Initial Characterization of the NREL Large-Amplitude Motion Platform

Bri Friedman, Casey Nichols, Andrew Simms, Calum Kenny, and Miles Skinner

National Renewable Energy Laboratory

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List of Acronyms

DOF	degree(s) of freedom
EDAS	EtherCAT Data Acquisition System
IMU	inertial measurement unit
JSON	JavaScript Object Notation
LAMP	Large-Amplitude Motion Platform
MAE	mean absolute error
NREL	National Renewable Energy Laboratory
PVA	position, velocity, and acceleration
QC	quality control
RRP	rotational reference point
WEC	wave energy converter

Executive Summary

The Large-Amplitude Motion Platform (LAMP) at the National Renewable Energy Laboratory (NREL) represents a significant advancement in the controlled testing of wave energy converters (WECs) under laboratory conditions. Originally designed by E2M as a six-degree-of-freedom (DOF) Stewart platform for flight simulation, LAMP has been adapted by NREL to facilitate the mounting and evaluation of WECs. This adaptation enables dry testing of WECs using motion profiles similar to the ocean, facilitating the iterative design, testing, and validation of WEC performance prior to ocean deployments.

This report presents the initial work completed to characterize LAMP, with particular emphasis on its stability and operational capabilities across various single and multi-DOF motion profiles. The report includes planned comparisons at three distinct mass payloads, aimed at assessing the platform's positional accuracy, frequency response, and endurance over extended runtime periods. These experimental tests are critical for establishing the platform's limitations and ensuring that the data generated during WEC validation are both accurate and reproducible.

The outcomes of this study not only contribute to a deeper understanding of LAMP's capabilities but also lay the groundwork for future advancements in WEC testing methodologies. By providing robust and reliable performance data within a controlled laboratory setting, the findings are expected to significantly enhance the development and commercialization of marine energy technologies. This report presents the initial findings of the LAMP characterization work and proposed steps to further understand and characterize LAMP.

Data collected during this work can be found on MHKDR at:
https://mhkdr.openei.org/submissions/602

Note that this report shares the measured/found instantaneous maximum operating range of LAMP. For most applications, the maximum operating range cannot be used for system health and longevity. The operating range and capabilities of LAMP will be evaluated on a case-by-case basis, and single-DOF position, velocity, and acceleration values presented in Tables 5–8 should be taken as instantaneous absolute maximum values. Future use of LAMP will likely be limited to smaller values.

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1 Introduction

In 2023 NREL acquired and installed the Large-Amplitude Motion Platform (LAMP), pictured in Figure 1 which expands the laboratory's testing capabilities by providing ocean-wave-like movement out of water, filling the gap for wave energy converter (WEC) laboratory testing. Traditional testing methods often fall short in capturing these dynamic interactions, making LAMP's capabilities particularly valuable. Through its advanced motion control system, LAMP can precisely simulate the movements and forces that WECs are subjected to, providing a highly accurate and repeatable testing environment.

This controlled environment is essential not only for performance evaluation but also for the iterative design process, where modifications to WEC designs can be rapidly tested and refined. By enabling a thorough understanding of how WECs behave under various conditions—such as different wave heights, periods, and directions—LAMP facilitates the development of WECs that are optimized for efficiency and durability in real-world ocean conditions.

Figure 1. The LAMP is located in NRELs 2.5-MW dynamometer facility at NREL's Flatirons Campus.

Photo by Bryan Bechtold, NREL

LAMP is a fully defined Stewart platform that uses six linear actuators to move a test object in 6 degrees of freedom (DOF): surge, sway, heave, roll, pitch, and yaw. The LAMP actuators are fully electric, requiring a maximum of 480-V/150-A power supply for all six actuators. According to the manufacturer (E2M), LAMP is capable of approximately 1.8–2.5 m linear displacement and 25°–30° of rotation in any axis. LAMP is rated to carry a maximum payload of 10,000 kg (this payload is limited by the frame, adaptor frame, and added hardware limitations). More details on LAMPs capabilities are provided in Table 1. These values were defined by E2Ms compliance matrix. The Windows control software is provided by the manufacturer E2M and can instruct a real-time industrial controller in the LAMP control cabinet to execute both pre-prescribed motions and real-time controls. The LAMP real-time industrial controller communicates with the user datagram protocol as a standard communication protocol to the Windows controls software. For this work the Windows control software was used to instruct the real-time controller to run test profiles in real time and monitor the status of the system. The system also has the functionality to be controlled by a user-developed host application that can use the user datagram protocol to instruct the real-time controller.

