# Overview of SLOPE Laboratory Testing Capabilities for Planetary Mobility and Traction Studies at NASA Glenn Research Center

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# mTRAX Planetary Exploration Labs at NASA Glenn

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Figure 1. View of the Simulated Lunar Operations Lab (SLOPE) at NASA Glenn Research Center.

# Simulated Lunar Operations (SLOPE) Lab

- SLOPE Lab by the numbers:
  - 4368 $ft^2$, climate-controlled, full vehicle test facility
  - 11.8x2.9x0.6m (464x114x24in) sink tank filled with Fillite
  - 11.8x3.0x0.6m (464x117x14in) lane filled with GRC-1
  - 6.7x4.7x0.3m (264x184x12in) hydraulically actuated tiltbed filled with GRC-1
- Testing equipment:
  - Traction and Excavation Capabilities (TREC) Rig
  - Drawbar pull rig
  - OptiTrack motion capture system

Figure 2. SLOPE laboratory soil bins. A: High-sinkage Fillite. B: GRC-1. C: Tiltbed.

# OptiTrack Motion Tracking Camera System


Figure 3. Prime$^X$ 41 motion tracking camera from OptiTrack [1].

- Cameras emit and receive infrared (IR) light
- Passive markers are reflective spheres that reflect emitted IR light
- Active markers are IR LEDs that themselves emit IR light in specific, identifiable patterns
- Listed spatial accuracy of ±0.10mm
- SLOPE Lab currently has 20 Prime$^X$ 41 cameras mounted on the walls, 8 Prime$^X$ 41 cameras on mobile tripods, and 4 Prime$^X$ 13 cameras on mobile tripods

# Moon Gravity Representation Unit (MGRU) 2.5 Testing

- MGRU 2.5 is an engineering model of the VIPER mobility system
- Configuration is approx. 1/6 of the expected VIPER mass
- Suspension is “active” and comprised of actuators
- Tested in the SLOPE Lab to characterize:
  - Drawbar pull performance
  - Slope traversal performance
  - Sinkage
  - Rock climbing performance

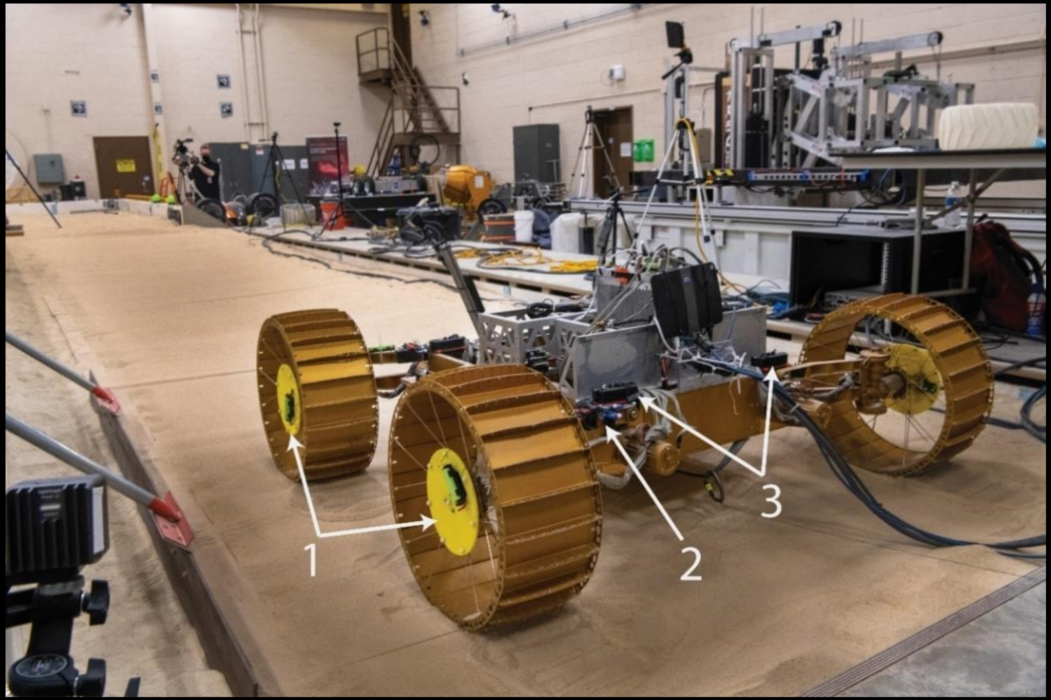


Figure 4. The MGRU 2.5 vehicle is shown with three different marker sets noted that are representative of how the vehicle was defined. 1) Active markers mounted to a laser cut disk for spacing and rigidity for the wheels, 2) Active markers mounted to a laser cut mount on suspension linkage. 3) Passively active markers develop by mTRAX team.

