Development of Lunar Simulator for research in autonomous algorithms for telerobotics

Photometric modelling of regolith and simulator framework development

Midhun S. Menon
University of Colorado, Boulder

Michael Walker
University of Colorado, Boulder

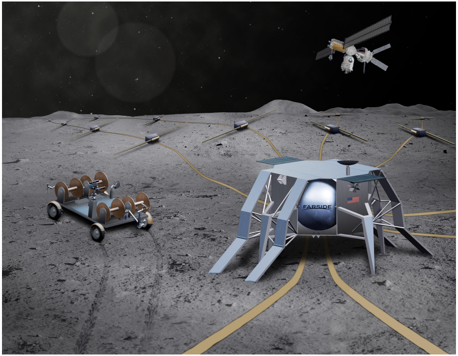
Daniel Szafir
University of Colorado, Boulder

Jack Burns
University of Colorado, Boulder

Terry Fong
NASA Ames Research Center

1. Outline
2. Resurgence of Lunar Exploration
3. Motivation
4. Problem 1: Photometric Modelling
   - Problem Statement
   - Scope of Work
   - BRDF Modelling
   - Results
   - Future Work
5. Problem 2: Lunar Simulator
   - Problem Statement
   - Scope of Work
   - Simulator Development
   - Results
   - Future Work
6. References

Return to the Moon - Artemis and FARSIDE



Low Radio Frequency Array on the Lunar Farside (FARSIDE, P.I.: Jack Burns). Figure courtesy JPL

- Lunar exploration is resurging
  - NASA returning to moon by 2024
  - Developing Lunar Gateway
  - Radio telescope program on lunar farside for exoplanet detection
- Complicated surface construction requirements specify robust telerobotic exploration capabilities

Motivation

- Simulators can play pivotal role here
  - Generate mission requirements from virtual analog missions
  - Provide training for astronauts
  - Help in operation planning
  - Reduce cognitive load by intuitive information exchange & semi-autonomy
- Simulators work in real-time framerates(25-30Hz) or higher & simulate environment physics to meet functional requirements

Outline

1 Outline
2 Resurgence of Lunar Exploration
3 Motivation
4 Problem 1: Photometric Modelling
- Problem Statement
- Scope of Work
- BRDF Modelling
- Results
- Future Work

5 Problem 2: Lunar Simulator
- Problem Statement
- Scope of Work
- Simulator Development
- Results
- Future Work

6 References

Towards fast and functional regolith photometric models

Question

Can we generate *functionally* photorealistic rendering of given lunar terrain geometry at near realtime frame rates (60Hz) or higher?

- Simulator must be close to real time (fast)
- Must provide a functionally accurate simulation of the optical response of lunar regolith in the visible spectrum
- Simulate visual artefacts (glare etc.) generated as a consequence in sensors (specifically optical), which might potentially affect autonomous algorithms onboard an exploration vehicle (SLAM, path/operation planners etc.)

Outline

1 Outline
2 Resurgence of Lunar Exploration
3 Motivation
4 Problem 1: Photometric Modelling
- Problem Statement
- Scope of Work
- BRDF Modelling
- Results
- Future Work

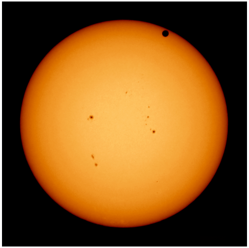
5 Problem 2: Lunar Simulator
- Problem Statement
- Scope of Work
- Simulator Development
- Results
- Future Work

6 References

University of Colorado Boulder

Scope of Work

Develop methods to render the observed photometric properties of lunar regolith



Limb darkening (sun)

No limb darkening

Opposition effect

How?

Bidirectional Reflectance Distribution Function a.k.a BRDF

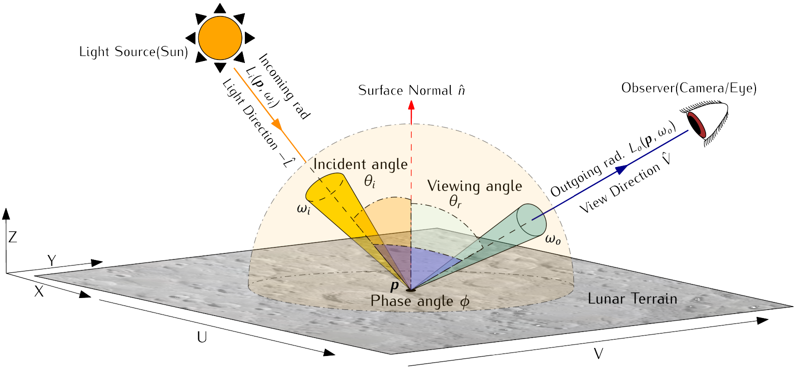
Outline

1 Outline
2 Resurgence of Lunar Exploration
3 Motivation
4 Problem 1: Photometric Modelling
- Problem Statement
- Scope of Work
- BRDF Modelling
- Results
- Future Work

