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Characterization of Infrared Optical Motion Tracking System in NASA's Simulated Lunar Operations (SLOPE) Laboratory

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June 2022

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Summary

This work characterizes the accuracy of a 16-camera OptiTrack motion tracking system installed in NASA Glenn Research Center's Simulated Lunar Operations (SLOPE) Laboratory. The position of a rigid body mounted on a motorized linear stage is compared to its position reported by the motion tracking system as it travels through the facility's 777-m^3 capture volume of interest. Experiments show that the mean error reported by the motion tracking system for the aggregate capture volume is in line with independent measurements collected using the motion stage. Error within regions of the capture volume exceed the mean error reported by the motion tracking system, likely due to occlusion, and suggests that additional cameras should be used to increase measurement accuracy in these regions. Overall, results show that error values reported by the motion tracking system are representative of the measurement error in a collected dataset and validates the system's use for characterizing the mobility and tractive performance of robots, rovers, and other vehicles for planetary exploration.

1.0 Introduction

Optical motion tracking systems are a popular tool in biomechanics research to measure and assess human movement (Ref. 1). By sensing infrared light emitted or reflected from markers in multiple cameras, such systems are able to measure the position and orientation of rigid bodies in three-dimensional space with submillimeter accuracy while eliminating the need for data and signal wires required by other sensors (Ref. 2). The compact, wireless nature of the system, plus its ability to natively sense rigid bodies, make it attractive to scientists and engineers studying unmanned aerial vehicles, legged robots, and wheeled vehicles (Refs. 3 to 5).

The Simulated Lunar Operations (SLOPE) Laboratory is a state-of-the-art test facility located at NASA Glenn Research Center for evaluating tractive performance and sinkage of robotic rovers and other vehicles in simulated lunar and martian soil. The facility contains three soil bins filled with simulant material (Figure 1): an 11.8- by 2.9- by 0.6-m (464- by 114- by 22-in.) sink tank filled with high-sinkage, high-slip Fillite (Tolsa USA, Inc.) that is meant to approximate dynamic conditions of iron(III) sulfate that were encountered by NASA's Spirit rover on Mars (Ref. 6); an 11.8- by 3.0- by 0.3-m (464- by 117- by 13-in.) driving lane filled with GRC–1 simulant that is designed to match the geotechnical properties of lunar regolith measured during NASA's Apollo missions (Ref. 7); and a 6.7- by 4.7- by 0.2-m (264- by 184- by 9-in.) hydraulically actuated tilt bed filled with GRC–1 to simulate sloped lunar terrain at up to 45° of inclination.

An OptiTrack motion capture system comprising 16 Prime^{x}41 cameras (PX41, NaturalPoint, Inc. DBA OptiTrack) was recently installed in the SLOPE Laboratory to enable real-time, in situ measurements of vehicle performance in the facility's soil bins (Ref. 8). This system supplements the facility's existing single-wheel characterization hardware and expands the laboratory's full-vehicle testing capabilities (Refs. 9 and 10).

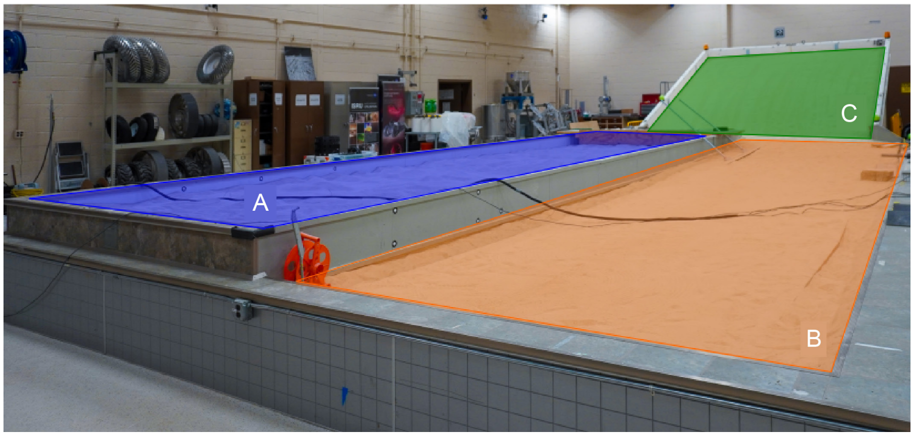

Figure 1.—Simulated Lunar Operations (SLOPE) Laboratory soil bins. A: High-sinkage Fillite (Tolsa USA, Inc.). B: GRC–1. C: Tilt bed.