# Moon Gravity Representation Unit (MGRU) 2.5 Testing

- Immediately evident that standard passive markers become occluded due to dust
- mTRAX team developed “Actively Passive” markers to mitigate dust occlusion
- Within Motive: Tracker software, markers can be grouped to form known rigid bodies

Figure 5. Actively passive marker board designed and built by the mTRAX team.

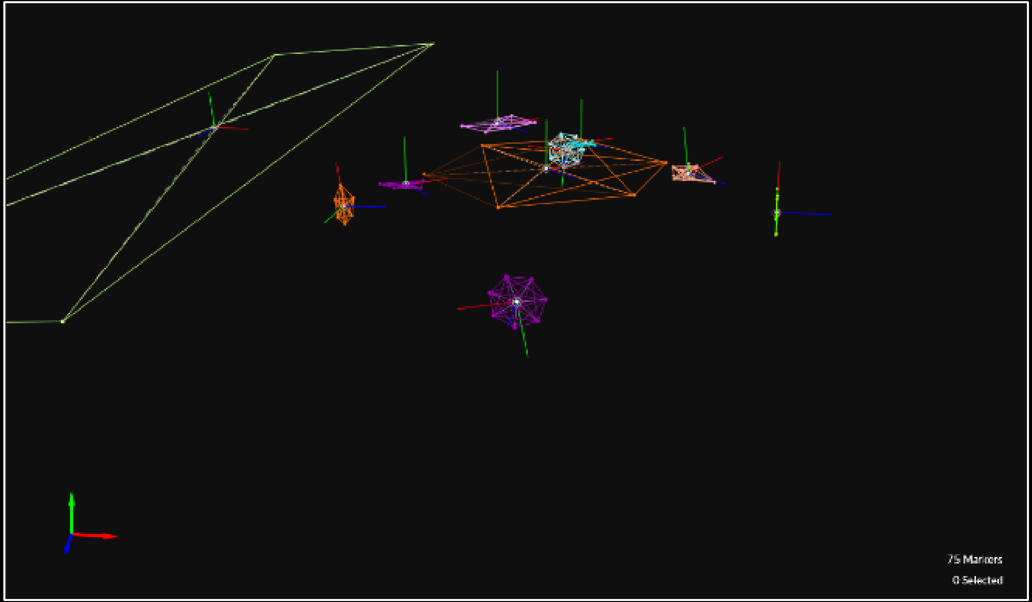

Figure 6. Wireframe view from the OptiTrack Motive: Tracker software that tracks the rover rigid bodies in real time.

# Moon Gravity Representation Unit (MGRU) 2.5 Testing

## *Cross Slope Analysis Methods*

- Longitudinal and normal slip distance vectors were calculated geometrically along the plane of motion
- Measurement reference frame was rotated to correspond with tilt bed traversal surface, using tilt bed orientation measured via motion capture
- Non-slip related rover motion was determined by calculating average vehicle heading during driving segments and projecting the integral of average wheel velocity for the duration of the driving segment to estimate ideal, non-slip rover final position
  - This value is compared to the rover's final position as measured with motion capture
- Longitudinal and normal slip values are calculated using the displacement value between the non-slip and measured rover position at the end of a driving segment

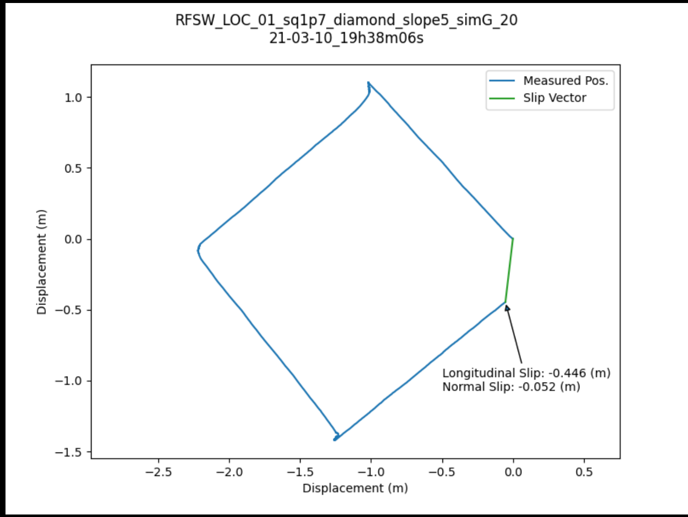


Figure 7. Position and calculated slip distance vector of the MGR 2.5 vehicle driving on a 5° incline in a diamond pattern in GRC-1 soil simulant.

