Strategic Autonomy for Reducing Risk of Sun-Synchronous Lunar Polar Exploration

Nathan Otten, David Wettergreen, and William Whittaker

Abstract Sun-synchronous lunar polar exploration can extend solar-powered robotic missions by an order of magnitude by following routes of continuous sunlight. However, enforcing an additional constraint for continuous Earth communication while driving puts such missions at risk. This is due to the uncertainty of *singularities*: static points that provide weeks of continuous sunlight where communication blackouts can be endured. The uncertainty of their existence and exact location stems from the limited accuracy of lunar models and makes dwelling at singularities a high-risk proposition. This paper proposes a new mission concept called *strategic autonomy*, which instead permits rovers to follow preplanned, short, slow, autonomous drives without communication to gain distance from shadow and increase confidence in sustained solar power. In this way, strategic autonomy could greatly reduce overall risk for sun-synchronous lunar polar missions.

1 Introduction

Solar-powered lunar rovers could achieve months of exploration by following sun-synchronous polar routes to maintain continuous sunlight for power and heating while avoiding prolonged exposure to extreme cold. These routes favor peak elevations at high latitudes and could be accomplished with slow driving speeds as low as 0.1 cm/s. Such routes are intriguing because of their extended durations and their proximity to areas of scientific and commercial interest. Planning reliable sun-synchronous routes prior to launch requires detailed maps of future lighting conditions, which can be estimated based on prior 3D models of the Moon. The resolution and certainty of predicted insolation maps is limited by the quality and accuracy of the underlying elevation models. The inherent uncertainty of lunar topography data

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leads to uncertainty that rovers following preplanned sun-synchronous routes will remain in continuous sunlight. The magnitude of this uncertainty is strongly influenced by the strictness of a mission's requirement for rover-to-Earth communication.

One ostensibly conservative strategy permits rovers to drive only when in direct communication with ground controllers to facilitate teleoperation and/or highly supervised autonomy. Sans satellite relay, rovers would be required to maintain an unobstructed view of Earth when driving. This strict requirement severely constrains rover movement and, in many cases, would force rovers to dwell motionless near the day–night terminator for weeks at a time to achieve multiple lunar days of operation. Locations of enduring sunlight must be reached prior to losing Earth communication, which must later be reestablished before driving can resume. Such locations are so small and rare that they effectively behave as single points or *singularities*, through which all valid routes must pass. Due to the uncertainty of predicted insolation maps, the existence of such points cannot be guaranteed. A mission dependent on dwelling at a presumed singularity that turns out not to exist will almost certainly terminate prematurely. So, while solar-powered missions with a strict requirement for sustained communication when driving require singularities to achieve multiple lunar days, the uncertainty of such phenomena makes them unreliable as a means to that end. Rather than reducing overall mission risk, this "conservative" strategy ultimately increases odds of failure.

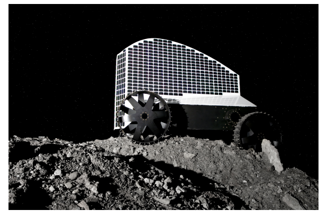


Fig. 1 Prototype solar-powered lunar polar rover "Polaris." Image credit: Astrobotic Technology, Inc.

This paper proposes an alternative strategy for achieving extended lunar polar rover missions. In the absence of Earth communication, *strategic autonomy* would permit short, slow, autonomous drives following preplanned paths in areas adjacent to singularities to guarantee continuous sunlight. Under this new mission concept, the majority of a rover's distance traveled could still be teleoperated and highly supervised. The key difference is that in situations where a communication blackout is inevitable, the rover would be liberated to drive autonomously to increase its estimated distance from shadow and thus improve its expectation of solar power. While the limited use of unsupervised autonomy does incur some additional risk, it is outweighed by increased confidence in uninterrupted sunlight. The adoption of strategic autonomy for sun-synchronous lunar polar exploration could substantially reduce overall risk and enable greater mission durations and returns.

The remainder of this paper is organized into five sections followed by a conclusion. Section 2 provides relevant background information regarding the lunar polar environment, sun-synchronous exploration, and the models used for route planning. Section 3 describes a common concept of operations for lunar roving that enforces a strict communication constraint and presents a baseline route. Section 4 introduces a 2D representation of dynamic 3D constraints useful for analyzing and comparing routes. Section 5 formulates the concept of strategic autonomy and presents a corresponding alternative route. Section 6 highlights the benefits of strategic autonomy.

2 Background

2.1 The Lunar Polar Environment

Water The abundance of water on the Moon is well-documented, and the next steps of exploration are surface missions to visit and characterize local concentrations. Lunar water is a key resource because it can be converted into breathable air, drinkable water, and combustible propellent, all three of which are vital to sustaining exploration beyond Earth. Orbiting satellites have collected overwhelming evidence of vast quantities of frozen water ice concentrated at the lunar poles [11, 3], and NASA is considering a solar-powered robotic surface mission to verify and quantify this water and other frozen volatiles [2]. The estimated subsurface depth of frozen water permafrost [10] at a candidate landing site near the lunar south pole is shown in Fig. 2. In addition to accessible water, Nobile exhibits a combination of topography and latitude ideal for demonstrating the advantages of strategic autonomy.

