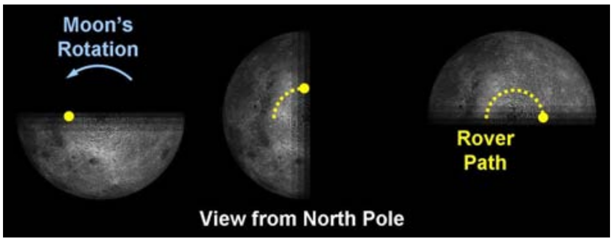

Fig. 3, Benign thermal conditions may be achieved by following the dawn terminator.

Through a migratory existence, sun-synchrony will revolutionize our notion of planetary exploration. All other alternatives for lunar surface exploration need to dwell near a lander, risking day/night cycling and limited exploration return. Sun-synchronous exploration will achieve a thousand-fold regional coverage improvement over any alternate scenario and can be realized near term in an affordable, safe, sustainable, non-isotope manner.

The achievement of sun-synchronous exploration will require agile, intelligent, and reliable rovers to comfortably exceed the pace of the Moon's rotation, allowing generous time to dwell and work. Practical Magellan routes must be far enough from a pole to avoid looming shadows, yet close enough to match circumpolar distance to vehicle speed. For example, the circumpolar distance of the Moon at latitude 84.7° is 1000 km. Given that there are roughly 709 hours in a lunar day, a rover progressing at an average speed of 1.4 km/h is sun-synchronous [7][8]. To attain 30 percent dwell time, the same rover would need to travel at an average speed of 2.0 km/h, which is comparable to human walking speed.

There are many issues associated with achieving these kinds of distances and speeds. Three key technical challenges have been identified that are somewhat unique to the sun-synchronous exploration concept. These key challenges are:

- The **identification of practical lunar Magellan routes**, based on the best known model of the terrain and illumination, and their documentation in a Lunar Magellan Atlas. Sun-synchronous routes must provide a halo of traversable terrain about a pole while providing a continual view of the sun and access to resource deposits.
- The development of **guidance, navigation, and control (GN&C)** capabilities to traverse lunar Magellan routes, accounting for power, thermal, speed, terrain, distance, localization, computational and communication constraints. Planning must provide a speed profile to achieve sun-synchrony, allocate dwell periods at target resource sites, and adapt automatically to evolving conditions during operations. Polar circumnavigation requires global positioning without a network of GPS spacecraft and a combination of supervisory and autonomous control while in and out of view of the Earth. In particular, the rover must be capable of considerably higher autonomy than past rover missions, due to the required 15-day traverse of the lunar far side.
- The development and testing of critical **locomotion for long life** components to meet the challenge of extremely high numbers of cycles in a lunar environment. Rovers must drive well over 10,000 km to complete several circumnavigations and years of exploration, requiring durable mechanisms and advanced lubricants.

Despite these hurdles, sun-synchrony lies within reach and can be achieved through a deliberate maturation of technology. The remainder of this paper will discuss each of these challenges in turn, thereby offering a roadmap to mature the relevant technology in each area.

2. IDENTIFICATION OF PRACTICAL LUNAR MAGELLAN ROUTES

Previous lunar missions have been specialized, with landers studying small scale (m-length) terrain features and orbiters studying large scale (km-length) terrain features. Sun-synchronous exploration is unique in that it must consider all scales of terrain simultaneously when determining a rover-navigable Magellan route. Accordingly, one of the largest challenges associated with identifying Magellan routes is creating an accurate lunar model.

The lunar terrain model should provide details of the physical nature of the lunar surface at both large and small scales. Small scale information should include such attributes as block size distribution and regolith properties applicable to rover mobility. Digital Elevation Models (DEMs) represent the large scale features and properties. Due to the lack of laser altimetry data for the lunar poles, the main problem associated with generating a DEM is the uncertainty in the existing elevation data, derived from Earth-based radar and Clementine stereo images. The lack of direct measurements results in large scale errors when producing stereo DEMs from images.

