

The background of the entire image is a deep space scene. It features a dark, velvety blue-black sky filled with numerous small, distant stars. On the right side, there are vibrant, glowing nebulae in shades of purple, magenta, and orange. A bright, fiery orange and yellow celestial body, possibly a star or a distant galaxy core, is visible in the lower right corner, emitting a strong glow. The overall atmosphere is one of cosmic wonder and vastness.

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25 OCTOBER 2022

On-orbit/On-surface Servicing, Assembly, and Manufacturing (OSAM) Architecture Simulation System (OASiS)



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BACKGROUND & METHODOLOGY

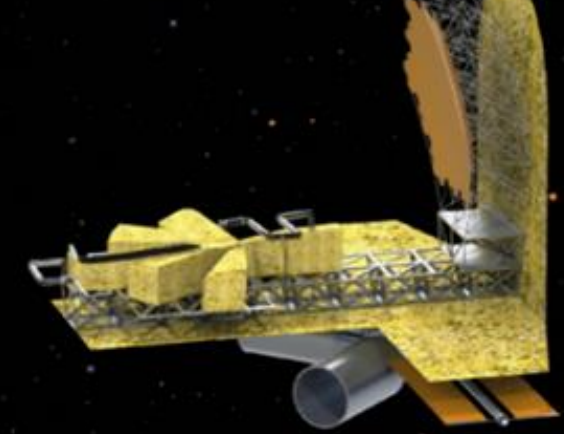
BACKGROUND

On-orbit/on-surface servicing, assembly, and manufacturing (OSAM) will play a critical role in the development, deployment, and long-term operation of large in-space structures

Mission developers need a comprehensive, reliable method for verifying and validating full-scale OSAM mission architectures without having to pay for large and costly facilities and hardware

- Goal: Develop modular, high-fidelity OSAM modeling and simulation (M&S) capabilities to help mission developers rapidly prototype and evaluate full-scale OSAM technologies and operational concepts

In-Space Assembled Telescope



Lunar Safe Haven



Lunar Gateway

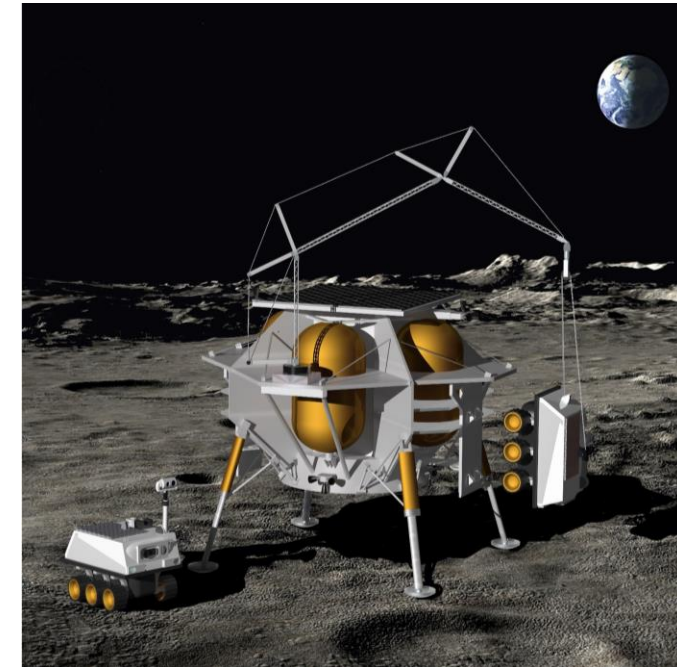


OBJECTIVE

Use newly developed capabilities to demonstrate and evaluate data from the simulation of a simple OSAM operation against an analogue hardware setup

- Evaluate the accuracy of the simulation environment against the behavior of real hardware
- Provide insight on how to further improve OSAM M&S capabilities
- Improve OSAM technology and operational concept designs

Demonstration	Generic M&S Capabilities to Develop
Lightweight Surface Manipulation System (LSMS) affixed with cable-capstan actuated end effector for carefully offloading payloads onto uneven Lunar surfaces	• Simplified methods for modeling complex multibody robotic/cable systems in low-gravity environments • Assessment of position-orientation (POSE) data using feedback from integrated metrology systems within the simulation environment



CURRENT OSAM MODELING AND SIMULATION CAPABILITIES

Vehicle/Robotic M&S Frameworks	Developer
Langley Standard Real-time Simulation in C++ (LaSRS++)	NASA LaRC
Marshall Vehicle Representation In C (MAVERIC)	NASA MSFC
Trick	NASA JSC
Gazebo	Commercial

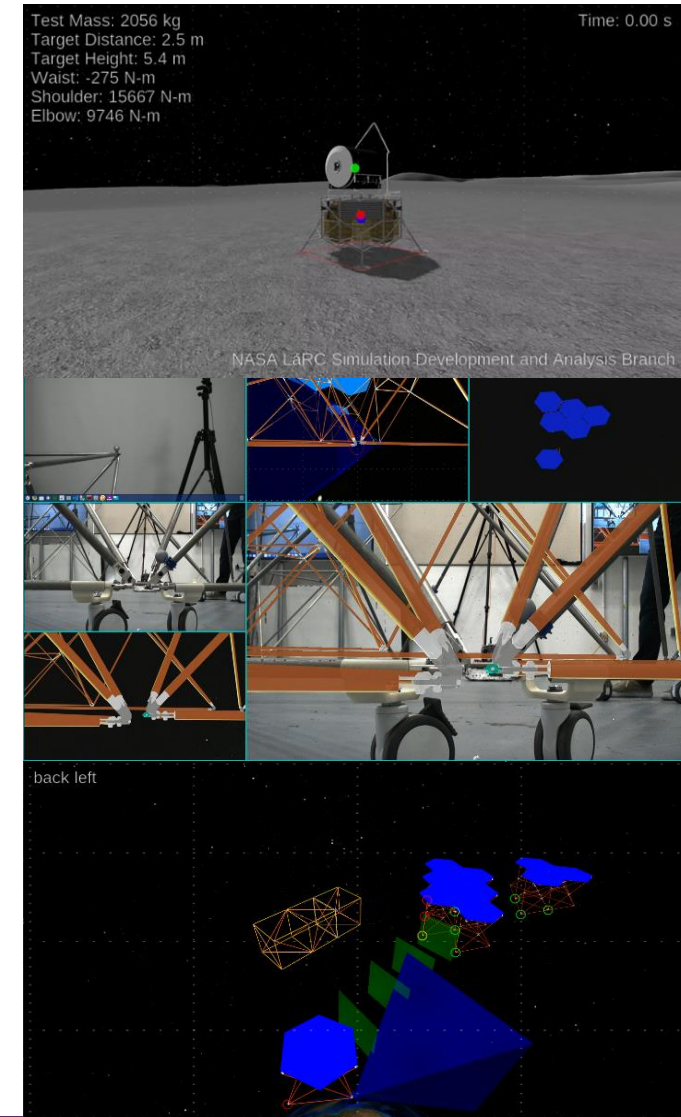
To support high-precision OSAM operational M&S, these frameworks would need to be updated for:

