A Lunar Surface Operations Simulator

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Abstract. The Lunar Surface Operations Simulator (LSOS) is being developed to support planning and design of space missions to return astronauts to the moon. Vehicles, habitats, dynamic and physical processes and related environment systems are modeled and simulated in LSOS to assist in the visualization and design optimization of systems for lunar surface operations. A parametric analysis tool and a data browser were also implemented to provide an intuitive interface to run multiple simulations and review their results. The simulator and parametric analysis capability are described in this paper.

1. Introduction

The National Aeronautics and Space Administration (NASA) is leading an international partnership to develop and deploy a series of missions to return astronauts to the moon in 2025 [1]. In addition to habitation on, and exploration of the lunar surface, these missions, developed under NASA's Constellation Program, will be precursors for subsequent manned missions to Mars. To enable these missions, new launch, crew transport, lander, and surface mobility vehicles and lunar habitat systems are being designed. Simulators are playing a vital role in assisting in the mission design and planning, visualization and design optimization of these systems.

The Lunar Surface Operations Simulator (LSOS) is one of the simulators under development within the Constellation Program. As its name suggests, it models surface systems, their mechanical properties, dynamic interactions and operations. In addition to simulating the dynamic interactions during operations, for example, soil interaction or component motion, LSOS also models associated environmental, and system mechanical and non-mechanical processes. These include thermal, radiation and power transients, lighting and shadows, and terrain. LSOS's integrated architecture allows use of common models and enables interactions between components operating in different domains to be easily modeled. For example, the illumination, solar panel power and thermal models use a common sun model and incidence angle. Simulations and post simulation analyses have been recently performed within LSOS to show that it can be a powerful tool to assist both in the design and planning of missions, and in component design optimization.

LSOS has been built on and extended from previous simulation packages developed at the Jet Propulsion Laboratory. Its core physics simulation engine is the DARTS package originally developed to simulate the Cassini spacecraft [3]. DARTS is a multi-body domain-independent dynamics engine. Subsequent development around DARTS has led to supporting packages and simulators for a variety of space applications. These include Dshell [4], SimScape [8], ROAMS [5, 6], and DSENDS [7].

This paper gives an overview of LSOS. We start in the next section with a description of the models that have been developed within LSOS. We have used LSOS in a batch mode to perform parametric analysis. Procedures developed to enable this capability are described with an example in the section on Parametric Analysis. We finally conclude with a description of our current status and future plans.

The results from simulators like LSOS, combined with the analytical approaches by others [2] are essential for successful and timely development of NASA's vision for our return to the moon.

2. Models

Simulations in LSOS are composed from models of many components. Some of the more important component models are described in this section.

2.1 Vehicle Models

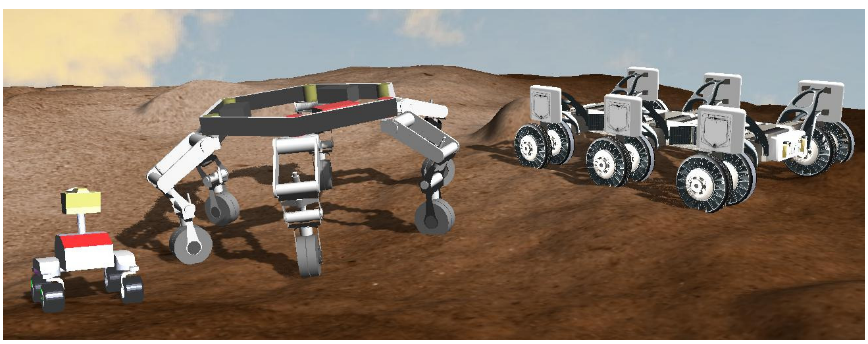

Fig. 1. The K-10 (left), ATHLETE (middle) and Chariot (right) rovers modeled in LSOS.