Prior to a data collection session, the motion capture system is calibrated using a wand with active motion tracking markers through OptiTrack's Motive software package. After completing the calibration, Motive gives a mean overall wand error quantifying the accuracy of spatial measurements taken with the OptiTrack system. This report presents work to validate the accuracy of this wand error, both across the entire volume of interest as well as smaller volumes within it, through independent measurements collected with a linear motion stage. Error values are calculated both for individual regions throughout the capture volume as well as for the range of typical tilt bed angles used during vehicle tests.

We find that the mean error reported by Motive is consistent with the independent measurements collected with the linear stage throughout the facility's 777-m^3 capture volume of interest, with a mean Motive-reported error of 0.17 mm and an independently calculated mean error of –0.06±0.65 mm across all trials, respectively. The majority of localized measurements within smaller volumes are also in line with the mean value reported by Motive. However, the measured error exceeds the Motive-reported mean error of the entire capture volume in some regions of the soil bins. These larger errors likely result from camera occlusion caused by other test hardware in the facility and suggests that additional cameras should be placed throughout the capture volume to increase measurement accuracy in these regions. In aggregate, results suggest that the error value reported by Motive is representative of the measurement error in a collected dataset, which validates the system's use for characterizing the mobility and tractive performance of robots, rovers, and other vehicles for planetary exploration.

2.0 Methods

The OptiTrack motion tracking array installed in NASA's SLOPE Laboratory consists of 16 PX41 cameras mounted on the facility's walls (Figure 2). Fourteen of the cameras are mounted at a height of 4.3 m (14 ft) to minimize occlusion resulting from the perimeter walkways around the soil bins. The two remaining cameras, located on the wall behind the tilt bed, are mounted at a height of 4.9 m (16 ft) to provide a view of the soil when the tilt bed is at its maximum inclination. Cameras were oriented during the installation process to maximize the soil bin area captured in each of their fields of view. The fields of view of neighboring cameras overlap to provide redundant views of regions in the soil bins.

In addition to validating the mean accuracy value reported by Motive, this work aims to quantify tracking accuracy within localized regions of each soil bin. To measure localized accuracies throughout the capture volume, the soil bins are divided into 12 roughly equally sized cells as shown in Figure 2.