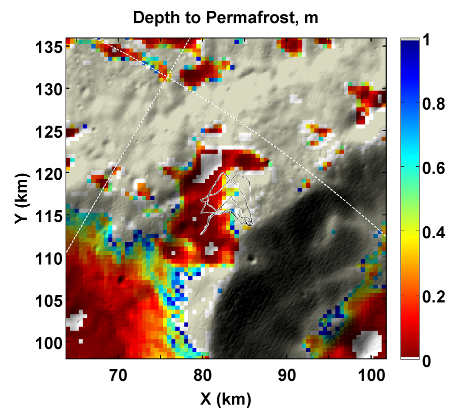


Fig. 2 Estimated depth of permafrost below the lunar surface for a roughly 40-by-40-km area of the Nobile Crater rim near 86°S [10]. Gray terrain indicates an estimated permafrost depth of greater than 1 meter. A 74-day sun-synchronous route, which crosses the steep gradient between deep and shallow permafrost several times, is located near the center of the area shown. Image credit: Richard Elphic

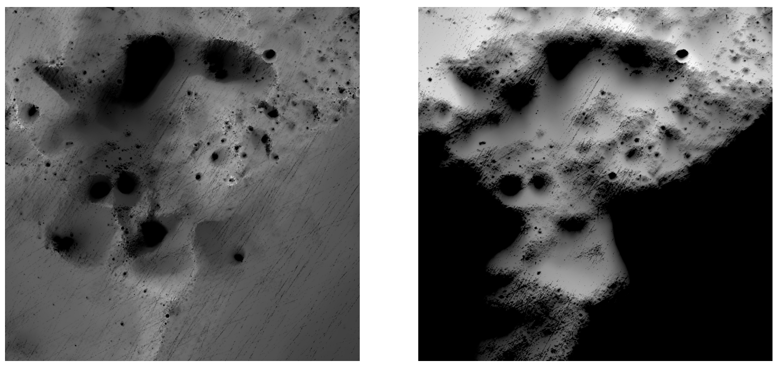
Sunlight Because the synodic period of the Moon averages approximately 708 hours, a single lunar day is equivalent to about 29.5 Earth days [4]. At non-polar latitudes, this yields alternating day and night periods of sunlight and darkness averaging 14.75 Earth days each. Limited to 2 weeks of solar power, slow-moving[1] rovers that lack a sustainable internal heat source (e.g., nuclear isotopes) are doomed by the unavoidable cryogenic temperatures characteristic of lunar night [9, 10, 15].

Near the poles, however, seasonal effects and local topography dominate, resulting in more dynamic and complex lighting conditions. The Moon's 1.5-degree axial tilt relative to the ecliptic induces seasons that are subtle relative to Earth's yet pronounced enough to leave the poles almost completely dark during winter and predominately lit during the summer. The Sun circles the summer pole once per lu-

[1] Here, less than 10 cm/s is considered slow. (Circumnavigating the equator requires $\sim$ 4.3 m/s.)

nar day and never deviates far above (or below) the horizon; thus, sunlight grazes the lunar polar surface. The low-angle light renders shadows that stretch many kilometers and sweep across the rough terrain, locally blocking out sunlight for days at a time. Although no polar peak is lit 100% continuously [6], slow-moving rovers can maintain uninterrupted solar power for 3–6 months by navigating strategic sun-synchronous routes. This enables mission durations an order of magnitude greater than what is possible at lower latitudes or without sun-synchronous planning.

A 4-month composite of polar illumination based on 3D modeling is shown in Fig. 3a. This is the same area as that shown in Fig. 2. The permanently shadowed regions (PSRs) generally correspond to high concentrations of ice, while the small points of maximum illumination at local peaks are characteristic of singularities.



(a) Polar Illumination Map (b) Polar Communication Map

Fig. 3 These images represent the composite illumination (**a**) and communication (**b**) coverage over a 4-month period of a 20-by-20-km area on the rim of Nobile Crater near the lunar south pole. Brighter values indicate greater cumulative exposure (to the Sun or Earth, respectively) as a percentage of total time: *white* indicates 100%, while PSRs appear as *black*. Earth is upward.

Communication After power, the most critical resource for lunar rovers is communication with Earth. Without frequent communication, rovers cannot adequately receive commands nor transmit telemetry and scientific data. A satellite relay could provide (near) constant communication with polar rovers, but such infrastructure is costly to deploy. Polar rovers can instead rely on direct line-of-sight to Earth-based antennae. Due to tidal locking, only one hemisphere of the Moon ever faces Earth; however, at the poles, the Moon's axial wobble causes the Earth to rise and set periodically as viewed from the surface. This induces intermittent communication coverage with periodic blackouts common at local depressions and on non-Earth-facing slopes. These conditions are not conducive to highly supervised autonomy or teleoperation. A composite of polar communication coverage (via line-of-site to Earth) is shown in Fig. 3b. The steepest communication gradient coincides with the peak of maximum illumination, another characteristic of singularities.