Because LAMP is a new piece of test equipment, the capability, accuracy, and overall performance of the system are expected to fall within the manufacturer specifications, but these specifications must be validated. It is necessary to carefully characterize this test platform so we can effectively communicate our research capabilities with external partners, the U.S. Department of Energy, future researchers, and any other stakeholders. Additionally, given LAMP's expected load and acceleration, this work is necessary to mitigate risks associated with dynamic testing. This report discusses the characterization of LAMP completed during 2024, drawn conclusions from this work, and proposed future actions.

Table 1. LAMP Manufacturer-Defined Single-DOF Position, Velocity, and Acceleration Factory Compliance Specifications

Source: E2M

Degree of Freedom	Travel From Neutral Position	Velocity	Acceleration
Surge	± 1.25 m	1.25 m/s	4.5 m/s²
Sway	± 1.15 m	1.25 m/s	4.5 m/s²
Heave	± 0.9 m	1.0 m/s	4.5 m/s²
Roll	± 25.5°	28.0°/s	120.0°/s²
Pitch	± 30.0°	30.0°/s	120.0°/s²
Yaw	± 26°	Not Provided	120.0°/s²

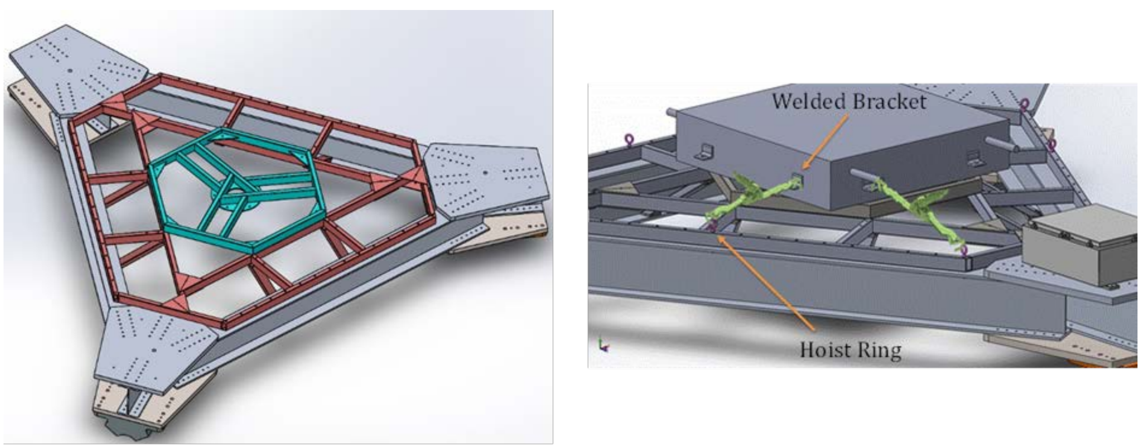
2 Test Plan and Collected Data

A test plan was created to characterize LAMP's amplitude and frequency limits and the effect DOF coupling has on these limits when LAMP is under different test loads. To complete this, test profiles were created that planned to push LAMP to its frequency and amplitude limits for different DOF and DOF combinations. Each of these test profiles were run while different payloads were mounted on LAMP.

2.1 LAMP Modifications and Test Masses

To reduce the time and cost of this project, concrete blocks from previous projects at NREL's Flatirons Campus were modified and used. The loads used were 0 kg (M0), 805 kg (M1), and 1,047 kg (M2). To mount the test masses, two frames were added to LAMP: the adaptor frame (red in Figure 2a) and the hex frame (blue in Figure 2a). These frames are designed to be modular and simple so a wide variety of WECs can be tested on LAMP with minimum redesign required for specific WEC mounting. Both frames were already built and have been used for previous projects (the HERO WEC [Jenne et al. 2024] and the Pioneer Array WEC testing [Coe et al. 2024]). Since these frames were initially designed for smaller WECs, the allowable payload of the system decreases significantly. While the maximum payload mass for LAMP is 10,000 kg, the existing modular frames built for previous testing are limited to 1,800 kg (4,000 lb).