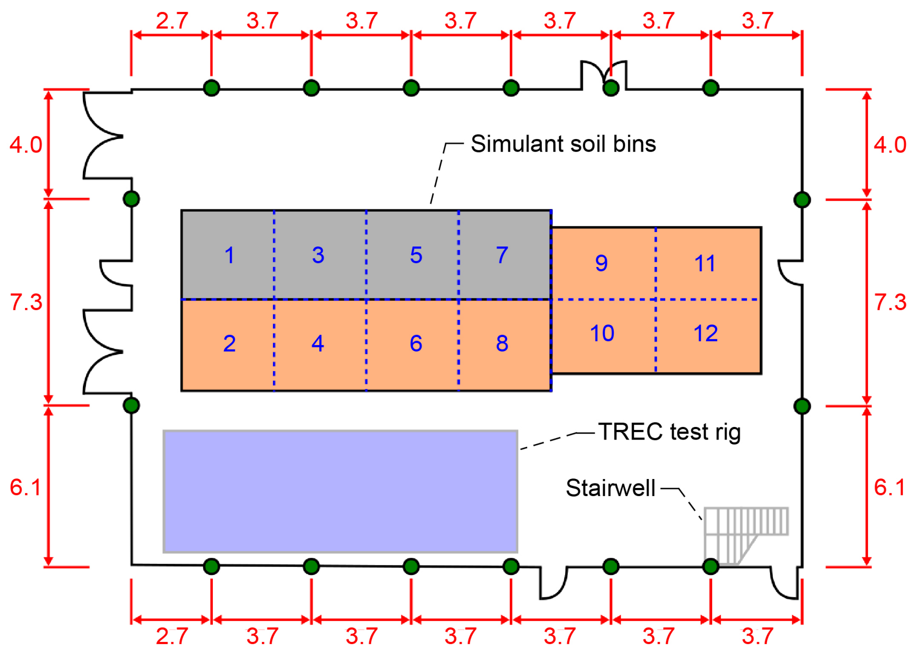

Figure 2.—Simulated Lunar Operations (SLOPE) Laboratory Prime[x]41 camera (PX41, NaturalPoint, Inc. DBA OptiTrack) placement. Cells 1, 3, 5, and 7: high-sinkage Fillite (Tolsa USA, Inc.) soil bin. Cells 2, 4, 6, and 8: GRC–1 soil bin. Cells 9 to 12: tilt bed. Dots indicate camera locations. Traction and Excavation Capabilities (TREC) Test Rig and stairwell callouts represent other spatial features that create partial camera occlusions. Dimensions are in meters.

2.1 Data Collection

Data is collected over four sessions. Sessions 1 to 3 aim to verify OptiTrack's reported measurement accuracy for "level-driving" scenarios across the soil bins and when the tilt bed is at a 0° inclination. Session 4 aims to verify OptiTrack's reported measurement accuracy for "sloped driving" in the tilt bed for inclinations of 0°, 10°, and 20°. Before each session, the motion tracking system is calibrated using an active calibration wand (CWA–500, NaturalPoint, Inc. DBA OptiTrack) and OptiTrack's Motive software package. After completing the calibration, Motive reports a mean overall wand error that quantifies the difference between the measured and known length of the active wand, which is representative of spatial measurement accuracies taken with the OptiTrack system over the total capture volume (Figure 3).

An OptiTrack active puck (ACTPUK0001, NaturalPoint, Inc. DBA OptiTrack) is tracked by the cameras during data collection. The puck contains eight infrared light-emitting diodes (LEDs) that can be uniquely identified by multiple cameras as they move through the capture volume. The puck is mounted to a 300-mm precision linear translation stage (LTS300, Thorlabs, Inc.) whose position is controlled through MATLAB (MATLAB R2020b, Mathworks, Inc.) to accurately position the puck and provide independent position measurements (Figure 4). The linear stage is mounted to aluminum extrusions that are attached to two heavy-duty tripods (Manfrotto 475B, Vitec Imaging Distribution, Inc.) to elevate the stage above the simulant and minimize contamination. For these experiments, the linear stage is assumed to move the puck in a single axis and have no off-axis deviation over its range of motion.

During each session, the linear stage assembly is placed in three random locations in every cell. For each placement, the linear stage is commanded to travel across its 300-mm range of motion at 10-mm increments, pausing at each location to collect 100 position measurements from the linear stage. Based on communication bandwidth and the asynchronous messaging interface between MATLAB and the linear

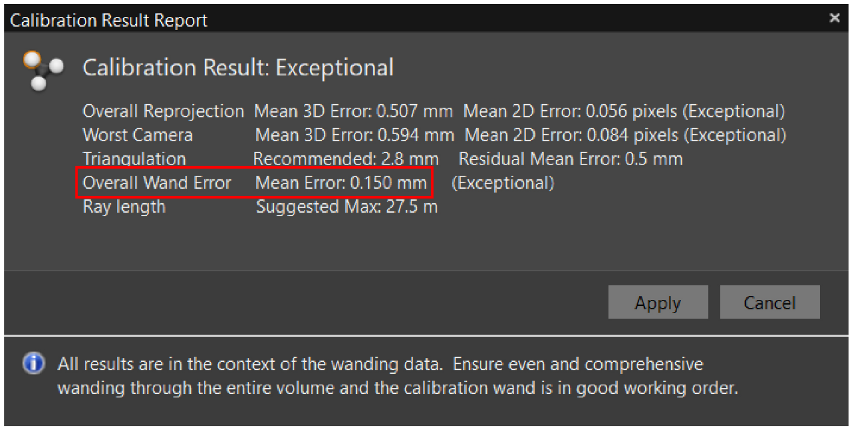

Figure 3.—OptiTrack Motive reported measurement accuracies. Red box: mean wand error across capture volume.