Topography Another important aspect of the lunar polar environment is local topography, which dictates not only the sunlight and communication available to rovers but also the terrain that must be negotiated. While rover-scale terrain features cannot yet be resolved using the best lunar data, topographic models do yield maps of gross ground slope, much of which is too steep for typical wheeled rovers to traverse.

2.2 Sun-Synchronous Mission Planning

Sun-synchronous circumnavigation routes for maximizing solar power and extending missions were first envisioned without the benefit of high-fidelity lunar terrain models [18]. The concept was later partially demonstrated in field experiments each spanning a single day on Earth [17]. The concept of mission-directed path planning was developed to enable global planning and navigation capabilities for planetary rovers over large scales and long durations amenable to sun-synchronous exploration [14]. The TEMPEST planner embodied a sun-synchronous navigation strategy tailored to solar-powered polar exploration and was demonstrated onboard the "Hyperion" rover on Devon Island north of the Arctic Circle. It was not extended to multiple diurnal periods, interplanetary communication, nor the use of lunar data.

Prior work by the authors presents examples of sun-synchronous lunar polar routes generated using data from Lunar Reconnaissance Orbiter (LRO) [8, 5]. South polar routes at Malapert Massif and Shackleton Crater maintain uninterrupted sunlight and traversable slopes for 2 months with maximum driving speeds of 1 centimeter per second and 1 millimeter per second, respectively, but do not account for communication [8]. A route near Nobile Crater (similar to the routes presented in this paper) achieves 74 days with a strict requirement for direct line-of-sight to Earth when driving [5]. Although this route dwells twice at a 'singularity,' prior research did not identify or define this concept nor did it address the related risk.

2.3 Lunar Models

Prior work as well as this research use predictions of future lighting generated using lunar digital elevation models (DEMs), lunar and solar ephemeris data, and ray-tracing software. The DEMs are a data product of LRO's Lunar Orbiter Laser Altimeter (LOLA) instrument.[2] The highest resolution LOLA DEM covering the Nobile Crater region is 10 meters per pixel [12]. This 2.5D elevation model, shown in Fig. 4, was converted into a 3D mesh model in Cartesian coordinates, and a simulated Sun[3] was positioned according to the SPICE toolkit [1]. Ray-tracing software renders an orthographic map of lighting conditions for each time in a predefined se-

[2] LRO data products are accessible via NASA's Planetary Data System Geosciences Node [7, 16].

[3] The Sun can be approximated as a directional or area light source. The latter yields a range of solar flux values, which can be thresholded to produce a binary output for planning purposes.

quence. The result is a 3D binary array that defines each (x,y,t) state as either lit or shadowed, in this case with spatial resolution of 10 meters and a temporal resolution of approximately 2 hours. The same process was used to estimate communication coverage by substituting the Earth's position for the Sun's.[4] Principal ground slope was computed by applying divided difference to the DEM.

The resolution and accuracy of LOLA data is orders of magnitude better than what was available previous to LRO [19]; however, uncertainty remains an issue. The accuracy of individual LOLA ground points is approximately 10 meters radially and 50–100 meters spatially [13], and gridded LOLA DEMs contain a myriad of visible artifacts. In low-angle lighting, these errors are magnified, resulting is substantial uncertainty about the exact location of sunlight–shadow boundaries. This uncertainty makes dwelling near the terminator a risky proposition.

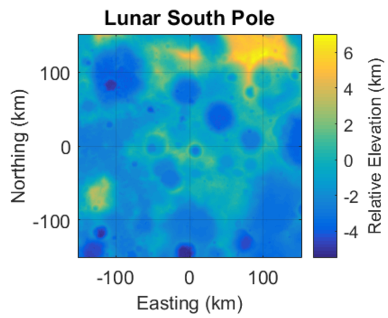


Fig. 4 This 10-meter LOLA DEM covers the lunar south pole out to 85°S. The Nobile Crater rim is among the peak elevations.

3 Supervised Teleoperation

This section describes a common concept of operations that uses a mix of highly supervised autonomy and teleoperation. An example route is presented as a baseline for later comparison with a route demonstrating the concept of strategic autonomy.

The default concept of operations is loosely modeled after those used by NASA's Mars rovers, albeit at an accelerated cadence. The Mars Science Laboratory "Curiosity" and the Mars Exploration Rover "Opportunity" are each actively managed by a team of rover operators that upload a sequence of commands no more than once per day based on previously returned telemetry and science data. Upon receiving the command sequence, the rover executes the actions (if possible) with the aid of a limited set of semi-autonomous navigation capabilities, transmits new data back to Earth, and awaits further instruction. This cyclical process generally repeats every 24 hours. The pace is dictated by the 20-minute average communication delay, limited solar flux, and the length of a sol. Real-time teleoperation is prohibited by high latency due to the large distance between Earth and Mars, and rover movement is highly supervised, never going beyond the previous day's horizon.