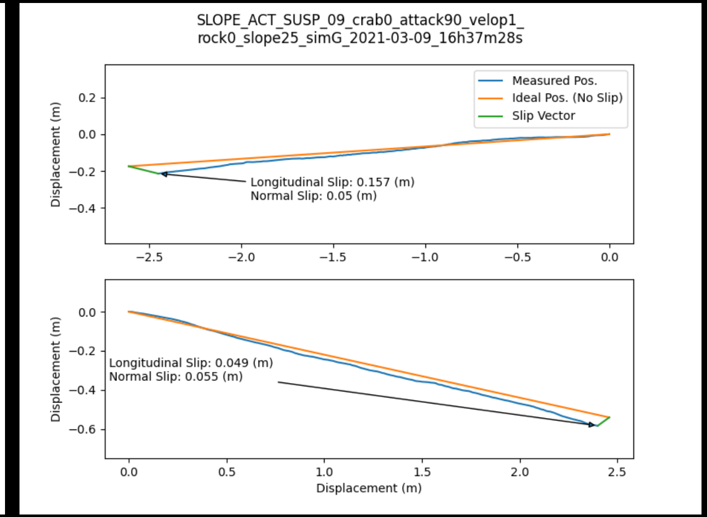


Figure 8. Commanded position, measured position, and calculated slip distance vector for a cross-slope traversal of the MGRU 2.5 vehicle on a 25° incline in GRC-1 soil simulant.

# Traditional Slip Measurements

$$Slip\ \% = \frac{r_r \omega_{encoder} - v_{measured}}{r_r \omega_{encoder}} \quad (1)$$

$r_r$: rolling radius, assumed to be measured outer radius to grouser tip

$\omega_{encoder}$: angular velocity determined using vehicle drive motor encoder data

$v_{measured}$: velocity of vehicle chassis using the derivative of motion capture position data

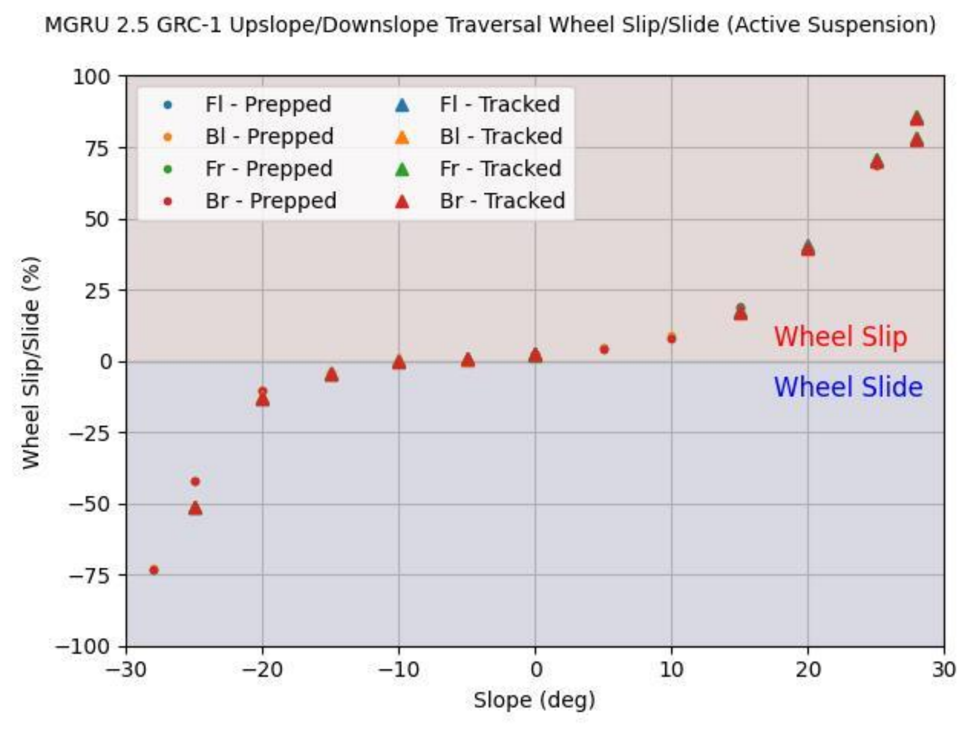


Figure 9. Slip % calculated for upslope and downslope traversals in GRC-1 soil simulant.