A number of prototype autonomous and teleoperated vehicles are have been developed for terrestrial demonstration of potential lunar surface operations. As development on and demonstrations of these vehicles for Lunar missions continue, they are being modeled and simulated in LSOS to facilitate visualizing and evaluating their performance under Earth and Lunar surface environmental conditions and to assist in design optimization.

The K-10 [9] built at the NASA Ames Research Center (ARC), ATHLETE [10] built at JPL and Chariot [11] built at the NASA Johnson Space Center (JSC) rovers are three prototypes being used in a series of field trials to demonstrate lunar operations capabilities. These vehicles, modeled in LSOS, are shown on Figure 1.

A generalized infrastructure for vehicle modeling in LSOS has led to a streamlined process for modeling the variety of kinematic, dynamic and constraint properties found in these vehicles. Re-use of common elements has allowed us to reduce the complexity and improve the reliability of the modeling and simulation software. Each vehicle model is configured by assembling it from a library of components. The use of common components allows each unique vehicle to inherit many wheeled vehicle properties, for example, inertial sensors or mobility and navigation yet maintain their unique properties. The models are composed of detail elements of the vehicle including mass and inertia tensors of all rigid-body elements and joints, actuators and sensors.

2.2 Habitat model

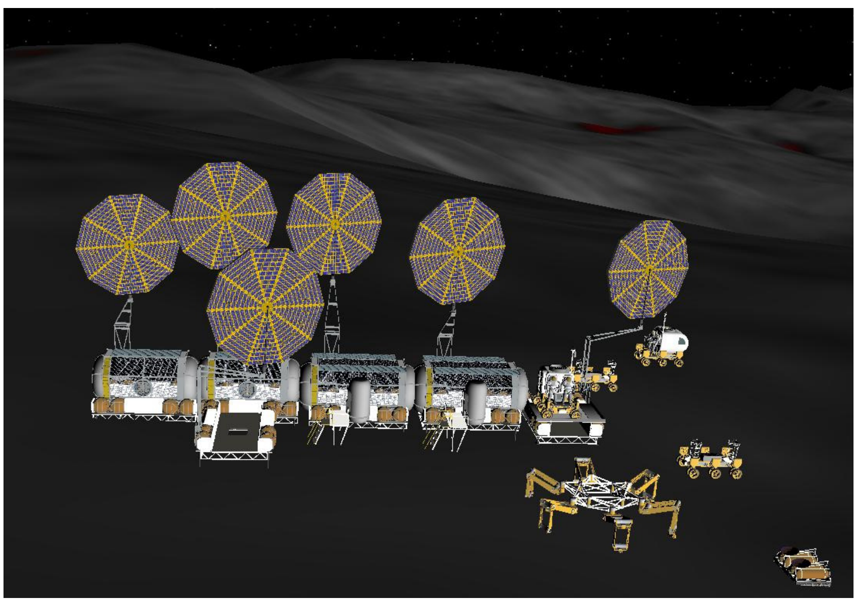

Fig. 2. LSOS visualization of a potential Lunar habitat system from NASA LaRC.

The Space Mission Analysis Branch [12] at the NASA Langley Research Center (LaRC) has been analyzing and developing models and scenarios of lunar surface systems for the Constellation Program. The development of a Lunar surface system architecture is a complex problem in which a wide variety of constraints have to be satisfied. Some design constraints are imposed from interactions with the supporting systems. For example the size of the habitat modules will have to fit within the space available in the launch vehicles.

Many other constraints have to be determined by evaluating performance under simulated operations. For example, the amount of power generated by the habitat solar panels depends on the location selected on the surface of the moon, the elevation and topography of the surrounding terrain, the kinematics and control of the solar panels, the efficiency of the solar panels and so on. In the design of systems as complex as the lunar habitat, the use of a simulator can assist in the design and optimization of components and the evaluation of overall performance.