Spatial resolution of the existing stereo data is 1 to 2 km/pixel with a vertical accuracy of 100 to 250 m [9]. Radar derived topography achieves 150 m/pixel with a vertical accuracy of 50 m, but coverage is limited predominantly to the nearside of the moon. To enable the identification of Magellan routes, we seek to achieve a lunar terrain model with a resolution of 40 m/pixel.

A DEM must be constructed for the polar regions of interest. To provide sufficient coverage, we should combine the best existing topography data sets, including Arecibo radar data and Clementine and Galileo stereo images (see Fig. 4). Combining the stereo with the radar topography will provide nearly full coverage of both poles. Any gaps (normally found in the floors of craters) should be filled by using topography profiles for craters of similar size.

Fig. 4, High-resolution mosaics, down to 40 m/pixel, should be used to generate the polar surface model.

Local slope information must be derived from the DEM and combined with a solar model to predict the illumination conditions that will be encountered by a rover. Specifically, the illumination state of a given spot on the Moon and its eclipse periods as a function of time over the course of a lunar day need to be modeled. We should test this integrated DEM/solar model in simulations corresponding to the lighting conditions of actual lunar images. The model data at small scales can be inferred through the use of the Apollo 16 landing site as a geological analog to the highlands terrain of the lunar polar regions, and can then be cross-checked using the data from the Apollo roving vehicles.

Our lunar model must also see the incorporation of the physical properties of the lunar soil. Using this model, the temperature may be computed for any point on the lunar surface. Thermal modeling is a key aspect of identifying Magellan routes as a rover must maintain an appropriate offset from the dawn terminator to exploit benign thermal conditions.

The completed lunar model will enable determination of potential Magellan routes that maximize available solar energy, minimize solar occultation, and exploit benign temperatures. The findings of this work should be catalogued in a Magellan route atlas.

3. GUIDANCE, NAVIGATION, AND CONTROL

Existing robotic rovers are limited in speed, range and exploration productivity due to insufficient available power and constrained rover mobility. Although sun-synchrony can provide abundant power, it increases the complexity of the guidance, navigation, and control required.

Sun-synchronous exploration has the dual goals of avoiding obstacles and reaching goal locations while also maintaining position and orientation relative to the sun for power, navigation and warmth. Challenges include following a rigorous schedule of traverse and dwelling, making local decisions quickly enough to maintain sun-synchronous speed requirements, and maintaining proper solar array pointing,

In July 2001, Hyperion (see Fig. 5), a solar-powered rover, completed two demanding sun-synchronous exploration experiments at Haughton Crater in the Canadian Arctic (75°N) [10]. Even with these successes, several challenges remain to be addressed in order to achieve flight-readiness for lunar polar sun-synchrony. The percentage of time available during a traverse to dwell and do work needs to be increased. This can be accomplished by advancing average rover speed. Total traverse distance also needs to be improved and demonstrated at a more relevant distance. Improved absolute localization needs to be carried out without the aid of GPS. Active solar panel sun-tracking needs to be implemented and accounted for in planning.

Consequently, we propose that the next step in maturing the requisite GN&C technology is to exhibit breakthrough capability in sun-synchrony field trials. Field trials should be conducted with a next-generation research-quality rover, which we will refer to as *Synchrobot*, capable of sun-synchronous traverse in terrestrial terrain (see Fig. 6).

Fig. 5, CMU's successful sun-synchronous rovers Hyperion (left) and Zoë (right).

Fig. 6, Artist's rendition of a next-generation sun-synchronous research rover, *Synchrobot*.

The goal of this GN&C work is to increase traverse difficulty and duration testing to mission-relevant levels. Average speed must be demonstrated at 8 km/h and distance traveled using low-bandwidth supervisory control (95% of the time autonomous) to 1000 km. Dwell duty cycle for relevant lunar scenarios must be demonstrated at 30%. Active panel point will be demonstrated to be on average within 10 degrees of optimal and autonomous localization in an absolute reference frame to be accurate to within 100 m.

3.1 Guidance

We use the term guidance to mean both long-range route planning based on a priori knowledge as well as short-range planning to avoid obstacles detected by sensors.