# Custom Drawbar Pull Rig

- Drawbar pull (DP) test applies a known, resistive load to a vehicle via an attached tensioned line, resultant slip of the vehicle is then quantified
- DP testing characterizes performance for off-world vehicles since exact terrain replication is not possible
- Custom rig configuration uses an electric motor to wind the line, a hysteresis clutch for load control, and a block and tackle assembly to integrate the load cell
- The vehicle is driven in a straight line on a flat track with resistive force from the rig applied for known dwell times or distances

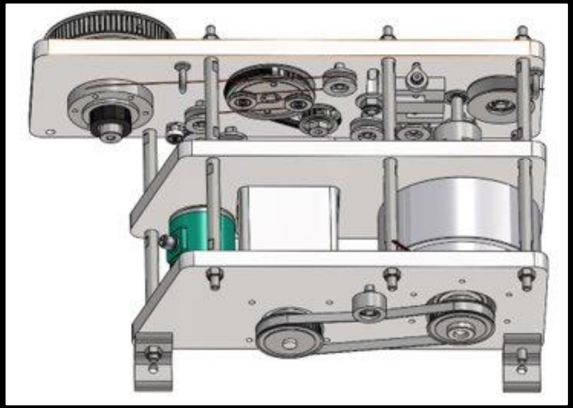

Figure 10. CAD model of the custom drawbar pull rig with components noted.

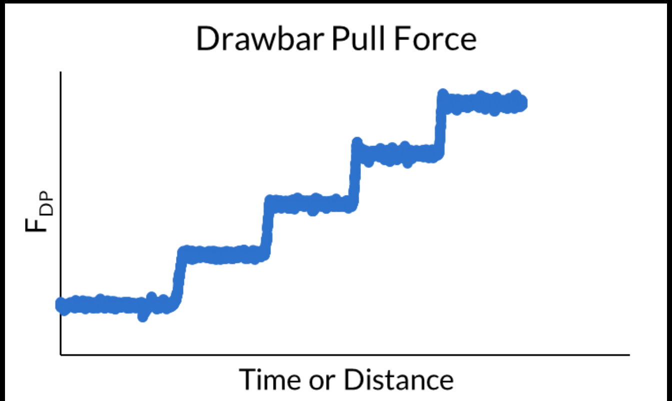


Figure 11. A representation of raw data from the drawbar pull rig

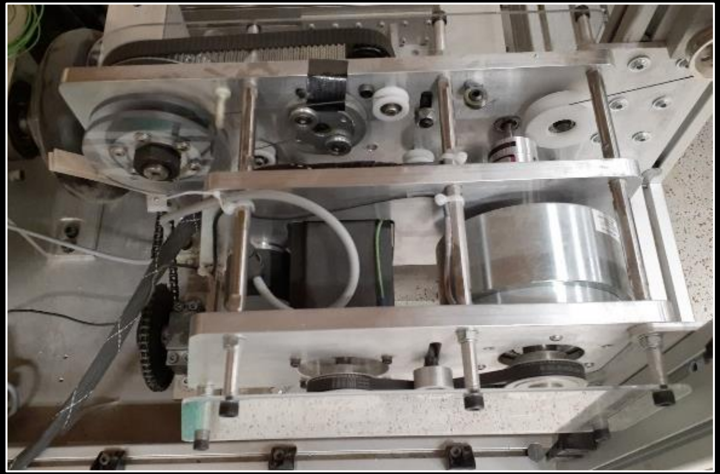

Figure 12. Fully installed drawbar pull rig.