- Reliable accuracy of metrology system modeling
- Flexibility to integrate unique and complex system modeling capabilities, such as:
 - Custom robotics, structures, sensors
 - Cable/flexible body dynamics
 - Thermal and radiative modeling
 - Enhanced lighting
 - Autonomous framework integration
 - Environmental and gravitational effects

LANGLEY STANDARD REAL-TIME SIMULATION IN C++ (LASRS++)

Mission-verified, high-fidelity, object-oriented simulation framework designed to modularize the process of modeling and dynamically testing any vehicle given a variety of environmental conditions

- Previous LaSRS++ OSAM M&S capabilities developed include:
 - Sensor/fiducial modeling and visualization
 - Trajectory and system performance visualization
 - Data sharing via a data distribution service (DDS)
 - Rigid multibody dynamic modeling
 - Simplified modeling of conservation of angular momentum for orbital multibody systems



DEVELOPMENT APPROACH

Develop

- Calibrate the real and simulated sensor using a position-orientation (POSE) estimation software and metrology markers
- Develop generic robotic guidance, navigation, and control capabilities to simplify the dynamic modeling of the LSMS and cable-capstan system

Model

- Model the LSMS/cable-capstan system with metrology markers in a simulated lunar environment using LaSRS++
- Build an analog hardware jig for the LSMS/cable-capstan system integrated with a sensor and metrology markers

Test

- Calculate the expected POSE data of the metrology markers based on the original CAD design of the cable-capstan system
- Gather metrology data from the simulation test using an image generation system and from the hardware test using the sensor
- Compare POSE data from simulation and hardware tests against the expected data to assess modeling accuracy and error