The LSOS team is working with lunar habitat designers at NASA LaRC to support the development of the lunar outpost. We have modeled the version of the lunar habitat shown on Figure 2 that was released in January 2008. Simulations were performed with this model for a power analysis assessment of the configuration. The model implemented in LSOS can place the static elements of the habitat on a terrain model at any user specified location. The supporting simulation sub-systems that enabled the power analysis simulation are described in the following sub-sections.

As the habitat design for the Lunar missions evolves, and as analytical and simulation needs arise, we will continue to update our habitat models and perform simulations and analysis to assist in the design of the lunar habitat.

2.3 Solar Panels

The current version of the lunar habitat implemented in LSOS has six solar panels. Each panel is mounted to a four degrees-of-freedom articulation system. The implementation of the solar panel system in LSOS used an existing software component for modeling robot arms. Six such robot arms with identical kinematics but placed at the six specified base attachment points were used for modeling the solar panel arms and articulation.

The configuration of the arms (shown on Figure 3) is a yaw joint at its base, a pitch joint at its elbow, a pitch joint at its wrist and a roll joint also at the wrist. The LSOS models derived the kinematics of the arms from the component graphics models we received from NASA LaRC. The LSOS models specify kinematics, and range of motion of the arm elements.

The objective in the control of the arms is to maximize the exposure of the solar panels to the sun while avoiding collisions between the arms and between arms parts and the habitat. Implicit in the goal of maximizing the solar panel exposure is the minimization of self-shadowing of the solar panels.

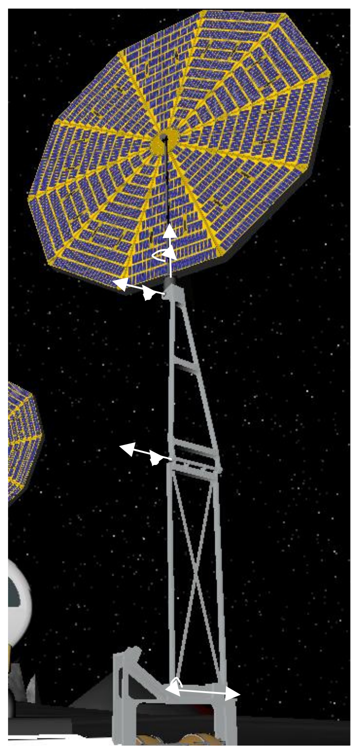

Fig. 3. Solar panel articulation in LSOS.

In our simulations, a simple algorithm was implemented for control of the solar panel arms. The motion of the sun with respect to the lunar habitat at the chosen location at the South Pole of the lunar surface is to traverse in a counter-clockwise direction very low on the horizon (between -3 degrees and +3 degrees) on a 27-day monthly cycle. Consequently, the solar panels should have their roll-axes vertical and be rotated to face the sun. The other three joints of the solar panel arms are periodically (four times during each monthly cycle) modified depending on the sun azimuth angle to translate the roll joint axis and improve the solar panel exposure to sunlight.

2.4 Terrain

Terrain models are an important component of surface simulations. LSOS uses the SimScape [8] package to incorporate terrain models. A number of terrain models have been generated for LSOS simulations. Among these are analog terrestrial field-trial locations at Meteor Crater in Arizona, USA and versions of lunar terrain models. Our lunar habitat simulator uses the recently released Goldstone Solar System Radar (GSSR) terrain model [13]. The GSSR terrain covers an area of about 300km by 600km at a 40m/pixel resolution. The terrain model was generated from radar images of the moon taken from the Earth. At the South Pole of the moon, the planned location of the lunar outpost, this terrain dataset is the best currently available.