# Coupled Drawbar Pull and Motion Tracking Data

- Motion capture system and DP rig systems were integrated for data syncing and timing
- DP coefficient is the DP force normalized by vehicle weight
- Due to the active suspension of MGRU 2.5, slip % for each wheel is determined using Equation 1
- This test setup can be applied to a wide range of vehicles

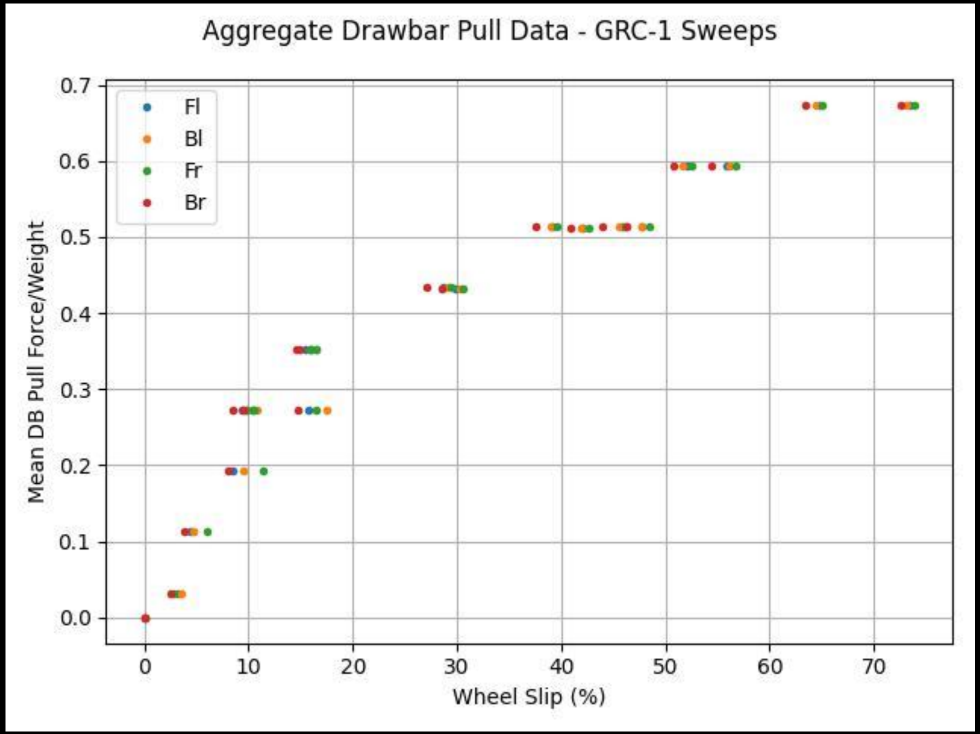


Figure 13. Composite plot of the drawbar pull coefficient as a function of wheel slip for the MGRU 2.5 vehicle for multiple drawbar pull force sweeps in GRC-1 soil simulant.

# OptiTrack Error Validation

- OptiTrack publications cite a spatial accuracy of ±0.10mm
- mTRAX team sought to verify this for the specific SLOPE Lab setup given it is not an ideal motion capture lab space
  - Reflective surfaces
  - Occlusions due to large, immovable lab equipment
  - Dust
  - Large capture volume of $777m^3$
- Position data was collected using <u>only</u> the original 16 mounted cameras representing what was used for MGRU 2.5 testing