THEORY

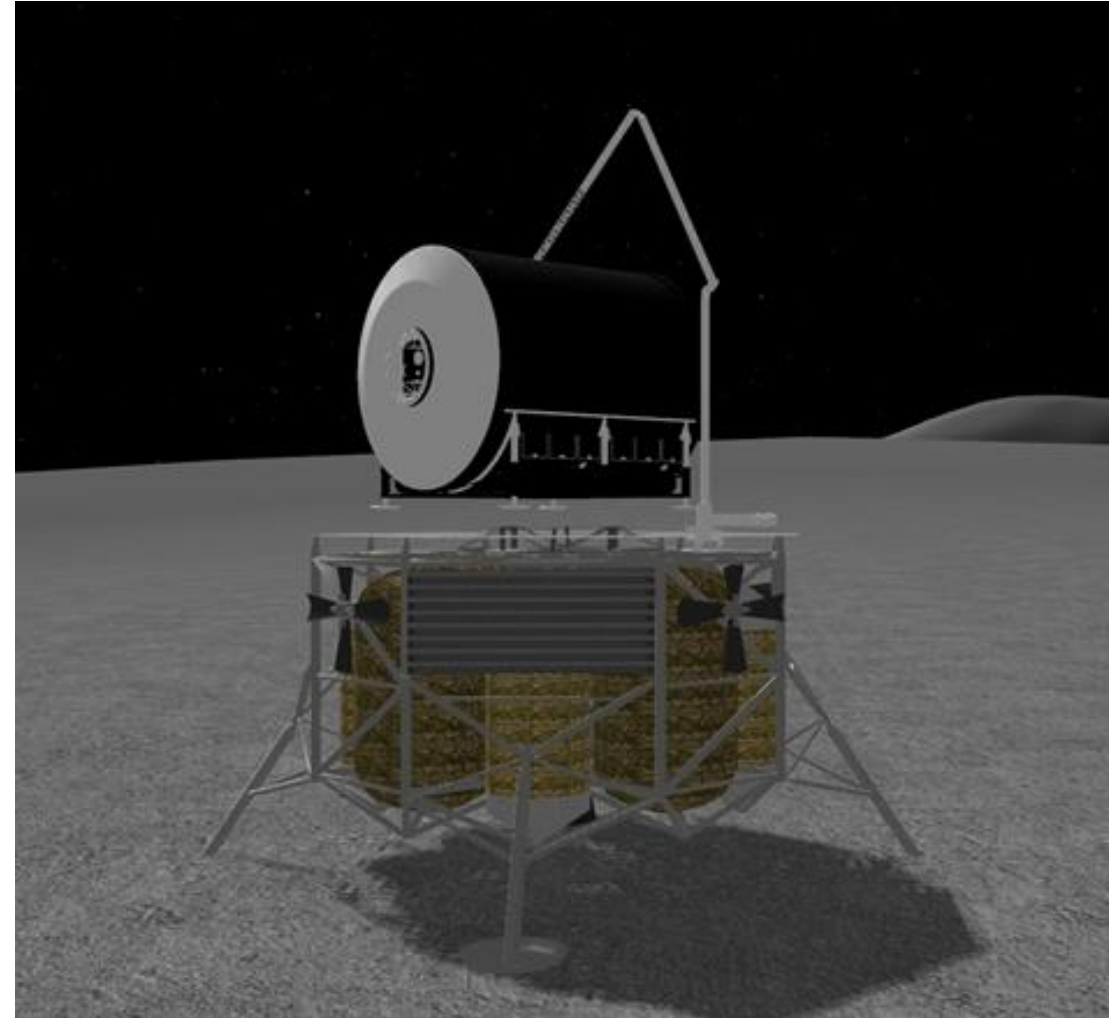
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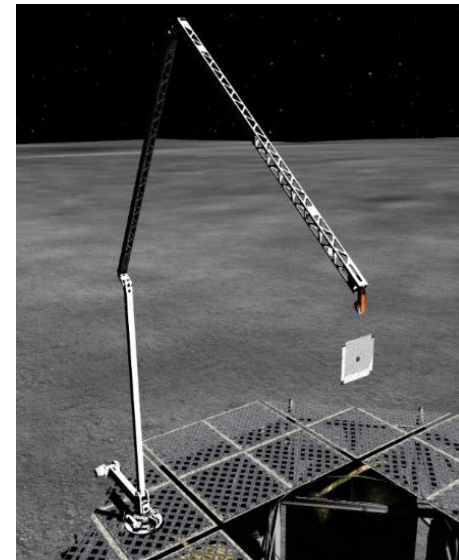
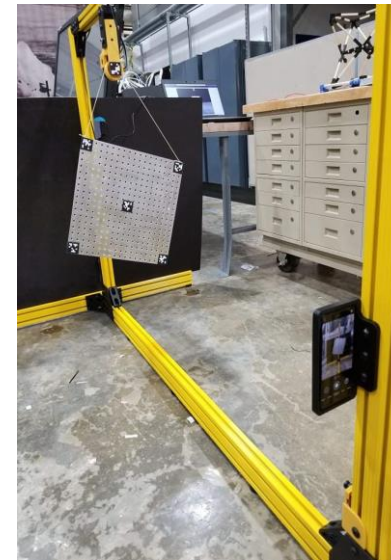
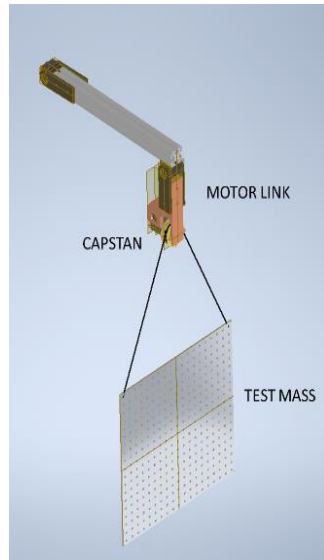
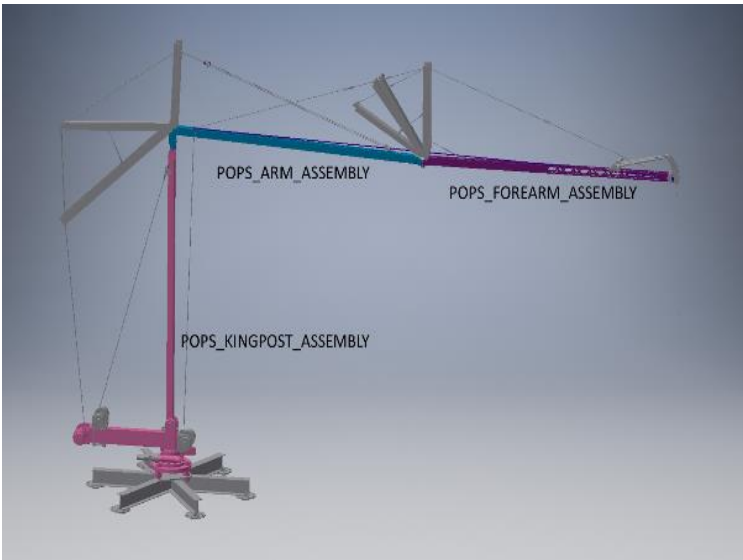
GENERIC ROBOTIC SYSTEM MODELING

Designed to easily simulate complex robotic systems and promote code reuse within LaSRS++

- Implements an inverse kinematic solver within the generic robotic guidance, navigation, and control (GNC) system deriving from Samuel Buss's *"Introduction to Inverse Kinematics with Jacobian Transpose, Pseudoinverse, and Damped Least Squares Methods"*
- Can model any number of links or joints (revolute and prismatic) in a multibody system
- Can integrate different robotic control laws

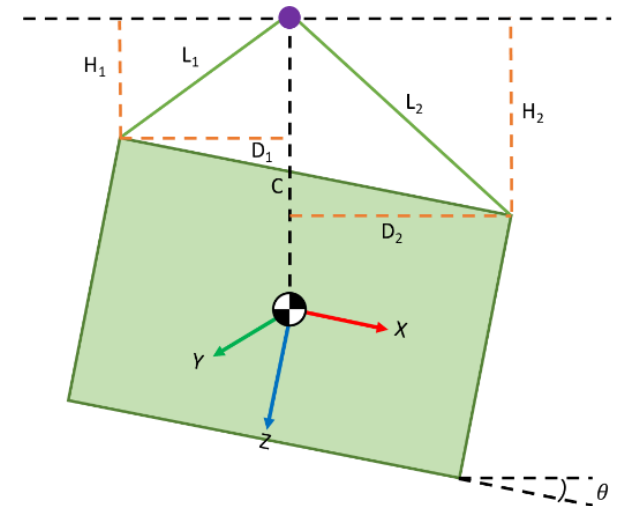


CABLE-CAPSTAN SYSTEM MODELING



OasisControlSystem

- Generic GNC classes apply initial forces on cable-capstan system to hold it static at the beginning of the simulation
- Iteratively apply small forces to cable translation actuators and calculate new force direction until cables achieve necessary lengths for desired test plate angle