Although challenging, long–range route planning for maximal power production can extend solar-powered missions. In 2001, using knowledge of orbital mechanics, local terrain, and expected power consumption, Hyperion planned and executed sun-synchronous routes to visit designated sites while obtaining the necessary solar power for continuous 24-hour operation. It traveled a loop of more than 6 kilometers in barren, Mars-analog terrain, returning with its batteries fully charged (see Fig. 7). Hyperion was notable for its reduced mass, reduced complexity, and vertically-oriented solar panels.

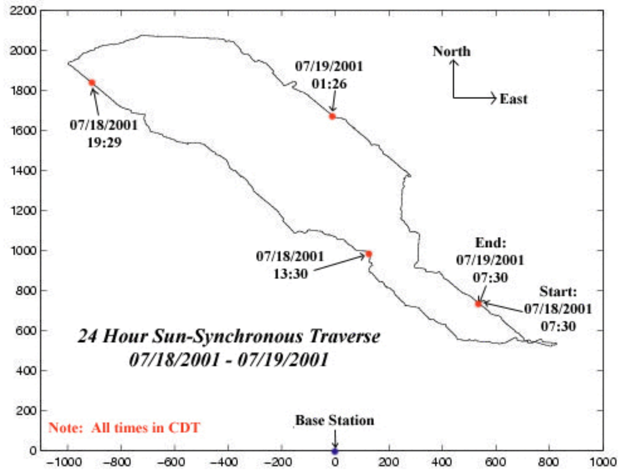

Fig. 7, Hyperion successfully completed a 6 km, 24 hour sun-synchronous route, returning with its batteries charged (reproduced from [10]:Figure7) .

In 2003 Hyperion carried out 90 traverses totalling 18 km in the Atacama Desert, Chile, where it conducted initial experiments in Sun and horizon-feature tracking for localization. Based on this experience, a descendent rover, Zoë, was developed with improved mobility, software and instrumentation. Zoë undertook follow-on field experiments in the Atacama during the fall of 2004 [11].

TEMPEST (Temporal Mission Planner for the Exploration of Shadowed Terrain) is the planning software used with Hyperion to synthesize trajectories synchronous with planetary rotation, and hence with the sun [12][13]. TEMPEST enables long-duration, solar-powered exploration of the poles of planets and moons of the solar system. The software solves the coupled path scheduling and resource management problem, a key aspect of sun-synchronous navigation.

For Synchrobot, we must enhance TEMPEST to minimize the operational overhead of planning and will develop strategies for rapid re-planning, contingency analysis and probabilistic plan evaluation to contend with the uncertainty of operations in a planetary environment. We should implement solar cognizant pre-mission planning and online replanning using a model of the test site (e.g., Arctic) with illumination to compute corridors for guiding sun-synchronous field tests.

An actively steered solar panel will require that the mission planner can output routes that maximize solar input to Synchrobot's solar panel as well as pointing directions for the solar panel. The mission plan will combine time-sequenced path plans, minimum required battery energy guidelines, and a schedule for battery recharge periods.

For short-range guidance to support obstacle avoidance, Synchrobot should use vision-based high-resolution obstacle detection with close-range laser scanning for redundancy and elimination of false obstacles. Hyperion's 2001 traverse on Devon Island showed the reliability of such detection, combining optimistic far-field evaluation and pessimistic near-field reaction [16]. A stable stereo vision perception system will limit the amount of steering activity (due to less false positives) and thereby reduce mechanical wear and energy waste. Combining estimations of slope, roughness, steps and holes, the navigator will select the best path direction and steer the rover at update rates proportional to vehicle speed.

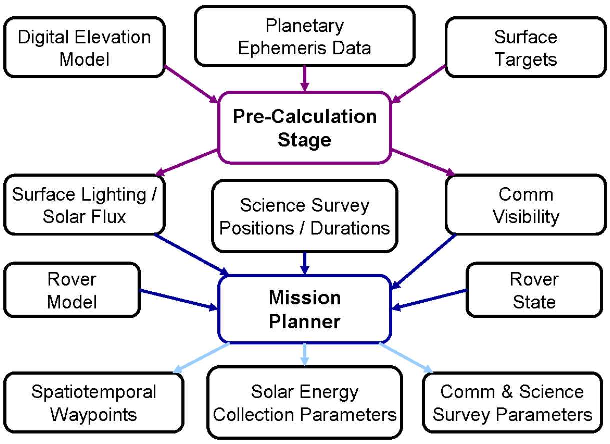

Fig. 8, The existing TEMPEST planner considers solar and terrain conditions before selecting spatiotemporal waypoints (reproduction of [12]:Figure1).