A similar approach could be used for lunar exploration but at a far more rapid cadence enabled by the Moon's proximity to Earth, greater solar flux, and lesser gravity. Command cycles could iterate every few hours or minutes instead of once per day. This pace approaches that of pure teleoperation, which is possible at slow

[4] Since radio waves behave differently than visible light, this yields a slightly optimistic estimate.

driving speeds and with low latency of a few seconds. In this strategy, no unsupervised rover autonomy would be required nor permitted. The rover would operate under constant supervision with humans in the loop ready to intervene if necessary.

Constraints The supervised teleoperation ("teleop") concept of operations imposes the following constraints on sunlight, communication, and terrain slope.

Sunlight The rover must remain in direct sunlight at all times and cannot enter or be overcome by shadow.

This constraint is constant and unconditional. While a rover's onboard battery, depending on its size, could enable it to operate, drive, and possibly even heat itself for a limited time in the absence of sunlight, it is simpler and safer to impose a strict constraint to always remain in sunlight.[5] This constraint guarantees consistent power and heating and leverages the unique character of polar lighting to extend operational life. For the work presented here, being in shadow is defined as being at any state (location and time) for which the ground is shadowed. Extensions that account for the height of the solar array above the ground are possible; however, the definition used here provides a reasonable and conservative approximation.

Communication The rover must maintain an unobstructed view of Earth at all times during which it is driving.

This constraint is conditional, as it is only active when the rover is moving. The proximity of Earth and the Moon enables a level of control not possible for Mars. The opportunity for near real-time communication invites a seemingly prudent approach that not only takes advantage of constant supervision but mandates it.

Slope The rover must remain on terrain of principal slope not exceeding 20 degrees.

This value was chosen such that it would not dominate route planning in the following examples. In practice, this constraint is dependent on the mobility platform and could be higher or (most likely) lower.

Planning Method The gridded lunar model representations described in Section 2.3 are conducive to grid-based planning methods. The distinctions of sunlight, communication, and slope yield a planning problem with heterogeneous constraints. Enforcing a constraint on slope is the simplest, since it is defined by a static 2D map of binary go/no-go conditions. Enforcing a constraint on sunlight is similarly simple, with the only difference being that the map is dynamic, represented by a 3D binary array composed of stacked 2D maps for each time step. The communication condition must be enforced at planning time, since it is conditional on whether or not two consecutive rover states share the same spatial position. For two graph nodes of differing positions to be legally connected by an edge, both must have communication coverage (and sunlight). Sunlit nodes of identical position are connected along the time dimension, regardless of communication coverage. This conditional constraint is straightforward to implement in the state transition or 'get_child_node' function of any standard heuristic graph search algorithm.

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[5] To complete certain science objectives, a rover may be required to enter a PSR or other unlit area for a brief period of time; however, this extension is outside the scope of the work presented here.

To generate the following example route, a starting point was selected based on favorable landing site criteria, and several major waypoints were manually selected such that the rover would visit numerous sites of scientific interest near PSRs. A minimum distance path passing through all waypoints was generated using A* graph search on a 3D adaptation of an eight-connected grid (see [8] for details). This was done first at a resolution of 80 meters, and then the coarse route was refined to a resolution of 20 meters using the 80-meter route sequence as waypoints for a second iteration of A*. This hierarchical approach was used to reduce computation time.