Figure 4.—Active puck and linear translation stage assembly.

stage[1], this results in a pause of approximately 6 s at each location. During each pause, the position of the active puck is simultaneously measured by the OptiTrack camera array at a rate of 100 Hz, resulting in approximately 600 OptiTrack position measurements of the puck at each position setpoint.

2.2 Data Processing

OptiTrack and linear stage measurements are aligned during postprocessing using logged time stamps in each dataset. The testing facility does not possess the capability to independently place the linear stage within the capture volume with an accuracy that is comparable to the OptiTrack system. As such, a translation offset is applied to the OptiTrack-measured position of the active puck so that its start position is located at [0,0,0] in Cartesian XYZ space. As stated previously, the linear stage is assumed to move the puck in a single axis and have no off-axis deviation over its range of motion. It is similarly not possible to physically align the orientation of the linear stage assembly with the OptiTrack system's coordinate frame with sufficient accuracy due to natural undulations of the soil in each bin. As a result, optimization is used to calculate rotation matrix parameters for the offset data in order to align the coordinate frames of OptiTrack and linear stage.

[1]Due to the communication protocol used by the stage to interface with MATLAB, it is not possible to receive position feedback from the stage while it is in motion. As a result, error quantification in this report is based on static puck measurements.

Linear stage position measurements are assumed to only occur in the x-axis. To align offset OptiTrack data ($\mathrm{x} = [x, y, z]$) with this frame ($\mathrm{x_r} = [x_r, y_r, z_r]$), unconstrained nonlinear optimization (fminunc(), MATLAB R2020b, Mathworks, Inc.) is used to calculate rotation matrix parameters α, β, and γ in order to minimize off-axis deviations y_r and z_r:

$$\min_{\alpha,\beta,\gamma} \sum \left(y_r^2 + z_r^2 \right), \text{ where: } \mathrm{x_r} = R_x(\alpha) R_y(\beta) R_z(\gamma)\mathrm{x} \tag{1}$$

and

$$R_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & -\sin(\alpha) \\ 0 & \sin(\alpha) & \cos(\alpha) \end{pmatrix} \tag{2}$$

$$R_y = \begin{pmatrix} \cos(\beta) & 0 & \sin(\beta) \\ 0 & 1 & 0 \\ -\sin(\beta) & 0 & \cos(\beta) \end{pmatrix} \tag{3}$$

$$R_z = \begin{pmatrix} \cos(\gamma) & -\sin(\gamma) & 0 \\ \sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{4}$$

Error analysis is conducted on values of $\mathrm{x_r}$ that have been transformed with optimized values of α, β, and γ.

2.3 Data Analysis

For each cell, the OptiTrack measurement error ε is calculated as the mean error between the commanded linear stage position x_{stage} and the measured x_r component of the active puck position

$$\varepsilon = \frac{1}{n} \sum_{i=1}^{n} \left(x_{\text{stage}} - x_r \right) \tag{5}$$

where n is the total number of OptiTrack position measurements for all stage placements in a cell during a session. These values provide localized measurement accuracies in each cell. An aggregate accuracy value ($\varepsilon_{sess}^{calc}$) that is directly comparable to Motive's reported mean overall wand error ($\varepsilon_{sess}^{motiv}$) is similarly calculated using all data points from a session. Finally, total accuracies across all sessions (ε_{tot}^{calc} and $\varepsilon_{tot}^{motiv}$) are calculated using all data from each session.

3.0 Results

Across all sessions, Motive reported a mean overall wand error of $\varepsilon_{tot}^{motiv}$ = 0.17 mm compared to a mean calculated error of ε_{tot}^{calc} = –0.06±0.65 mm using data collected across the capture volume of interest with the linear motion stage (n = 2,249,327).[2] The mean overall wand error for data taken during each day exhibited a similar accuracy and is summarized in Table 1.

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[2]Two datasets collected on day 4 (cell 12, 0° tilt bed inclination, trials 2 and 3) were excluded from this calculation due to marker occlusion during data collection.