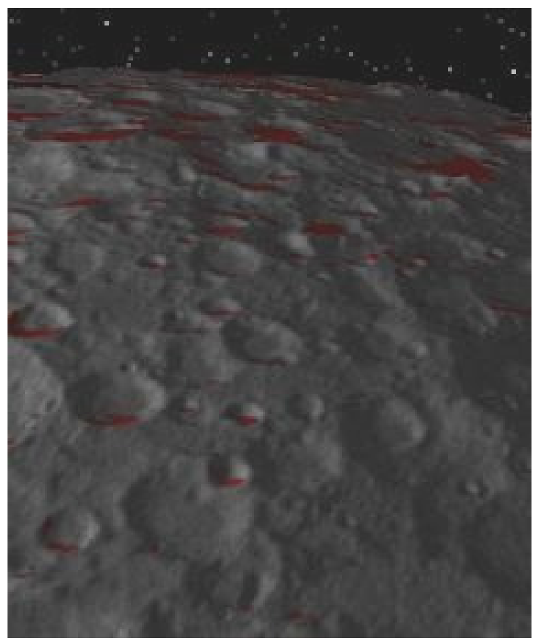

Fig. 4. GSSR model of South Pole region of the moon.

Due to the process used in generating the GSSR terrain model, regions not viewable from the Earth (because they are obscured by terrain features) are *holes* in the terrain. In LSOS, these regions have been *filled* with interpolated values shown in red on Figure 4. While the 40m resolution of the GSSR terrain model is adequate for the habitat simulation, the terrain model will have to be enhanced to centimeter-level resolution to be good enough for accurate simulation of vehicle-terrain interactions.

2.5 Sun propagation

LSOS uses the Spacecraft Planet Instrument C-matrix Events (SPICE) database and toolkit [14] to determine the locations of the moon, the sun and other planetary bodies at specified times during simulations. This data is used to compute the relative location of the sun with respect to specified locations on the surface of the moon at specified times.

The sun azimuth and elevation angle derived from the SPICE interface is available in the simulation environment for use by any algorithm. In the lunar habitat simulation, it is used to drive the roll angle value for each solar panel arm and for illumination modeling. In vehicle simulations, it is additionally used for computing heat radiation to the vehicle and ground, for solar panel lighting in the vehicle power analysis.

3. Parametric Analysis

One of the most powerful uses of LSOS is in performing parametric analysis to explore the behavior of systems as simulation parameters are varied. The software infrastructure to enable this was developed for the ROAMS [15] simulator to vary terrain and soil parameters and DSENDS [7] simulator to vary atmospheric conditions in entry, descent and landing simulations. This parametric analysis infrastructure was adapted for LSOS to orchestrate batch runs of lunar habitat simulations. In addition, the parametric analysis tools enable specification of parameters to vary the statistics of parameter variation, and data collection and storage from the simulations.

3.1 Parameters

Two parameters, height of the habitat and location of the habitat, were varied in a demonstration of parametric analysis applied to the lunar habitat simulation.

The height parameter placed the habitat at the specified height above the local terrain height (see Figure 5). In computing power generation, it was found that, because the sun is always low on the horizon, surrounding terrain features often obscure the solar panels from the sun. An advantage can be gained by increasing the height of the habitat because it raises the panels above the terrain shadows. This parameter was selected to determine the sensitivity of habitat height to the power generation. During the parametric analysis batch simulations, the height parameter was varied uniformly between 0 and 30m.

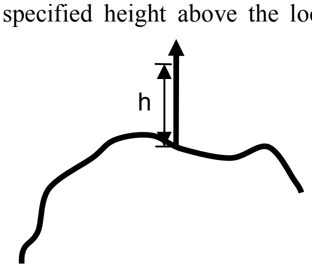

Fig. 5. The height parameter is measured from the local terrain height.

Locations at the South Pole of the moon have been identified as likely landing sites for lunar missions. This is motivated by the possibility that ice may be found close to the surface at the bottom of craters and the sun may be visible year-round from selected locations. For these reasons, Shackleton Crater, located almost exactly at the South Pole of the moon is an ideal site. Choosing a specific location on the rim of Shackleton is not as easy a task because surrounding terrain features obscure some areas, the elevation of the rim and proximity to the South Pole varies at different locations.