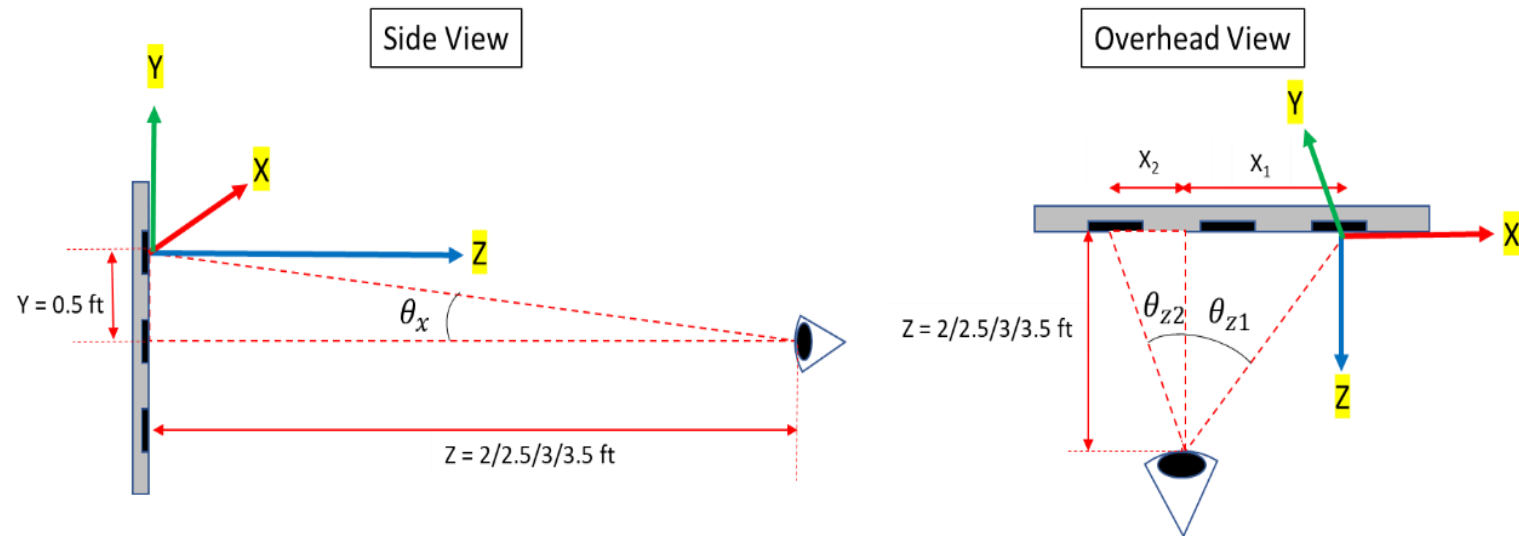
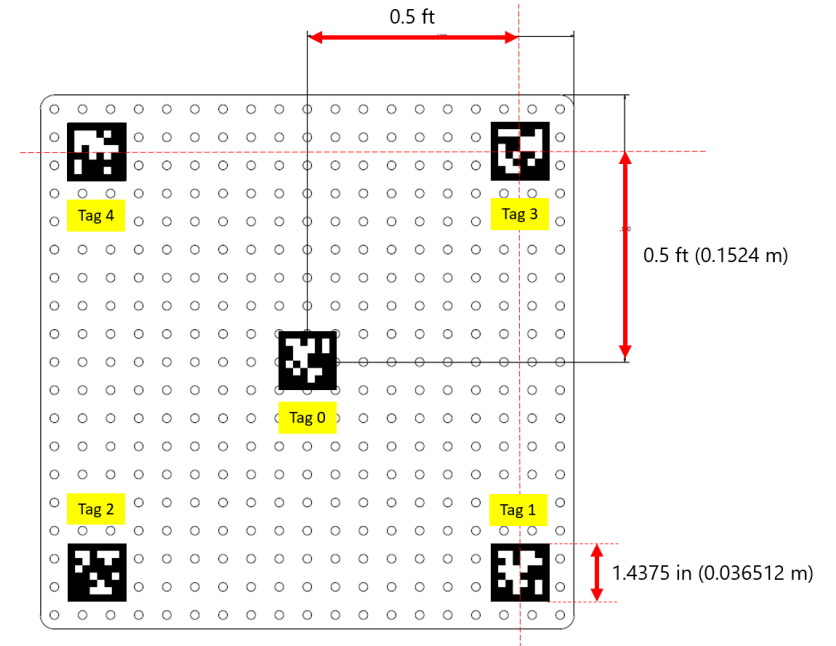


POSITION-ORIENTATION (POSE) ANALYSIS

Accurate POSE data feedback is necessary for efficient, real-time autonomous robotic control system operations

POSE Estimation Software: ArUco

- Open-source C++ library dependent on OpenCV which can be used to create square fiducial markers
- OASiS fiducial markers: Apriltag Library Tag36h11 with IDs 0, 1, 2, 3, and 4