3.2 Navigation

We use the term navigation to mean both long-range localization (1-1000 km) in an absolute coordinate system and short-range localization (1-1000 m) in a relative coordinate system.

The long-range navigation system could consist of a star-tracker, a local gravity sensor, ephemeris, and a clock to determine the full six degree-of-freedom pose of the rover in an absolute reference frame. Test data will be verified against high accuracy GPS pose estimates. Periodic skyline registration might also be incorporated into this system.

The short-range (e.g., < 1 km) navigation system could consist of visual odometry [14][15] using a wide-baseline stereo-camera and should be fused with the long-range system.

3.3 Testbed and Field Trials

The Synchrobot rover should be developed by derivation and evolution, primarily from the existing Hyperion and Zoë robots. Zoë has the appropriate scale, and mass, with improved spatiotemporal planning and navigation capabilities. In outfitting Synchrobot, we should improve on Zoë's ability to climb, its speed and its suspension, and develop a lunar-relevant computing and sensing design. The chassis is discussed further in the next section.

Sun-synchronous experimental field trials must demonstrate the requisite GN&C technology by running Synchrobot through a set of lunar-relevant outdoor environments (e.g., desert, Arctic) that approximate the terrain and moving solar conditions on the Moon. Tests should consist of 24-hour sun-synchronous loops and speeds starting at 1 km/hr and increasing incrementally up to 8 km/hr. We should increase Synchrobot's distance traveled under autonomous or low-bandwidth supervisory control from 10 km incrementally toward 1000 km. We must demonstrate that Synchrobot has available energy in its duty cycle to dwell (simulate drilling).

4. LOCOMOTION FOR LONG LIFE

There are unique challenges associated with the locomotion components of a sun-synchronous lunar rover. Previous missions have seen rovers traverse tens of kilometres. For lunar sun-synchrony, rover wheels, electric motors, bearings and lubricants must achieve repeated thousand-kilometer circumpolar traverses.

We must demonstrate actuators with 100 million cycle life expectancy (or equivalent of 10000 km rover traverse). Average rover speed should be advanced to 8 km/h with lunar equivalent gravity and power availability. Overall rover chassis life expectancy in a lunar environment must be demonstrated at 1000 km.

Our discussions of locomotion will be broken to three topics: tribology/life, chassis mobility, and energetics.

4.1 Tribology/Life

Given the long distance requirements and assuming appropriate gear ratios, drivelines must deliver reliable operation over tens or even hundreds of millions of cycles. To achieve these extreme numbers of cycles we must develop and employ advanced lubricants and mechanism seals. Fortunately, an advantage of sun-synchrony is that the thermal conditions can be selected to be benign and steady, reducing the degree of tribological challenge.

To address the locomotion for long life issue, an actuator tradeoff study is needed to provide the early technology development needed to ensure a flight rover can meet the long duration mission expectations. A wide range of drive technologies should be considered, including face gears, conventional gearing and harmonic drives, as well as non-conventional forms such as conformal gearing, traction drives or hybrid conventional/traction transmissions, and infinitely variable toroidal transmissions. To mitigate risks associated with continuous operation to 10,000 km, the selected actuators for a lunar rover chassis design should undergo accelerated life testing in thermal vacuum.

4.2 Chassis Mobility

To show that we are able to meet the speed requirements on lunar terrain, we must develop a system design of a prototype lunar rover chassis. A prototype of this chassis design should be incorporated into the design of Synchrobot, mentioned above. The chassis will need to demonstrate terrain traversability, maneuverability, payload capability, obstacle crossing, power use effectiveness, as well as other mobility requirements. For each function of the mobility subsystem (i.e., steering, propulsion, suspension and stability) we must define and analyze concepts that deliver the extreme cycle life and meet the other defined requirements expected in worst-case scenarios.