The complex interaction of these properties makes the analytical determination of the best habitat location complex. Varying the location in multiple simulations and determining power generation for each location is an alternative approach to determine ideal locations for the placement of a habitat.

Figure 6 shows the locations around the rim of Shackleton that were selected for the parametric analysis. Thirty locations, approximately equally spaced, were selected. The coordinates for these locations were entered in a table. During the parametric analysis simulations, an index into the table was uniformly varied to select a particular location to use for the simulation.

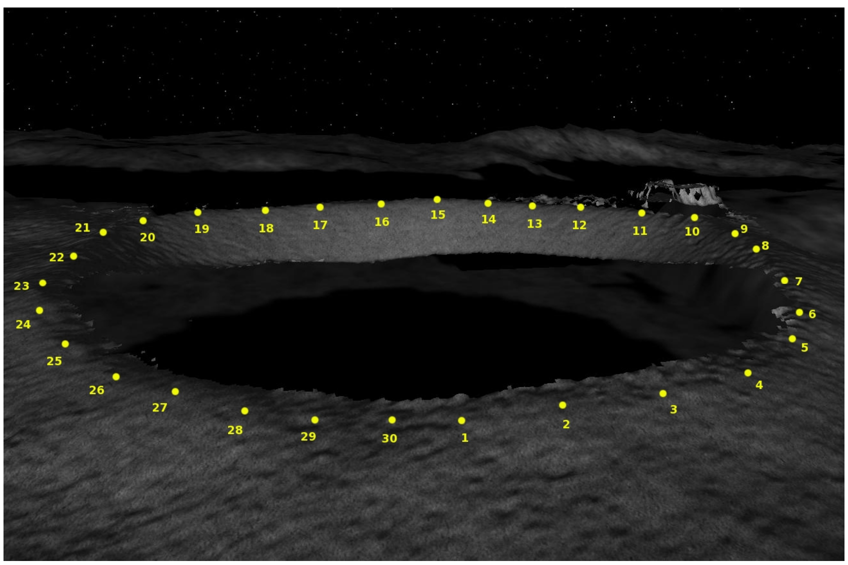

Fig. 6. Locations around the rim of Shackleton Crater varied as a parameter.

3.2 Parametric Analysis Runs

A total of 200 simulations were run in the parametric analysis. Each simulation ran a one-month (720 hours) simulation with time incremented in one hour steps. The start time use in the simulations was March 7, 2011, GMT 01:00:00.

To illustrate the parametric analysis, a simple power model was implemented in the simulation runs. At each step, the power generated was computed by multiplying the exposed solar panel area by 400 Watts/m^2 to factor the solar power collected and converted into useful energy. This approximates the solar panel efficiency to be about thirty percent. A battery model with a capacity of 100000 Watt-hrs was used in the simulations to store the power generated. A constant drain on the battery of 200 Watts was also implemented to model power usage during surface operations. The simulations were initialized with the battery at fifty percent charged, i.e. with 50000Watt-hrs of energy. Data collected during the simulations include the time, habitat height and location, the sun azimuth and elevation angles, current power, battery charge and total accumulated power.

Data collected from the simulations was stored in HDF5 format. A browser, developed to retrieve data from the HDF5 store and selectively view the data, provides an intuitive interface to inspect the results from the simulations.