TABLE 1.—AGGREGATE ACCURACY VALUES

Measurement	Day 1	Day 2	Day 3	Day 4
$\varepsilon_{sess}^{motiv}$, mm	0.19	0.15	0.16	0.16
$\varepsilon_{sess}^{calc}$, mm	–0.08±0.50	–0.04±0.83	–0.11±0.59	0.04±0.66

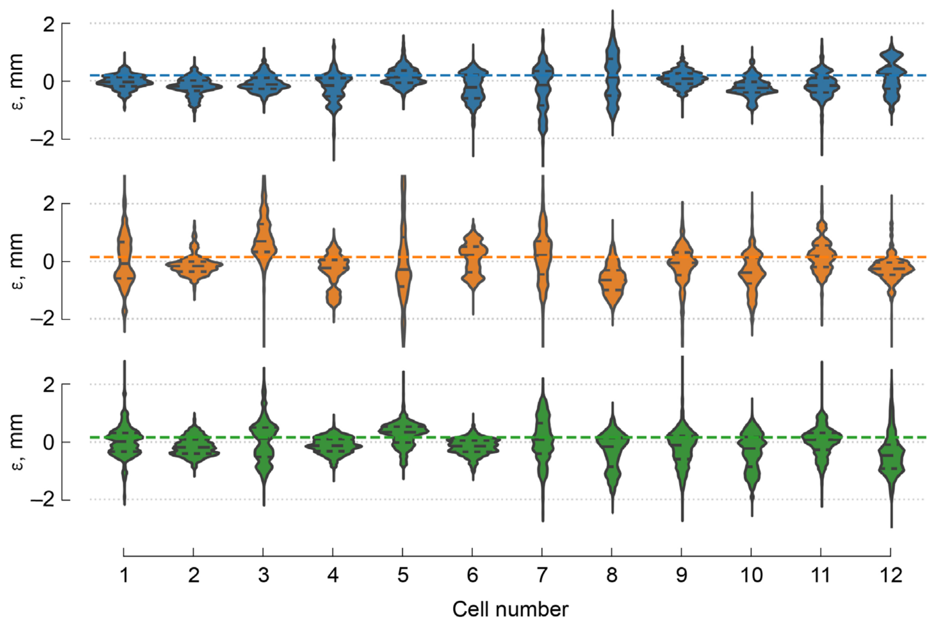

Figure 5.—Violin plot with interquartile ranges of mean cell error for “level-driving” scenarios. Blue: day 1. Orange: day 2. Green: day 3. Colored dashed lines: OptiTrack Motive-reported mean overall wand error during calibration for respective day.

Mean measurement error in localized regions in the soil bins collected during days 1 to 3 ($\varepsilon_{\text{cell}}^{calc}$), which simulate “level-driving” scenarios, were also in-line with Motive reported values (Figure 5 and Table 2), though evenly numbered cells more frequently exhibited greater absolute localized error relative to their respective aggregate $\varepsilon_{sess}^{motiv}$ values than oddly numbered cells (i.e., $\left|\varepsilon_{\text{cell,even}}^{calc}\right| > \varepsilon_{sess}^{motiv} = 12$ and $\left|\varepsilon_{\text{cell,odd}}^{calc}\right| > \varepsilon_{sess}^{motiv} = 6$).

This phenomenon was observed in cell 10 for each day of testing. While Motive-reported error values are still in the submillimeter range and therefore provide measurements with sufficient accuracy in these cells for vehicle tests conducted in SLOPE, this increased error is likely the result of partial camera occlusions due to another test apparatus located in the lab and a stairwell in the corner of the room (Figure 3). Both of these items are permanent fixtures in SLOPE and cannot be moved. Employing additional tripod-mounted cameras to compensate for occlusions may increase measurement accuracy. The benefit of adding cameras will be explored during future testing.

Sloped-driving trials also exhibit submillimeter accuracy, though 66 percent of trials exhibited greater absolute mean localized error relative to the Motive-reported value (Figure 6 and Table 3). Standard deviations of errors in each dataset are comparable to those observed for level-driving scenarios. The error magnitude does not show a positive correlation with the tilt bed angle. Examining individual trials shows that this mean error is representative of individual trial accuracies and is not skewed by data from a single trial that had a large error (Table 4 and Table 5). A possible reason for this increased error may be due to differences in calibration quality between multiple days. Future testing will investigate the impact of adding additional cameras to better cover occluded areas and the tilt bed.