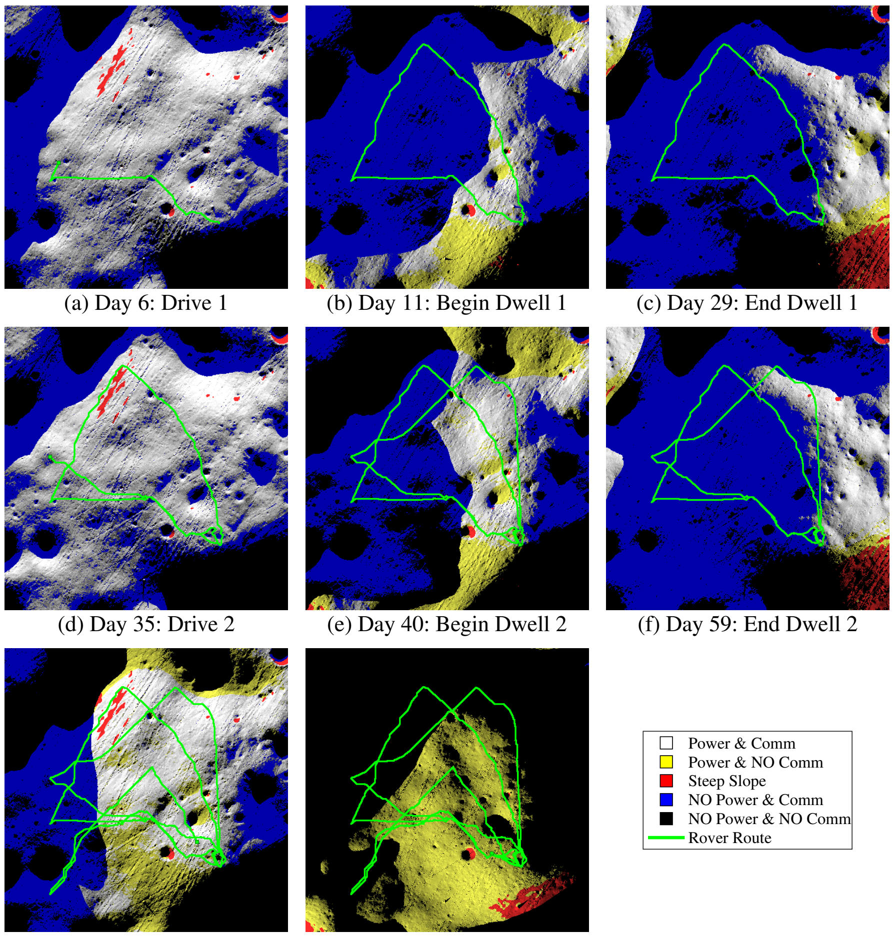
Supervised Teleoperation Route The baseline teleop route is illustrated by a series of snapshots in Fig. 5. Each frame represents only a single instant in time; however, each path represents the full route history up to that point. Hence, *green* path overlaid on top of *black* or *blue* ground does not indicate that the rover passed through shadow, only that a visited location later became shadowed. The route covers approximately 63.5 kilometers in 74 Earth days without exceeding 10 centimeters per second. It returns to its starting point after each of three drives to wait out the communication blackout. Dwelling at this singularity is the only means of achieving three lunar days of solar-powered exploration under the given constraints.

4 Route Analysis

Visualizing 3D Route Constraints in 2D This section introduces a novel method for visualizing three-dimensional spatiotemporal routes in two dimensions. The route's spatial proximity to an ordered set of dynamic constraint conditions is viewed as a function of time. This 2D projection is useful for visualizing, analyzing, and comparing routes, particularly where 3D formats (e.g., videos) are prohibited. Furthermore, this technique reveals the risk associated with dwelling at singularities.

This 2D graphical representation was inspired by weather radar history graphs and can be explained using that analogy. A video playback of weather radar can be condensed from three dimensions to two by plotting the distance from a given location (e.g., a city center) to the nearest storm front in any direction for all times. An even richer representation can be constructed by plotting the most severe weather condition that occurs a specific distance away (in any direction) for all distances with a given range and for all instants over a span of time. Essentially, this type of graph displays the minimum distance to the worst case conditions as a function of time. A similar graph can be constructed for a moving vehicle instead of a static point, where distances are relative to the vehicle's instantaneous position. Rover constraints (e.g., sunlight, communication, slope, and combinations thereof) can be substituted for weather conditions as long as they are ordered by severity.

Applying this concept to the teleop route yields the graph shown in Fig. 6. The y-axis represents time and advances downwards like a strip chart. The x-axis marks distance from the rover's instantaneous position, which is indicated by a vertical green line. Distances are relative and can be in any direction. Each row of the plot



(a) Day 6: Drive 1 (b) Day 11: Begin Dwell 1 (c) Day 29: End Dwell 1
(d) Day 35: Drive 2 (e) Day 40: Begin Dwell 2 (f) Day 59: End Dwell 2
(g) Day 67: Drive 3 (h) Day 74: End Route

Fig. 5 *Supervised Teleoperation*: This sequence of snapshots illustrates a 3-lunar-day route near Nobile Crater. The route starts in the bottom-right quadrant and proceeds in a clockwise fashion with a long dwell period at a singularity near the starting point between each of the three drives. The rover is stationary from Day 11 (**b**) to Day 29 (**c**) and from Day 40 (**e**) to Day 59 (**f**) due the communication constraint. It theoretically maintains uninterrupted solar power near the edge of the terminator while dwelling, but this is uncertain. The terrain is color-coded by constraint conditions.

represents a snapshot of the dominant constraints at each distance from the rover's position at that instant in time. To the right of the green line is the worst-case condition at every distance, analogous to the distance outside the storm's edge. To the left of the green line is the best-case condition at every distance (distance inside the storm's edge). The precedence of the color-coded conditions match that of Fig. 5 and are in order of increasing severity: white (power & comm), yellow (power & no comm), red (steep slope), blue (no power & comm), black (no power & no comm).

