ROBOTIC LUNAR SURFACE OPERATIONS 2. B. Sherwood[1], A. Austin[1], T. Colaprete[2], J. Elliott[1], A.S. Howe[1], S. Magnus[3], P. Metzger[4], R. Polit-Casillas[1], H.H. Schmitt[3], M. Sims[5], G. Voecks[1], K. Zacny[6], [1]Jet Propulsion Laboratory (M/S 321-625, 4800 Oak Grove Dr, Pasadena CA 91001, brent.sherwood@jpl.nasa.gov), [2]NASA Ames Research Center, [3]Consultant, [4]Univ Central Florida, [5]Ceres Robotics, [6]Honeybee Robotics.

Introduction: Results are reported from a new, ongoing lunar base study with a concise architectural program: build and operate a habitable lunar base that produces enough oxygen and hydrogen from lunar polar ice resources for four flights per year of a reusable lander shuttling between Gateway and the base.

Context: The RLSO study [1][2] developed the first integrated design/operations analysis of an oxygen-producing lunar base enabled by autonomy and robotics. The RLSO2 study updates this work with new assumptions for 1) resources – lunar polar ice instead of ilmenite; 2) solar power – polar lighting conditions instead of the 28-day equatorial cycle; 3) transportation – based on multiple flight systems now in development and planning; 4) base site plan – a range of options near, straddling, and inside permanently shadowed regions; 5) ISRU scenarios – for harvesting ice and constructing radiation shielding from regolith.

Study structure: Like the original study, RLSO2 combines US experts in mission design, space architecture, robotic surface operations, autonomy, ISRU, operations analysis, and human space mission and lunar surface experience. Three members provide continuity from the original team. The integrated performance of purpose-designed base elements is captured in a numerical operations model. This allows rapid iteration to converge system sizing, and builds a legacy analysis tool that can assess the performance benefits and impacts of any proposed system element in the context of the overall base.

We summarize the study groundrules, assumptions, and methodology. We present maturation status of the operations model, preliminary element designs comprising the base, and first-round base siting analyses. We describe quantitative findings to date.

Results: RLSO2 follows the original RLSO statement of task, but with contemporary assumptions: 1) harvesting of water ice at a polar base rather than hydrogen reduction of ilmenite at a nearside mid-latitude base; 2) use of a DHRO Gateway transportation node rather than an energetically preferable low lunar orbit; 3) logistics scenarios incorporating lander downmass capacities in three ranges: 10s, 1000s, and 10,000s kg rather than just a very large NASA lander.

Base siting analysis is informed by the Traverse Planning Tool developed by the Resource Prospector pre-project; datasets from multiple LRO instruments are synthesized into a time-varying, latitude-longitude-specific illumination model, making insolation and power storage duty cycle a variable dependent on base location and element geometry.

Three resource and base siting schemes are analyzed: 1) entire base located in a PSR (permanently shadowed region), where the ice resource has highest concentration but the operating temperature is ~100 K; 2) resource recovery in a PSR but with base habitat and depot located in a nearby PLR (persistently lit region); 3) entire base located in a PLR, where the ice resource has lowest concentration but large traverse distances are avoided.

Predicted findings validated by RLSO2 include several generalizable principles [3]: 1) Most lunar base operations, most of the time, must be robotic. 2) Substantial base infrastructure can be constructed, and base operations conducted, with only a few short, intermittent crew visits, if robotic operations is the dominant mode. 3) Reusable-lander cargo capacity (e.g., of order 20 tons downmass), configuration, and flight rate fundamentally affect base element design. 4) Moving a crippled lander is the bounding requirement for cargo mobility on the surface. 5) Automation and robotics considerations become driving requirements for all base elements. 6) A detailed three-dimensional sitemap including subsurface characterization at 10-cm resolution is essential. 7) High-power (>10 hp) vehicles are not necessary for an early base to produce propellant at 100 t/yr rates. 8) Paving routine traffic routes is the driving requirement for construction timelines. 9) Hierarchical supervisory control is enabling, but full autonomy is not. 10) ~15% of delivered mass is required for spares inventory, as long as component-level repair is a primary crew activity. 11) Habitat systems and other complex components should not be buried directly with regolith. 12) Crew time is valuable; EVA time is even more valuable. Shifting tasks from crew to robots has positive value. 13) Equipment repair at the sub-component level requires robotic remove-and-replace operations, equipment airlock and dust-cleaning, and a workshop.

New or counterintuitive findings include: 1) Long-distance "exploration sortie" scenarios that are NASA's traditional focus are largely incompatible with infrastructure buildup in a single location, which is required for the contemporary interest in sustainability through ISRU. 2) Lunar ice resources are not significantly easier than mineral harvesting of oxygen. Excavation to 10s cm depth is required even to reach 2-5 wt% concentrations; surface “frost” is unusably sparse; potential paleo-ice would be meters deep. By contrast, ilmenite is widely available on the surface. 3) Siting in a PLR may be best for volatiles production. Water-ice resource concentrations are only 2-5x lower than in PSRs, but in flatter terrain and without the complication of regional energy transmission. 4) PLR lighting is more challenging than commonly thought. Lunation nighttimes last days for mining-size areas around fixed locations, and are highly dependent on topography and solar array elevation above grade. 5) Nuclear power is not enabling. Contemporary “kilopower” concepts produce only ~10 kWe, necessitating many reactors for production-scale ISRU. Reactor shielding requires extensive surface operations before startup. Solar power and RGC (regenerable fuel cell) storage are not obviated, and are highly scalable. 6) Gateway is an inefficient node location for materiel exchange (e.g., lunar volatiles “up” and cargo “down”) between a polar base and cislunar space. Δv inefficiency burdens a sustainable architecture throughout its lifetime. 7) Excavationless extraction using tented solar heating [4] is conceptually elegant but not ready for quantitative planning due to undemonstrated coupling margins and losses.

References:

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