To aid in the chassis design, we must simulate lunar terramechanics. This can be accomplished using laboratory scale-model technology and equipment using lunar soil simulants [17][18], and numerical simulations [19][20]. State-of-the-art scale model technology includes numerical machine and operator models controlling physical "soil bins" in real time.

Fig. 9, Artist's rendition of the lunar rover chassis in a test fixture in a thermal vacuum chamber to emulate the lunar environment for testing.

On the path to flight, an engineering model of the lunar rover chassis will need to be constructed and life tested in a large thermal vacuum chamber such as those found at NASA JSC. This will be facilitated by a mobility fixture (similar to a treadmill) to allow the chassis to be run while experiencing an accelerated life test equivalent to a thousand-kilometer lunar traverse. This lunar environmental testing is a necessary step in advancing the locomotion system toward flight readiness.

4.3 Energetics

There are additional locomotion challenges associated with providing demonstrations in lunar relevant environments. The expected average rover speeds approaching 8 km/h in terrestrial gravity with terrestrial solar irradiance will be a formidable challenge. For lunar sun-synchronous exploration, this situation is not nearly as dire as the gravity is 0.17 times Earth's while the irradiance is 1.4 times Earth's. From an energy point of view there is an eight-fold advantage for lunar operations. We will refer to the combined study of power and gravity as energetics. Demonstrating that our prototype rover can achieve target speeds in Earth's higher gravity with Earth's lower power would be a sufficient condition to show flight readiness. However, it is only necessary to achieve target speeds in a lunar relevant environment. The Russian VNIITRANSMASH team addressed this issue for their Lunakhod rover development program by emulating the Moon using a gravity-compensation system [21][22].

Fig. 10, Artist's rendition of lunar energetics experiments conducted using a gravity compensation system.

A study of lunar energetics should be carried to assess the advantages of reduced gravity and increased solar insolation on rover speeds and power mobility requirements. These energetics experiments serve to capture the higher solar insolation and lower gravity on the lunar surface through appropriate scaling of terrestrial gravity and/or available power. This could be accomplished using a companion vehicle to offset 0.83 of Synchrobot's weight by applying uplift force using a constant-force spring apparatus (see Fig. 10). Lunar solar insolation could be emulated using tethered power. Synchrobot should be designed with easily interchangeable gearing enabling testing at various gear ratios appropriate to both Earth and the Moon. Lunar energetics testing might be comprised of one-kilometer trials at average speeds ranging from 1 km/h to 8 km/h.

5. DISCUSSION

The establishment of Magellan routes on the Moon by rovers offers a great deal as a precursor to human presence. In the short term, resources and potential base sites can be identified by rovers establishing these routes [6]. In the medium term, the same routes and/or rovers could be reused as transportation infrastructure for affordable logistics positioning both prior to and after establishing a human presence (see Fig. 11). In the long term, the now well-established routes could be used to help create circumpolar solar arrays and rail lines, and to lay telecommunication infrastructure and pipelines for resource delivery [23].

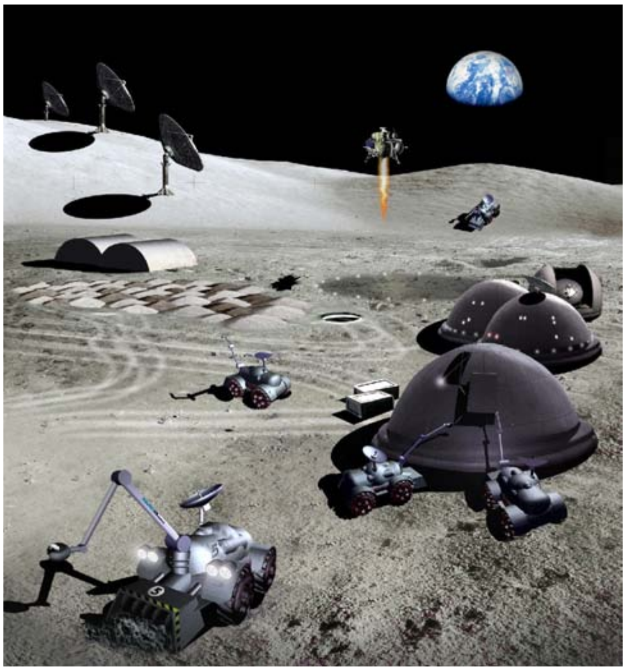

Fig. 11, Sun-synchrony may serve as a key stepping stone in the establishment of lunar infrastructure.