5 Problem 2: Lunar Simulator
- Problem Statement
- Scope of Work
- Simulator Development
- Results
- Future Work

6 References

What is a BRDF?



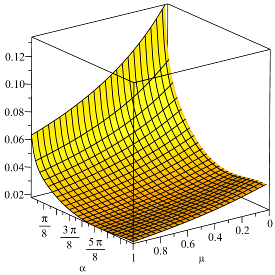
BRDF simulates the reflective response of a surface-material combination. It is part of the rendering equation(Kajiya 1986)

$$\underbrace{L_o(p, \omega_r)}_{\text{Light reflected towards eye}} = \int_\Omega \underbrace{f(p, \omega_r, \omega_i, \alpha)}_{\text{BRDF}} \times \underbrace{L_i(p, \omega_i)}_{\text{Incoming light}} \times \underbrace{\mu_0}_{\text{Angle weighting}} \times d\omega_i$$

How is Lunar Surface Photometry Modelled?

- Sun is modeled as directional reddish source (R:255,G:235,B:238)
- Base terrain→Lunar Reconnaissance Orbiter Camera(LROC) Narrow Angle Camera(NAC) Digital Elevation Model(DEM)
- It is synthetically enhanced from $\approx \mathbf{0.5m}$/pixel resolution to sub-mm resolution by fractal expansion (Allan et al. 2019)
- Surface reflectance modeled by BRDFs→$f\,(\mu_0 = \cos\theta_i, \mu = \cos\theta_r, \alpha)$ & parameters (Single Scattering Albedo(SSA)) etc

BRDF Models Used



Hapke BRDF for incident factor $\mu_0 = \cos 45^\circ$, viewing factor $0 \leq \mu \leq 1$ and phase angle $0 \leq \alpha \leq \pi$

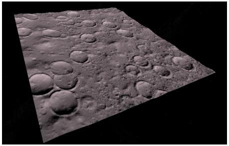
- Two BRDFs have been implemented
  - **Hapke model**: Expensive but accurate (B. Hapke 2012; Sato et al. 2014)
  - **Hapke-Lommel-Seeliger model**: Inexpensive, less accurate (B. W. Hapke 1963; Jensen et al. 2001)
- *Physically Based Shaders* used in Classical rendering pipeline
- Raytracing avoided because
  - SSA of lunar regolith is very low ($\approx \mathbf{0.15}$) $\Rightarrow$ secondary light sources are negligible
  - Raytracing is more expensive

Outline

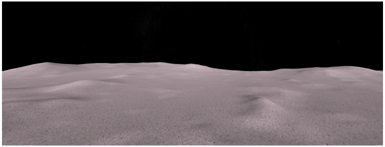
1. Outline
2. Resurgence of Lunar Exploration
3. Motivation
4. Problem 1: Photometric Modelling
   - Problem Statement
   - Scope of Work
   - BRDF Modelling
   - Results
   - Future Work
5. Problem 2: Lunar Simulator
   - Problem Statement
   - Scope of Work
   - Simulator Development
   - Results
   - Future Work
6. References

Results

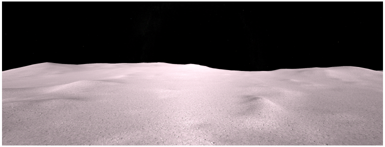
The modeling and rendering was done in Unity3D



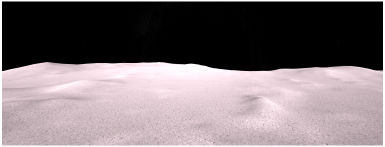
Input Terrain



Normal shader



Hapke Shader



Hapke-Lommel-Seeliger Shader

By altering parameters, various tests scenarios can be generated