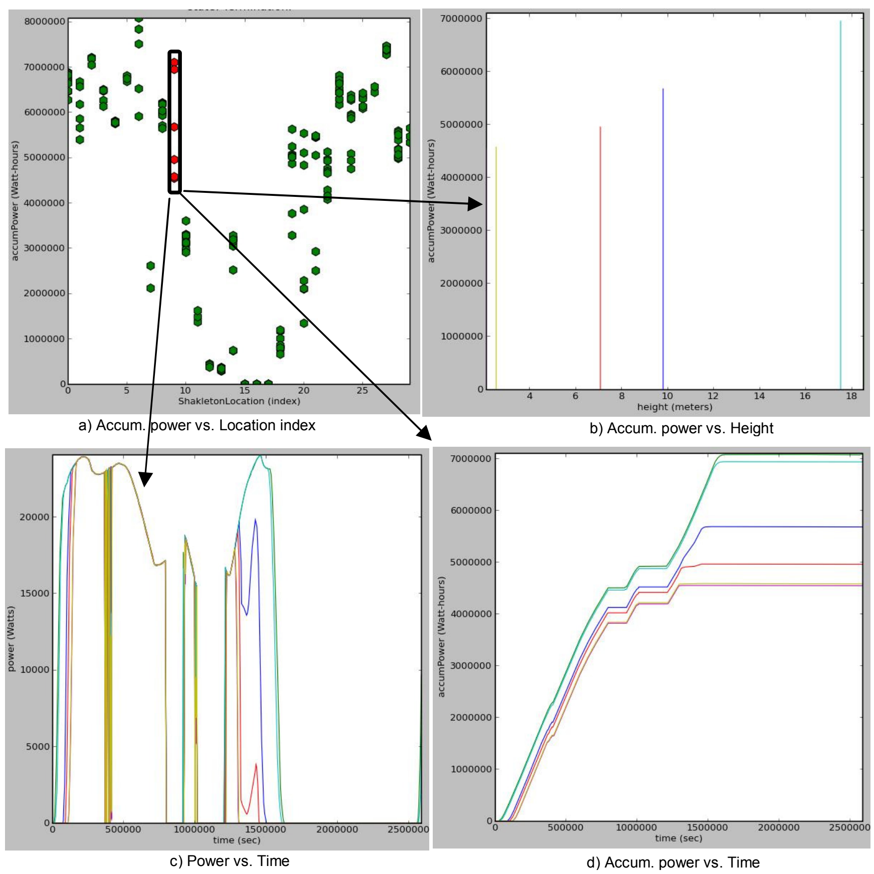

Fig. 7. Browser display of parametric analysis data: a) scatter plot of accumulated power versus location for all 200 simulation runs, b) Accumulated power versus height for selected simulation runs at location 9, c) Power versus time for selected simulation runs at location 9, and d) Accumulated power versus time for selected simulated runs at location 9.

Screen shots from the data browser display are shown on Figure 7. A scatter plot of accumulated power versus location index for all the simulation runs is shown on Figure 7a). For the simulation conditions used (terrain, habitat model, etc), the results indicate that locations 1-10 and 20-30 are generally better than locations 11-19. The browser allows the user to select simulations from the scatter plot to view in detail.

We can see from Figure 7b) that, not surprisingly, at location 9, increasing height improves power accumulation. Figure 7a), however, shows that power generation at some locations are more sensitive to height changes than at other locations. Figure 7c) and 7d) show that, at location 9, a terrain feature probably blocks the sun about 1600000 secs (about 444 hours or about 18.5 days) after the start of the simulation.

We used this simulation and parametric analysis example to illustrate the utility of applying high-quality simulations to assist the design of systems. The capability to select and view any parameter or simulation variable plotted against any other parameter or simulation variable can be used to identify hidden relationships in the data that may lead to new revelations to optimize designs.

4. Conclusions

We have presented, in this paper, preliminary results from our development of LSOS. It has been used to demonstrate the simulation of a variety of models and operational scenarios. We also describe a parametric analysis package to manage batch execution of multiple simulations with varying parameters. A demonstration of this capability is used to illustrate how simulations can be used effectively to aid in the optimization of designs.

Future development plans for LSOS include extensions to handle new lunar vehicle types, simulate more complex operations and scenarios, incorporate models of other physics-based processes, share models and data with other lunar mission simulators and support design and development activities and field trial planning for NASA lunar missions. Plans are also underway to generate high-resolution terrain models using re-construction techniques based on physical process models [16].

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