The development of sun-synchronous exploration technology is applicable to missions on other planetary bodies including Mercury and Mars [8]. The temperature conditions on Mercury are even more extreme than on the Moon. This fact, combined with its slow rotation, makes Mercury an ideal location for terminator-following exploration.

Sun-synchrony would also be a useful tool on Mars, where a long duration migratory mission would be possible. A rover could remain in the North Pole region during the Northern summer and then migrate on a yearly basis to the Southern hemisphere to avoid the constant darkness of the northern winter. Both of these mission scenarios involve long duration missions with aggressive science and/or exploratory goals that are only achievable using sun-synchronous exploration technology.

The autonomous operations that have been proposed in this paper have implications on a wide range of mission scenarios. The advancement of the level of proven, reliable autonomy will enable more aggressive mission timelines that will result in higher mission returns for future projects involving autonomous operations.

Several aspects of the autonomy proposed here (e.g., high-speed motion planning and perception) are immediately applicable to missions that are not sun-synchronous.

The locomotion system that is proposed here will revolutionize planetary exploration technology. The highly capable system will, for the first time, enable planetary-scale exploration. This ability has obvious applications in the survey and exploitation of planetary resources by manned and unmanned vehicles, and it enables safe and reliable long distance transport for travel within and between human bases. The long-life components that must be designed and validated could be used in a variety of situations, including other types of mobility systems, in situ resource exploitation systems such as drilling and sample handling, and in the power and habitation systems for future manned bases.

The Synchrobot rover prototype, testing facilities, advanced lunar models, and Magellan routes that have been proposed in this paper will provide the necessary tools for future technology maturation toward flight. Synchrobot will have a highly advanced mobility system that will enable other projects to explore more difficult and interesting terrain than previous testbeds have allowed. The testing environment created will be directly applicable to other planetary surface missions. The thermal vacuum mobility test fixture that are proposed would be an ideal apparatus to test other vehicles in relevant terrain conditions. The lunar polar models and Magellan atlas will offer missions a more accurate basis for future exploration strategies, including route planning and resource surveying.

6. CONCLUSION

We have proposed that a sun-synchronous lunar polar rover could be used as a first step in returning to the Moon. Three key technical challenges were identified in the path to mature sun-synchronous exploration technology toward flight readiness: identifying practical lunar Magellan routes, autonomous guidance/navigation/control, and locomotion for long life. Each of these challenges was examined and in each case a path forward was proposed to address the technical issues. We believe that through the implementation of our proposed maturation plans, a sun synchronous rover could be ready for a near term flight.

ACKNOWLEDGEMENTS

The authors would like to thank Paul Spudis and Ben Bussey (Applied Physics Laboratory, Johns Hopkins University), Jeff Taylor (University of Hawai'i), Rob Ambrose (NASA Johnson Space Center), Phillip Abel (NASA Glenn Research Center), David Wettergreen and Chris Urmson (Carnegie Mellon University) for useful discussions during the preparation of this paper.