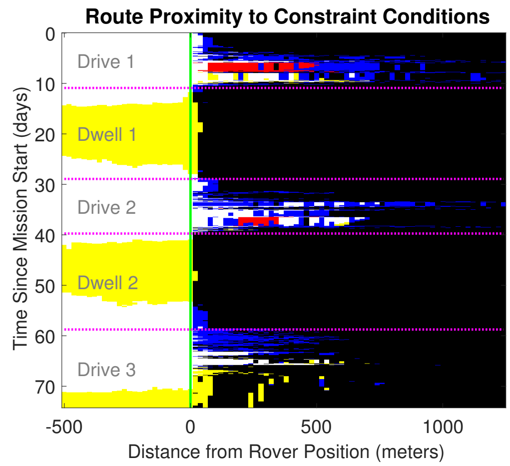


Fig. 6 This graph shows the proximity of the teleop route to the best- and worst-case constraint conditions as a function of time. The vertical *green* line at 0 represents the relative position of the rover's planned path. On the right side of the *green* line is the most dominant constraint at every distance from the rover's position. On the left side is the least dominant constraint. The horizontal *magenta dotted* lines mark when the rover arrives at and departs from the singularity. See Fig. 5 for color-coding.

Computational Method The graph is computed one row at a time. Distance is divided into discrete uniform bins, each defined by two radii. For example, at a distance of d = 100 meters with a resolution of 20 meters, r_1 = 90 meters and r_2 = 110 meters. All unique constraint conditions lying within the ring formed by the two radii are isolated. The most severe condition within that subset is plotted at distance d, and the least severe condition is plotted distance $-d$. This is repeated for every distance to complete the first row and for every row to complete the graph.

Interpretation The proximity graph efficiently conveys useful information about the route plan and reveals potential concerns. By examining Fig. 6, it is clear that rover spends two periods of nearly 20 days each within 10–30 meters of total blackout from sunlight. This happens when the rover is parked at a singularity as the terminator rotates about the peak. During this time, the rover is not permitted to move due to communication denial. Because the DEM contains errors of up to 50–100 meters, the location of this single point of light may vary significantly, or it may not even exist. Both cases would strand the rover in darkness and cold for weeks, likely ending the mission before communication is restored.

5 Strategic Autonomy

The concept of strategic autonomy is motivated by concerns of dwelling at an uncertain singularity as illustrated by the constraint proximity graph. This new operational concept seeks to reduce overall mission risk by distancing the rover from singularities (akin to the way robotic manipulators avoid kinematic singularities). This comes at the cost of some accepted added risk related to unsupervised autonomy during communication outages. This paper asserts that this tradeoff is beneficial.

Constraints Strategic autonomy is defined by the following constraints.

Sunlight The rover must remain in direct sunlight at all times (same as teleop).

Communication The rover must maintain an unobstructed view of Earth when driving except when doing so would cause the rover to dwell at a singularity for a period of time exceeding 24 hours. In this case, the rover is permitted to drive autonomously without communication at 20% of the nominal maximum drive speed.

This is the key distinguishing feature of the strategic autonomy concept of operations. This modified constraint prevents the rover from dwelling motionless at a singularity for long periods of time. Instead, the planner is free to maximize the rover's distance from shadow and thus confidence of sunlight.

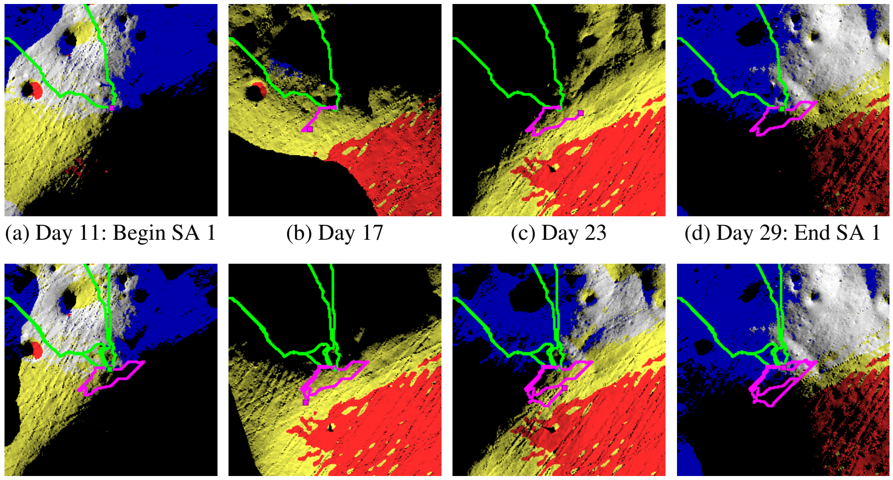
Slope Principal ground slopes must not exceed 20 degrees (same as teleop).

Planning Method The planning method begins with the baseline teleop route and modifies discrete segments according to the altered communication constraint. Singularities are identified manually with the aid of the 2D constraint proximity graph. At the instant the rover reaches an identified singularity, the altered constraints are activated. A small set of new waypoints are selected (manually, for this example) to maximize distance from darkness and steep slopes such that the new route segment splices into the original route at the instant the original dwell would have ended. Minimum distance paths passing through all new waypoints are computed using the same A* method as before with reduced maximum drive speed (from 10 to 2 centimeters per second) while suspending the requirement for communication.

Strategic Autonomy Route Using this method, two instances of dwelling at singularities were identified and replaced. The altered route segments, which exhibit strategic autonomy, are shown in Fig. 7. All other route segments remain unaltered and are identical to those in Fig. 5. Like the baseline, the strategic autonomy route spans 74 Earth days but covers a total distance of 71.8 kilometers, a 11.5% increase compared to the teleop route. The constraint proximity graph is shown in Fig. 8.