TESTING

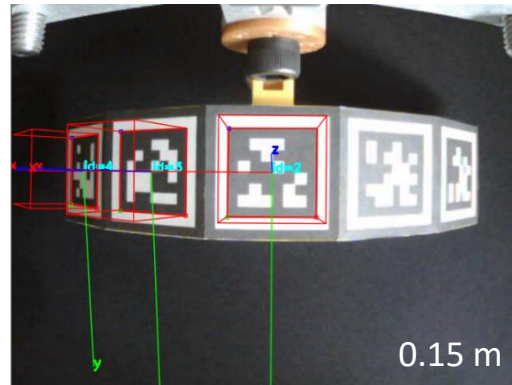
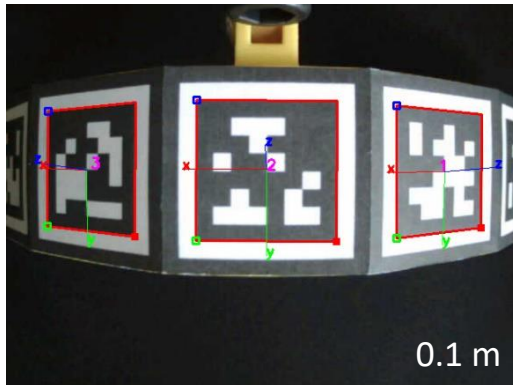
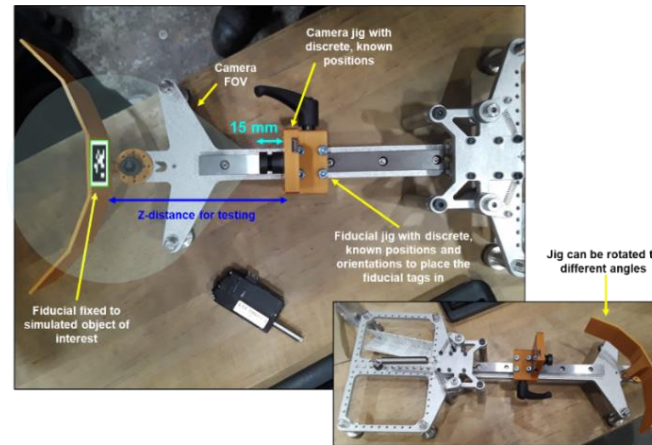
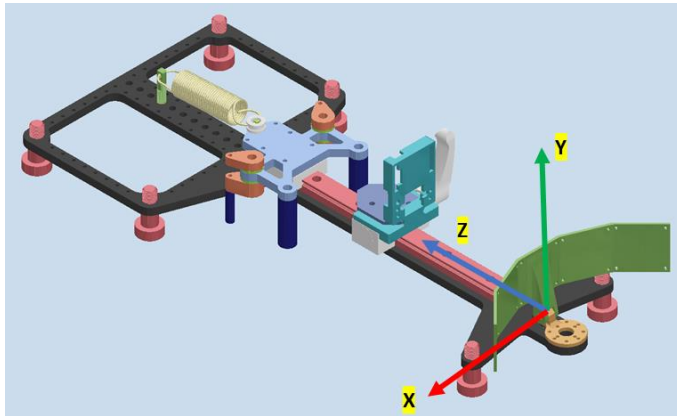
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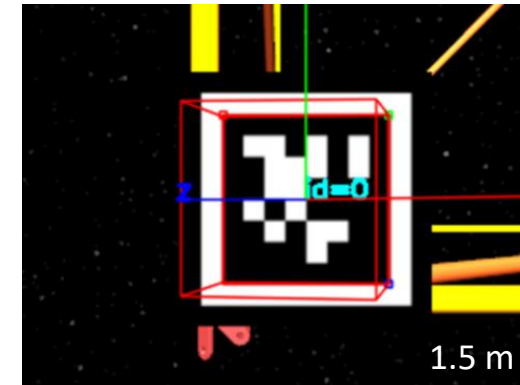
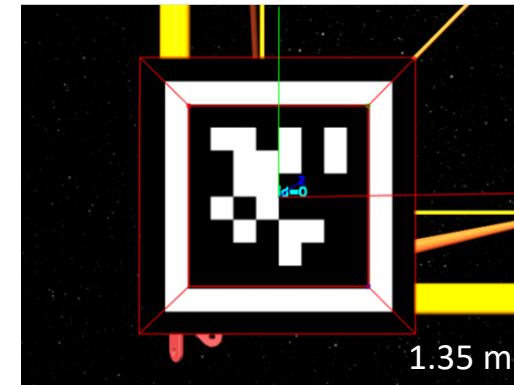
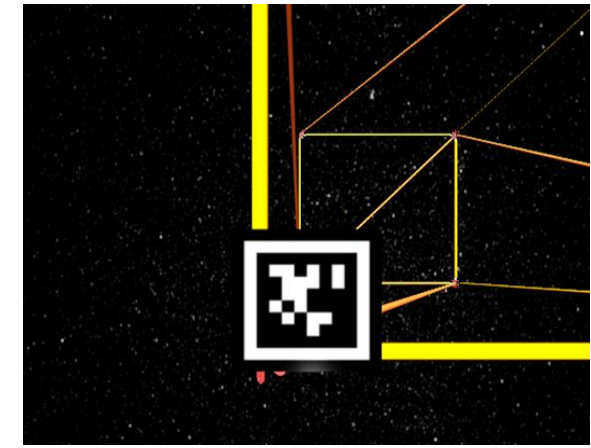
SIMPLE METROLOGY SYSTEM

Goal: To generate calibration files and gain a general understanding of how well fiducial markers like Apriltags could be recognized and processed by the ArUco software for the OASiS tests