TABLE 2.—MEAN CELL ERROR DAYS 1 TO 3

$\varepsilon_{sess}^{motiv}$, mm	Day		
	1	2	3
	0.19	0.15	0.16
Cell	Error, mm		
1	–0.04±0.25	0.03±0.86	0.01±0.51
2	–0.20±0.31	–0.13±0.35	–0.16±0.32
3	–0.08±0.29	0.85±0.77	0.03±0.71
4	–0.24±0.48	–0.36±0.59	–0.13±0.29
5	0.15±0.32	0.09±1.5	0.26±0.41
6	–0.23±0.49	0.11±0.54	–0.17±0.29
7	–0.26±0.77	0.18±0.84	0.09±0.74
8	0.13±0.78	–0.63±0.50	–0.34±0.63
9	0.08±0.27	–0.14±0.67	–0.21±0.59
10	–0.23±0.34	–0.39±0.66	–0.34±0.63
11	–0.15±0.42	0.20±0.55	0.02±0.49
12	0.15±0.56	–0.26±0.43	–0.42±0.70

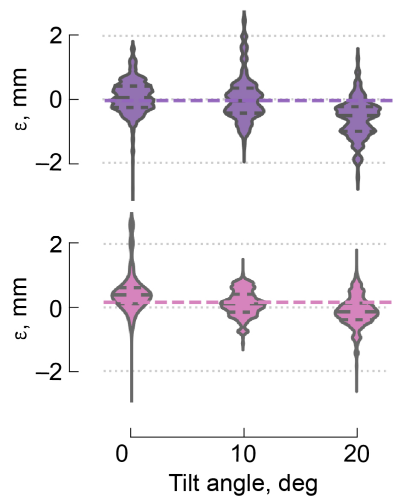

Figure 6.—Violin plot with interquartile ranges of mean cell error for "sloped-driving" scenarios. Violet: cell 11. Pink: cell 12. Colored dashed lines: OptiTrack Motive-reported mean overall wand error during calibration for day 4.

TABLE 3.—MEAN CELL ERROR FOR VARIOUS SOIL BIN TILT BED ANGLES

[$\varepsilon_{sess}^{motiv}$ is 0.16 mm.]

Cell	Angle		
	0°	10°	20°
	Error, mm		
11	0.28±0.52	0.23±0.72	–0.40±0.62
12	0.27±1.17	0.12±0.41	–0.12±0.47

TABLE 4.—CELL 11 INDIVIDUAL TRIAL ERROR
[$\varepsilon_{sess}^{motiv}$ is 0.16 mm.]

Tilt	Trial		
	1	2	3
	Error, mm		
0°	0.71±0.39	–0.04±0.24	0.17±0.54
10°	0.79±0.84	0.28±0.26	–0.37±0.32
20°	–0.40±0.80	–0.18±0.24	–0.62±0.58

TABLE 5.—CELL 12 INDIVIDUAL TRIAL ERROR
[$\varepsilon_{sess}^{motiv}$ is 0.16 mm.]

Tilt	Trial		
	1	2	3
	Error, mm		
0°	0.27±–1.17	-------------	---------------
10°	0.15±0.22	0.37±0.43	–0.16±0.36
20°	–0.15±0.26	–0.10±0.40	–0.11±0.66

4.0 Conclusions

The 16-camera OptiTrack motion tracking system installed in NASA Glenn Research Center's Simulated Lunar Operations (SLOPE) Laboratory is able to provide real-time measurements of rigid bodies with submillimeter accuracy across the facility's 777-m^3 capture volume of interest. The mean reported error by the motion tracking system is in line with independent measurements collection using a linear motion stage. Error within localized regions of the capture volume exceed the mean error reported by the motion tracking system, likely due to occlusion. Additional cameras should be used to increase the measurement accuracy in these regions. Overall, error values reported by the motion tracking system are representative of the measurement error in collected datasets, which validates the system's use for characterizing the mobility and tractive performance of robots, rovers, and other vehicles for planetary exploration.

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