6 Discussion

Notable differences between the supervised teleoperation and strategic autonomy routes are shown in Table 1. Most notable is the increased mean distance to shadow. Whereas the teleop route dwells approximately 10 and 30 meters from the nearest shadow (the day–night terminator) the corresponding strategic autonomy route segments achieve a mean separation of approximately 180–190 meters. On a 10-meter DEM, this is the difference between 1–3 pixels and nearly 20. This difference becomes even more significant when considering that the LOLA topography models have an estimated spatial accuracy of 50–100 meters. If this translates to an error of up to 100 meters, the supervised teleoperation route is problematic, whereas the strategic autonomy route might still retain a safety margin of almost 100 meters.



(a) Day 11: Begin SA 1 (b) Day 17 (c) Day 23 (d) Day 29: End SA 1

(e) Day 40: Begin SA 2 (f) Day 50 (g) Day 55 (h) Day 59: End SA 2

Fig. 7 *Strategic Autonomy (SA)*: This sequence of snapshots (zoomed in relative to Fig. 5 and centered at the route's starting point/singularity) illustrates the two autonomous route segments that differ from the baseline teleop route. The top row (**a–d**) replaces first teleop dwell period, and the bottom row (**e–h**) replaces the second teleop dwell period. The autonomous drive segments are drawn in *magenta*, whereas unaltered route segments are *green*. See Fig. 5 for terrain color-coding.

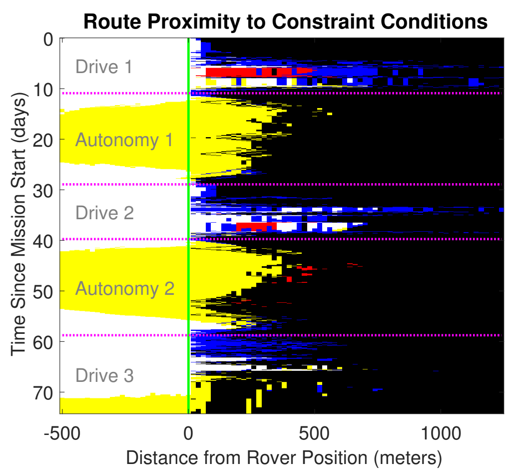


Fig. 8 This visualization shows the proximity of the strategic autonomy route to the best- and worst-case constraint conditions as a function of time. The vertical *green* line at 0 represents the position of the rover as it traverses the planned path. This plot should be interpreted in the same manner as Fig. 6. Likewise, constraints are color-coded as in Fig. 5. The large *yellow* areas to the right of the *green* line indicate a wide margin of predicted sunlight in all directions around the rover.

Compared to dwelling at uncertain singularities, this added buffer substantially increases the likelihood of maintaining solar power and continued exploration.

Strategic autonomy is not without drawbacks. Its reliance on unsupervised autonomous driving, even at very slow driving speeds, incurs some added risk. The total magnitude of this risk depends on numerous complex factors related to the rover's

Table 1 Route Segment Comparison

Route Segment	Total Time (days)	Dwell Time (%)	Distance Traveled (km)	Max Speed (cm/s)	Mean Speed (cm/s)	Min Dist. to Shadow (m)	Max Dist. to Shadow (m)	Mean Dist. to Shadow (m)
Dwell 1	18	100	0	0	0	10	50	29
Dwell 2	19	100	0	0	0	10	30	12
Autonomy 1	18	36	4.1	1.5	0.26	10	390	191
Autonomy 2	19	38	4.2	1.6	0.26	10	370	178

Dwell: supervised teleoperation dwell segment; **Autonomy**: strategic autonomy drive segment

perceptual, computational, and mechanical design and can therefore not be estimated easily or without rigorous testing of the actual systems. However, the high level of risk inherent to dwelling at an uncertain, unverified singularity the size of which is less than the estimated error of the models used to predict such a point almost certainly exceeds that of short, slow, autonomous drives preplanned to favor regions of almost certain sunlight.

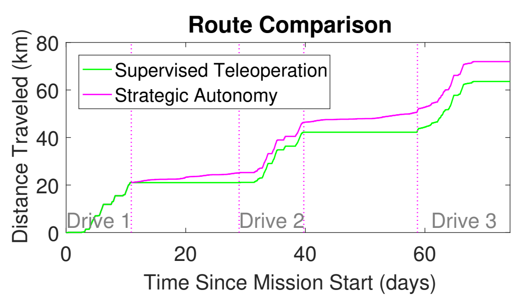


Fig. 9 The supervised teleoperation route dwells statically at singularities while the strategic autonomy route continues driving to avoid them. Vertical lines mark the start and end of the two dwell/autonomy segments corresponding to Table 1. The three segments labeled "Drive" are identical between the two routes.