Hardware



Simulation

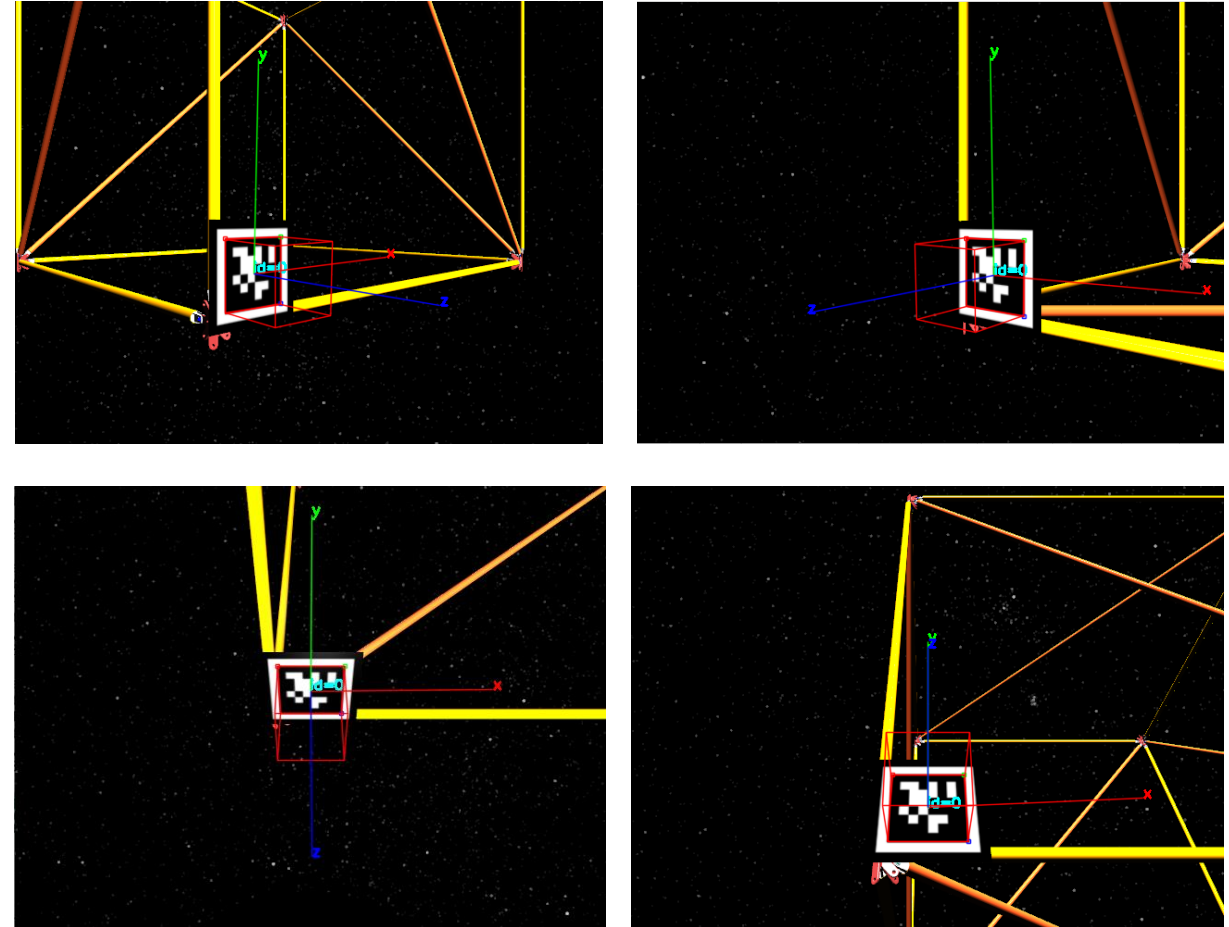


SAMPLE TEST CONFIGURATION IMAGES

Hardware



Simulation



GENERIC ROBOTIC GNC CAPABILITIES

Verification and validation of the new generic GNC systems was achieved in LaSRS++ by:

- Translating/rotating the LSMS robotic links to reach a target end effector position
- Comparing generic testing results to the results from using the original LaSRS++ solution

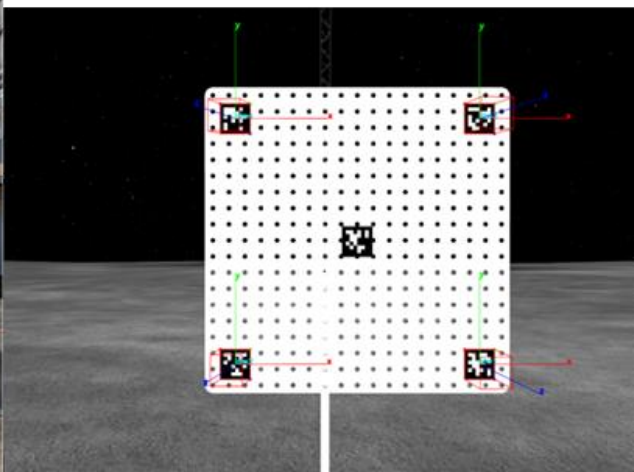
Testing Dimension	Testing Configuration	Joint Combinations (R = Revolute; P = Prismatic)	Phase	Link Lengths (in)			Target End Effector Position (in)		
				Link 1	Link 2	Link 3	X	Y	Z
Two-dimensional	All Revolute Joints	RRR	1	166.82	148.62	145.89	100	214	0
			2				180	214	0
			3				100	0	0
	Mixed Revolute-Prismatic Joints	RRP	-	100	100	75	250	125	0
		PRR		75	100	100	250	125	0
		RPR		100	75	100	250	125	0
Three-dimensional	3D Target Position	RRR		100	100	100	150	100	25
	"Out of reach" 3D Target Position	RRP		100	100	75	225	50	10

FINAL HARDWARE AND SIMULATION TESTS

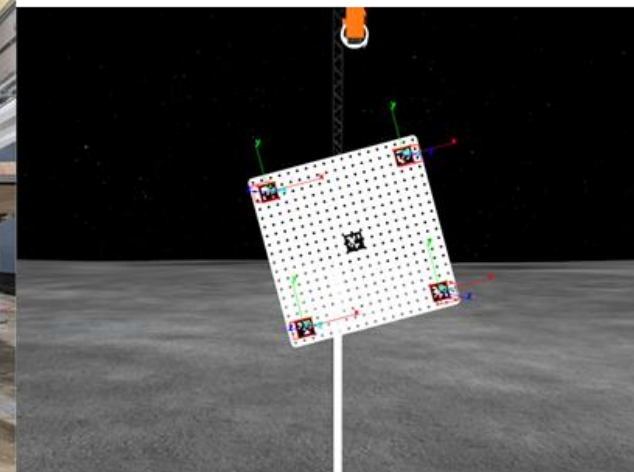
Eyepoint Distance to Test Plate (ft)	Test Plate Angle (deg)	Calibration File Used for Final Image Analysis
2 2.5 3 3.5	0 +15 -15	openmv3calibration.yml