The concrete blocks sat on the hex frame and were secured to LAMP using ratchet straps connecting hoist rings on the adapter frame to angle brackets welded to the concrete blocks (Figure 2b). Each ratchet strap is rated for 2,268 kg, and a total of eight straps were used. Sufficient pre-tension was applied to each strap to ensure they all remained in tension during testing. Two ratchet straps were wrapped around the test mass and the hex frame to limit vertical movement of the test mass relative to LAMP and its frames.



(a) (b)

Figure 2. (a) Final assembly of LAMP including the LAMP frame (gray), adaptor Frame (red), and hex Frame (blue). (b) Concrete mass mounting method.

2.2 Test Profiles

For each test mass, the same test profiles were run. For this initial characterization, an emphasis was placed on understanding individual DOF limitations and collecting data to later explore

DOF interactions. For this reason, most of the test profiles are 1-DOF profiles, where LAMP is instructed to move in only one of the 6 DOF.

For efficient testing, a sweeping sine wave (chirp) approach was developed and implemented in Python to generate signals with constant amplitude and linearly increasing frequency (ramping frequency) and signals with linearly increasing amplitude and constant frequency (ramping amplitude) (see Figure 3). Each test profile was individually specified to target the frequency limitations for a given amplitude, with the expectation that LAMP's accuracy will degrade at higher frequencies. Typically, a test profile consists of 10 discrete steps of the non-ramping value joined together. Each step begins with 10 s at the zero position and ends with a 10-s slowdown to the zero position. This was done to ensure that the LAMP returns to its initial state before starting the next step in the test to eliminate any interactions between the end of one step and the start of another. The test profiles were generated at 100 Hz, which is within the allowable sample rate of the LAMP control system, and output as comma-separated value (csv) files. Also saved during profile generation was a specification of the test profile in JavaScript Object Notation (JSON) format and a visualization of the position, velocity, and acceleration (PVA) time series.