7 CONCLUSION

Solar-powered rovers are a logical next step for exploring the poles of the Moon, and multi-month missions are possible using a new concept of operations called strategic autonomy. Strategic autonomy maintains continuous exposure to sunlight by permitting short, slow, autonomous drives during periodic communication blackouts—a natural consequence of sun-synchronous routes. These drives follow preplanned paths and distance rovers from the day–night terminator where sustained insolation is uncertain. Mission concepts that prohibit autonomy and enforce a strict requirement on constant communication for teleoperation inevitably force rovers to dwell stationary for weeks at small peaks of predicted sunlight; however, the existence and exact locations of such singularities cannot be confidently predicted due to limitations in lunar topographic data. This paper asserts that the risk associated with dwelling at uncertain singularities exceeds that of driving autonomously with guaranteed solar power. Strategic autonomy ultimately reduces overall mission risk while enabling extended lunar polar exploration. Future work will quantify this claim.

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References

1. Acton, C.H.: Ancillary data services of NASA's navigation and Ancillary Information Facility. Planet. Space Sci. **44**(1), 65–70 (1996)
2. Andrews, D.R., Colaprete, A., Quinn, J., Chavers, D., Picard, M.: Introducing the Resource Prospector (RP) Mission. In: AIAA SPACE 2014 Conf. and Expo. Reston, Virginia (2014)
3. Colaprete, A., Schultz, P., Heldmann, J., Wooden, D., et al.: Detection of Water in the LCROSS Ejecta Plume. Science **330**(6003), 463–468 (2010)
4. Heiken, G.H., Vaniman, D.T., French, B.M.: Lunar sourcebook - A user's guide to the moon. Cambridge University Press, New York, New York, USA (1991)
5. Heldmann, J., Colaprete, A., Elphic, R.C., Bussey, B., McGovern, A., Beyer, R., Lees, D., Deans, M.C., Otten, N., Jones, H., Wettergreen, D.: Rover Traverse Planning to Support a Lunar Polar Volatiles Mission. In: LEAG. NASA Ames Research Center (2015)
6. Mazarico, E., Neumann, G., Smith, D., Zuber, M., Torrence, M.: Illumination conditions of the lunar polar regions using LOLA topography. Icarus **211**(2), 1066–1081 (2011)
7. NASA: Welcome to the Planetary Data System. URL `https://pds.nasa.gov/`
8. Otten, N.D., Jones, H.L., Wettergreen, D.S., Whittaker, W.L.: Planning routes of continuous illumination and traversable slope using connected component analysis. In: 2015 IEEE International Conference on Robotics and Automation (ICRA), pp. 3953–3958. IEEE (2015)
9. Paige, D.A., Foote, M.C., Greenhagen, B.T., Schofield, J.T., et al.: The Lunar Reconnaissance Orbiter Diviner Lunar Radiometer Experiment. Space Sci. Rev. **150**(1-4), 125–160 (2010)
10. Paige, D.A., Siegler, M.A., Zhang, J.A., Hayne, P.O., et al.: Diviner Lunar Radiometer Observations of Cold Traps in the Moon's South Polar Region. Science **330**, 479–482 (2010)
11. Pieters, C.M., Goswami, J.N., et al.: Character and Spatial Distribution of OH/H2O on the Surface of the Moon Seen by M3 on Chandrayaan-1. Science **326**(5952), 568–572 (2009)
12. Smith, D.E., Zuber, M.T., Jackson, G.B., et al.: The Lunar Orbiter Laser Altimeter Investigation on the Lunar Reconnaissance Orbiter Mission. Space Sci. Rev. **150**(1-4), 209–241 (2010)
13. Smith, D.E., Zuber, M.T., Neumann, G.A., Lemoine, F.G., et al.: Initial observations from the Lunar Orbiter Laser Altimeter (LOLA). Geophys. Res. Lett. **37**(18) (2010)
14. Tompkins, P., Stentz, A., Wettergreen, D.: Mission-level path planning and re-planning for rover exploration. In: Robotics and Autonomous Systems, vol. 54, pp. 174–183 (2006)
15. Vasavada, A.R., Bandfield, J.L., Greenhagen, B.T., Hayne, P.O., et al.: Lunar equatorial surface temperatures and regolith properties from the Diviner Lunar Radiometer Experiment. J. Geophys. Res.-Planet. **117**(4) (2012)
16. Washington University in St. Louis: PDS Geosciences Node Data and Services: LRO LOLA. URL `http://pds-geosciences.wustl.edu/missions/lro/lola.htm`
17. Wettergreen, D., Tompkins, P., Urmson, C., Wagner, M., Whittaker, W.: Sun-Synchronous Robotic Exploration: Technical Description and Field Experimentation. Int. J. Robot. Res. **24**(1), 3–30 (2005)
18. Whittaker, W.L., Kantor, G., Shamah, B., Wettergreen, D.S.: Sun-synchronous planetary exploration. In: AIAA Space (2000)
19. Wieczorek, M.: The gravity and topography of the terrestrial planets. Treatise Geophys. (2007)