2 ft Eyepoint Distance and 0° Plate Angle



3.5 ft Eyepoint Distance and +15° Plate Angle



RESULTS

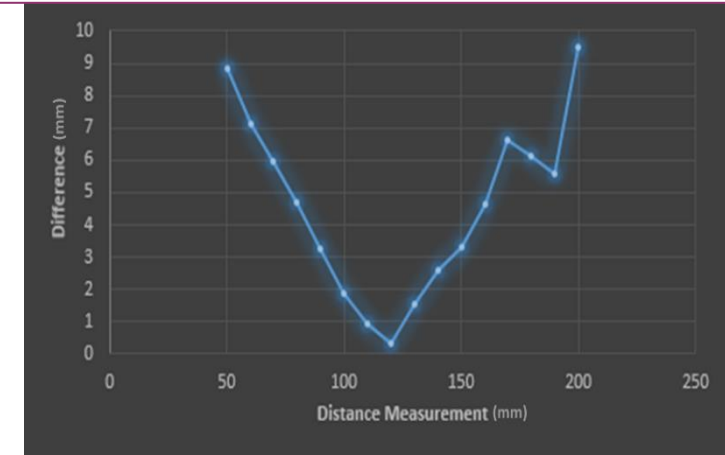
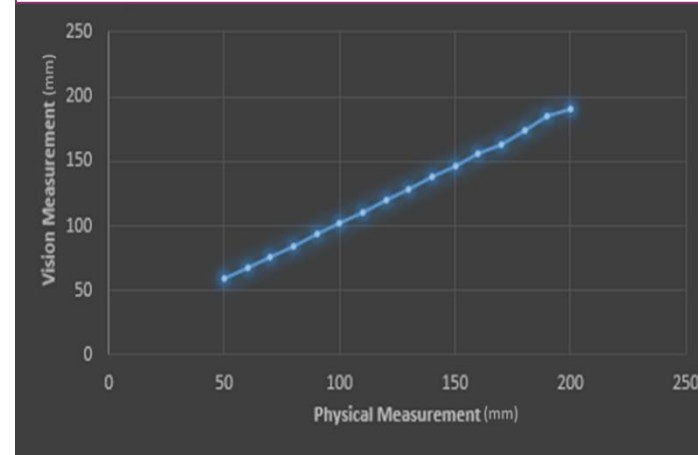
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SIMPLE METROLOGY TEST AND CALIBRATION FILE ANALYSIS

- Optimal calibration file for final data analysis: openmv3calibration
- Translational error for all tests were substantial and the rotational error values are still too high for modeling high-precision operations
- Identified levels and trends of error to expect when extracting POSE data from the final hardware and simulation tests

Initial OpenMV3 Image Analysis



Test	Eyepoint Distance (m)	Average Rotational Error (deg)		
		X	Y	Z
Hardware	0.1	14.84	5.83	30.57
	0.15	15.27	4.83	30.40
Simulation	1.35	7.62	6.82	5.36
	1.5	10.00	7.07	12.17

GENERIC ROBOTIC GNC SYSTEM ANALYSIS

- **Original LSMS Control System Solver:** Reliant on inverse cosine calculation, constrained to output positive angles. Target end effector position not always achieved.
- **New Generic GNC Solver:** Consistently placed the end effector at the desired target locations. Demonstrated the importance of using a complex inverse kinematic solution.

Testing Dimension	Testing Configuration	Joint Combinations (R = Revolute; P = Prismatic)	Target End Effector Position (in)			End Effector Position Error with New Solver (in)		
			X	Y	Z	X	Y	Z
Two-dimensional	Mixed Revolute-Prismatic Joints	RRP	250	125	0	0.01	0.01	0.00
		PRR	250	125	0	0.24	0.23	0.00
		RPR	250	125	0	0.00	0.00	0.00
Three-dimensional	3D Target Position	RRR	150	100	25	0.01	0.02	0.01
	“Out of reach” 3D Target Position	RRP	225	50	10	0.91	0.08	0.07