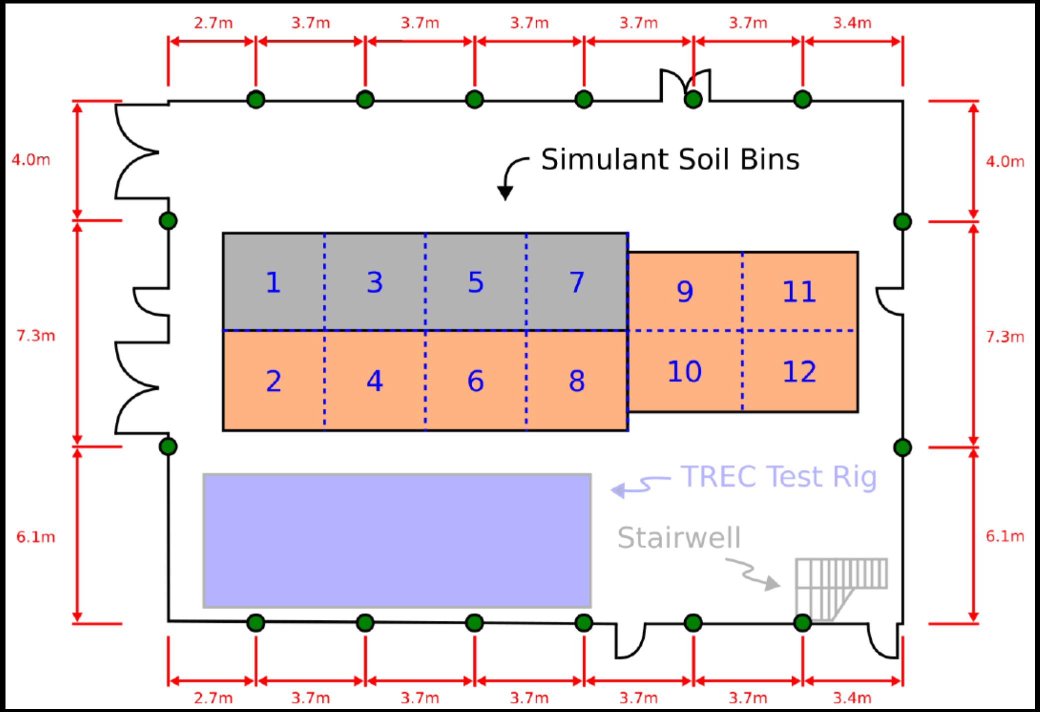


Figure 14. SLOPE laboratory Primex41 camera placement. Cells 1, 3, 5, 7: High sinkage Fillite soil bin. Cells 2, 4, 6, 8: GRC-1 soil bin. Cells 9, 10, 11, 12: Tilt bed. Dots indicate camera locations. TREC Test Rig and Stairwell callouts represent other features in the space that create partial camera occlusions.

# OptiTrack Error Validation

- An Active Puck and Thorlabs LTS300 linear stage were used to collect position data in the zones from Figure 14
- LTS300 stage has bidirectional repeatability and backlash ratings of 2 µm
- Data was collected over 4 total days of testing, system calibration was conducted each day


Figure 15. Active puck and linear translation stage assembly.

# Determined Error Values

- Days 1-3 of testing investigated residuals all cells with the tilt bed at 0° of incline
- Day 4 of testing investigated residuals in cells 11 and 12 with the tilt bed at increase inclination angles

$$\epsilon = \frac{1}{n}\sum_{i=1}^{n}(x_{stage} - x_{active\ puck}) \qquad (2)$$

- Aggregate errors for each day are in agreement with the reported OptiTrack calibration value
- Errors for the tilt bed at various angles were determined to be higher than the aggregate value reported by the OptiTrack calibration
  - Error values still acceptable for vehicle testing

| | Day 1 | Day 2 | Day 3 | Day 4 |
|---|---|---|---|---|
| $\epsilon_{sess}^{motiv}$ (mm) | 0.19 | 0.15 | 0.16 | 0.16 |
| $\epsilon_{sess}^{calc}$ (mm) | -0.08±0.50 | -0.04±0.83 | -0.11±0.59 | 0.04±0.66 |

Table 1. Aggregate accuracy values from four days of testing.

| | $0^o$ | $10^o$ | $20^o$ |
|---|---|---|---|
| $\epsilon_{sess}^{motiv}$ (mm) | | 0.16 | |
| Cell 11 error (mm) | 0.28 ± 0.52 | 0.23 ± 0.72 | -0.40 ± 0.62 |
| Cell 12 error (mm) | 0.27 ± 1.17 | 0.12 ± 0.41 | -0.12 ± 0.47 |

Table 2. Mean cell error for various soil bin tilt bed angles.

# Summary

- SLOPE Lab added significant new capabilities
  - OptiTrack motion capture array (32 total cameras)
  - Developed and built custom drawbar pull rig and integrated data stream with motion capture system
- Tested the MGRU 2.5 engineering model mobility platform for the VIPER program
- Verified the motion capture error for the SLOPE Lab specific setup

# Questions?

# References

[1] NaturalPoint, Inc., “Motion Capture Systems,” OptiTrack. [Online]. Available: https://optitrack.com/. [Accessed: 07-Apr-2022].

[2] C. Creager, V. Asnani, H. Oravec, and A. Woodward, “Drawbar Pull (DP) Procedures for Off-Road Vehicle Testing,” no. August 2017, 2017, [Online]. Available: http://www.sti.nasa.gov.

[3] ThorLabs, 300 mm linear translation stage with integrated controller, Stepper Motor. [Online]. Available: https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=7652&pn=LTS300%2FM. [Accessed: 07-Apr-2022].

[4] A. Schepelmann, S. Gerdts “Characterization of an Infrared Optical Motion Tracking System in NASA’s Simulated Lunar Operations (SLOPE) Laboratory,” In Review