REFERENCES

[1] Whittaker W, "The Case and Means for Polar Exploration", written testimony to The President's Commission on Moon, Mars, and Beyond (2004)

[2] Duke MB, "Lunar Polar Ice: Implication for Lunar Development", J. Aero. Eng., 11(4): 124-128 (1998)

[3] Spudis P, DoD News Briefing Transcript, (1996) www.pxi.com/Clementine/data/ice_dod.html

[4] Bussey DBJ, Spudis PD, Robinson MS, "Illumination Conditions at the Lunar South Pole", Geophys. Research Letters, 26(9): 1187-1190 (1999)

[5] Zuber MT, Smith DE, "Topography of the Lunar South Polar Region: Implications for the Size and Location of Permanently Shaded Areas", Geophys. Research Letters, 24(17): 2183-2186 (1997)

[6] Taylor LA, Taylor DS, "Consideration for Return to the Moon and Lunar Base Site Selection Workshops", J. Aero. Eng., 10(2): 68-79 (1997)

[7] Wettergreen D, Shamah B, Tompkins P, Whittaker W, "Robotic Planetary Exploration by Sun-Synchronous Navigation", Proc. Int. Symp. on Art. Int., Rob. & Aut. in Space (iSAIRAS '01), (2001)

[8] Wettergreen D, Wagner M, Shaw F, Planetary Circumnavigation, Final Study Report, USRA #07600-102, NAIC, (2002)

[9] Heiken GH et al. (eds), Lunar Sourcebook: A User's Guide to the Moon, Cambridge Univ. Press (1991)

[10] Wettergreen D, Dias MB, Shamah B, Teza J, Tompkins P, Urmson C, Wagner MD, Whittaker W., "First Experiment in Sun-Synchronous Exploration", Proc. IEEE Int. Conf. on Rob. & Aut. (ICRA 2002), 3501-3507 (2002)

[11] Wettergreen D, Cabrol N, Teza J, Tompkins P, Urmson C, Verma V, Wagner MD, Whittaker W, "First Experiments in the Robotic Investigation of Life in the Atacama Desert of Chile", Proc. IEEE Int. Conf. on Rob. & Aut (ICRA05), (2005)

[12] Tomkins P et al., "Automated Surface Mission Planning Considering Terrain, Shadows, Resources and Time", Proc. Int. Symp. on Art. Int., Rob. & Aut. in Space (iSAIRAS '01), (2001)

[13] Tomkins P et al., "Mission Planning for the Sun-synchronous Navigation Field Experiment", Proc. IEEE Int. Conf. Rob. & Aut., 4: 3493-3500 (2002)

[14] Barfoot T, "Online Visual Motion Estimation using FastSLAM with SIFT Features", Proc. Int. Conf. on Intelligent Robots and Systems (IROS '05), (2005)

[15] Se S, Barfoot T, Jasiobedzki P, "Visual Motion Estimation and Terrain Modeling for Planetary Rovers", Proc. Int. Symp. on Art. Int., Rob. & Aut. in Space (iSAIRAS '05), (2005)

[16] Urmson C et al., "Stereo Vision Based Navigation for Sun-Synchronous Exploration," Proc. IEEE Int. Conf. on Int. Robots and Systems (IROS02), 1: 805-810 (2002)

[17] Klosky JL, Sture S, Ko H-Y, Barnes F, "Geotechnical Behavior of JSC-1 Lunar Soil Simulant", J. Aero. Eng., 13(4): 133-138 (2000)

[18] Perkins SW, Madson CR, "Mechanical and Load-Settlement Characteristics of Two Lunar Soil Simulants", J. Aero. Eng., 9(1): 1-9 (1996)

[19] Bauer R, Leung W, Barfoot T, "Experimental and Simulator Results of Wheel-Soil Interaction for Planetary Rovers", Proc. Int. Conf. on Intelligent Robots and Systems (IROS '05), (2005)

[20] Bauer R, Leung W, Barfoot T, "Development of a Dynamic Simulator for the ExoMars Rover", Proc. Int. Symp. on Art. Int., Rob. & Aut. in Space (iSAIRAS '05), (2005)

[21] Kemurdjian AL, Gromov VV et al., "Soviet Developments of Planet Rovers in Period 1964-1990", Proc. Missions, Technologies and Design of Planetary Mobile Vehicles, 25-43 (1992)

[22] Kemurjian AL, Hahanov IA, "Mobile Complex for Terrestrial Testing of Planet Rovers", Proc. Int. Conf. on Adv. Rob. (ICAR '95), 301-307 (1995)

[23] Schrunk et al., The Moon: Resources, Future Development and Colonization, Wiley-Praxis (1999)