HARDWARE AND SIMULATION POSE DATA ANALYSIS

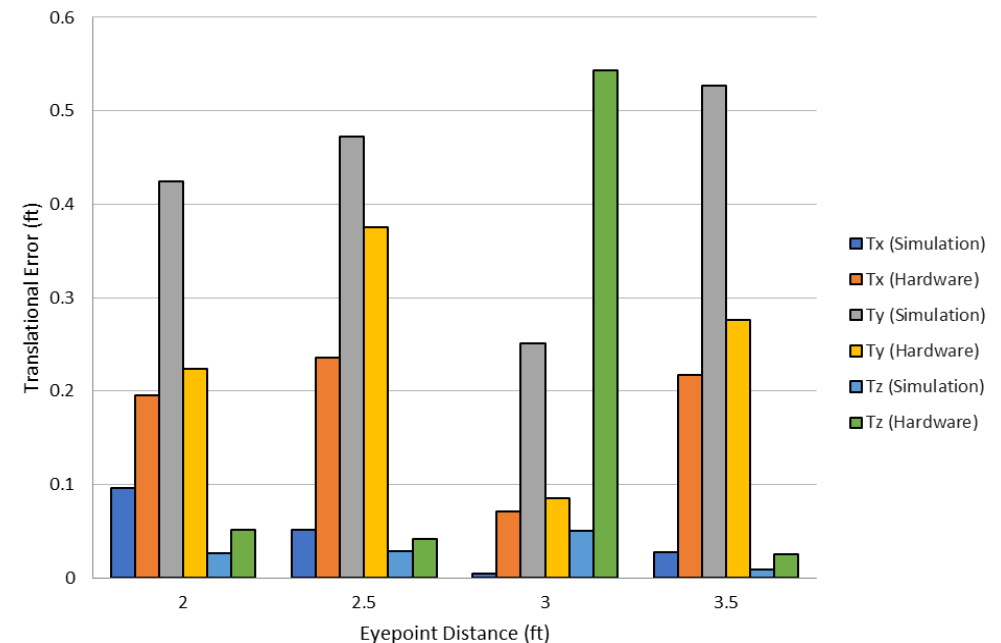
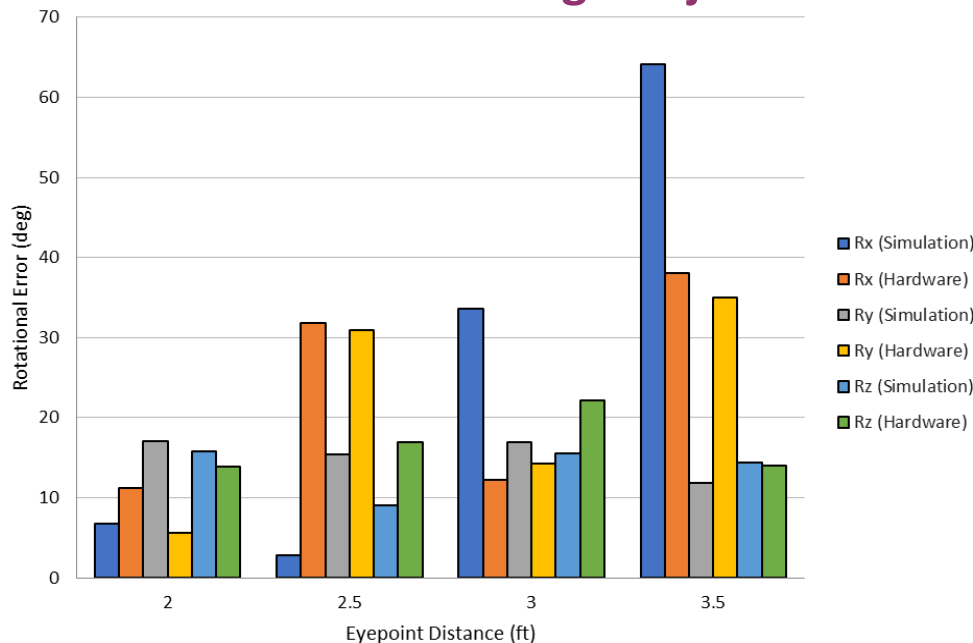
- For each set of images captured at a certain eyepoint distance, average translational and rotational error were calculated for every Apriltag based on expected POSE from CAD
- Average error was applied as a correction to the “raw” ArUco POSE data, producing an “adjusted” set of POSE data for the Apriltags in each image

			Eyepoint Distance (ft)							
			Hardware				Simulation			
			2	2.5	3	3.5	2	2.5	3	3.5
Raw Data Error	Rotational (deg)	X	56.12	71.49	97.31	72.51	56.12	71.49	97.31	72.51
		Y	73.82	73.49	99.13	72.41	73.82	73.49	99.13	72.41
		Z	38.59	35.19	40.25	44.55	38.59	35.19	40.25	44.55
	Translational (ft)	X	0.36	0.45	0.42	0.31	0.36	0.45	0.42	0.31
		Y	0.54	0.45	0.5	0.36	0.54	0.45	0.5	0.36
		Z	0.4	0.52	0.93	0.74	0.4	0.52	0.93	0.74
Adjusted Data Error	Rotational (deg)	X	11.2	31.87	12.27	38.06	6.78	2.76	33.64	64.09
		Y	5.66	30.92	14.26	35	17	15.38	16.87	11.84
		Z	13.85	16.97	22.15	13.99	12.59	11.04	12.35	7.34
	Translational (ft)	X	0.2	0.24	0.07	0.22	0.1	0.05	0	0.03
		Y	0.22	0.37	0.09	0.28	0.42	0.47	0.25	0.53
		Z	0.05	0.04	0.54	0.03	0.03	0.03	0.05	0.01

HARDWARE AND SIMULATION POSE DATA ANALYSIS

- Error is minimized both rotationally and translationally at certain eyepoint distances along different axes. Will need to investigate why these trends are apparent using ArUco data.
- **Overall error is still too high to be useful for high-precision OSAM activities.** Much more refinement and testing will be required to further minimize the error in the simulation.

Average Adjusted Rotational/Translational Data Error



CONCLUSIONS

DISCUSSION

Hypotheses for Error During Hardware/Simulation Development & Testing

Camera focal length and resolution affecting data accuracy depending on eyepoint distance

Poor lighting conditions and glare

Natural lens distortion not modeled perfectly

ArUco POSE data processing may be indeterministic

Color contrast between edges of Apriltags and objects in scene

Material properties not matching between hardware/sim

Imperfections in hardware configuration

TECHNOLOGY MATURATION

The OASiS team intends to continue developing capabilities to advance the state of the art in the real-time OSAM modeling and predictive simulation field, including:

- Enhancing metrology system modeling and data feedback accuracy during operations
- Applying error models either to the entire simulation environment or to specific targets
- Advancing dynamic robotic system modeling capabilities, including multibody modeling and flexible body modeling for cable-actuated systems
- Streamlining the process of modeling both existing and conceptual OSAM hardware
- Enhancing environmental and lighting effects to replicate the final mission environment
- Conducting assessment of commercial modeling and simulation tools and integrating into a cohesive simulation environment

CONCLUSION

OSAM M&S capabilities were used to demonstrate and evaluate POSE data from the simulation of a lunar payload offloading operation against an analogue hardware test

- Developed object-oriented, generic robotic GNC software to simplify the dynamic modeling of the LSMS and other multibody robotic systems
- Conducted the final simulation and hardware tests modeling the two-point cable-capstan end effector
- Gained a better understanding on what level of accuracy of POSE data to expect in a simulation environment using different sensors at positions relative to fiducials
- Error between the adjusted POSE data values and expected results is still not low enough to support modeling high-precision operations at this time

By refining and testing the OSAM M&S capabilities, POSE data error will be minimized within the simulation environment and OSAM mission developers will have more confidence in testing their large-scale, complex OSAM architectures prior to launch