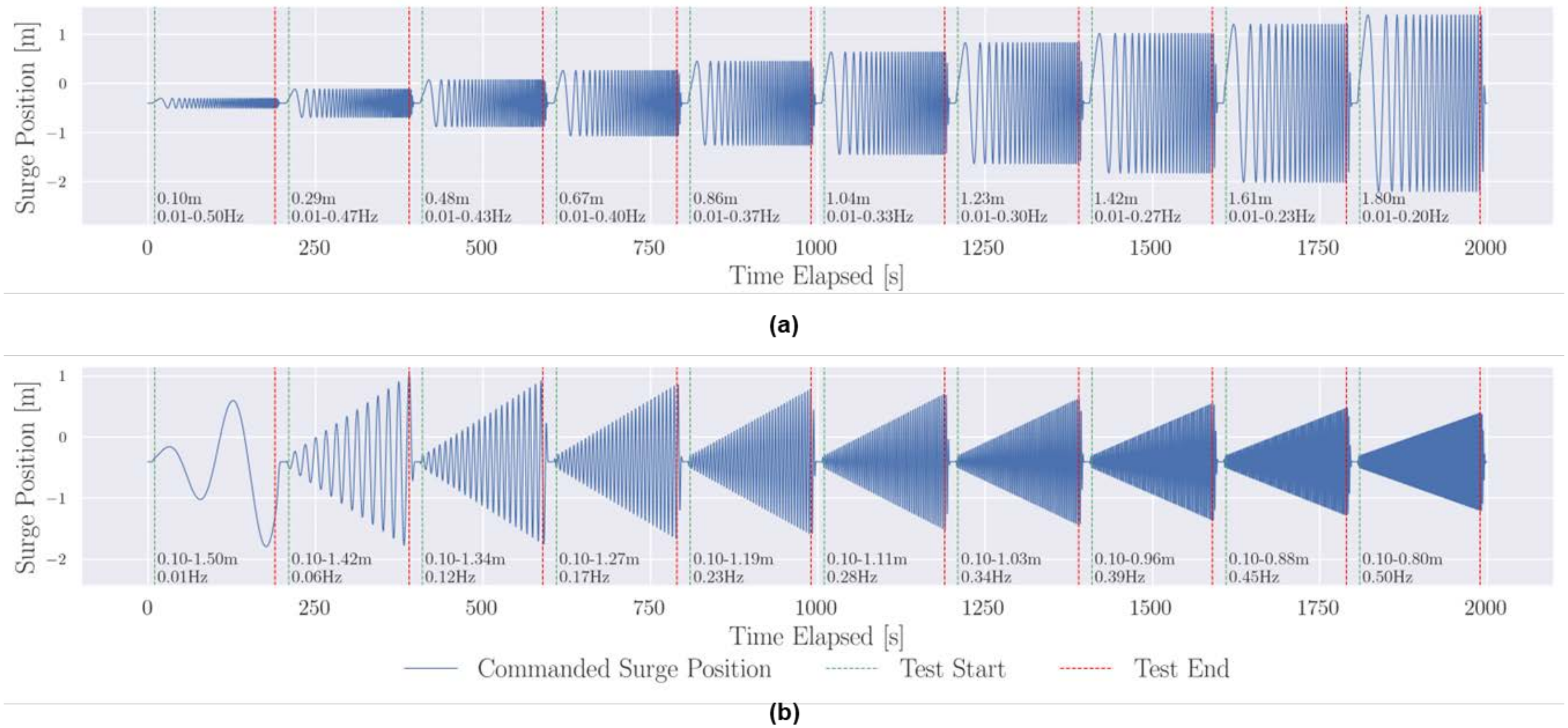


Figure 3. Commanded surge position over time for (a) Test Profile (TP) 101 (ramping amplitude, continuous frequency) and (b) TP 111 (continuous amplitude, ramping frequency). The green line represents each step's start, and the red line represents each step's end.

Twelve 1-DOF test profiles (TPs) were created for this work and are summarized in Table 2 and Table 3. Test profiles have 10 different amplitude steps, and for each step the frequency continuously increases (ramping frequency). For example, the input test profile for TP 101 directs LAMP to only move in surge. For the minimum amplitude (0.1 m), the frequency continuously increases from 0.01 Hz to 0.5 Hz. The amplitude and frequency ranges to be tested were determined based on initial knowledge of the system to ensure the limitations of the system were reached. Note that LAMP has internal actuator PVA limits that are never exceeded by the controller; thus, test profiles beyond LAMP's limits could not cause harm to LAMP. Figure 3a shows the whole test profile for TP 101 where each step begins at a green line and ends at the next red line. Table 3 test profiles have 10 different frequency steps, and for each step the amplitude continuously increases (ramping amplitude). For example, the input test profile for TP 111 directs LAMP to only move in surge. For the minimum frequency (0.01 Hz), the amplitude continuously increases from 0.1 m to 1.5 m. Figure 3b shows the whole test profile for TP 111 where each step begins at a green line and ends at the next red line.

Table 2. Single-DOF Test Profiles With 10 Ramping Amplitude Steps and Continuous Frequency

Each amplitude step is 180 s, with 10 s of static time at the start and end of each test, yielding a total test length of 2,000 s.

Test Profile Name	DOF	Frequency Range at Minimum Amplitude (Hz)	Frequency Range at Maximum Amplitude (Hz)	Amplitude Range	Tested Masses
TP 101	Surge	0.01–0.5	0.01–0.2	0.1–1.8 m	M0, M1, M2
TP 102	Sway	0.01–0.5	0.01–0.2	0.1–1.5 m	M0, M1, M2
TP 103	Heave	0.01–0.5	0.01–0.2	0.1–1.3 m	M0, M1, M2
TP 104	Roll	0.01–0.8	0.01–0.5	1–30°	M0, M1, M2
TP 105	Pitch	0.01–0.8	0.01–0.5	1–35°	M0, M1, M2
TP 106	Yaw	0.01–0.8	0.01–0.5	1–30°	M0, M1, M2

Table 3. Single-DOF Test Profiles With Continuous Amplitude and 10 Ramping Frequency Steps

Each frequency step is 180 s, with 10 s of static time at the start and end of each test profile, yielding a total test length of 2,000 s.

Test Profile Name	DOF	Frequency Range (Hz)	Amplitude Range at Minimum Frequency (m or deg)	Amplitude Range at Maximum Frequency	Tested Masses
TP 111	Surge	0.01–0.5	0.1–1.5	0.1–0.8 m	M0, M1, M2
TP 112	Sway	0.01–0.5	0.1–1.5	0.1–0.8 m	M0, M1, M2
TP 113	Heave	0.01–0.5	0.1–1.3	0.1–0.7 m	M0, M1, M2
TP 114	Roll	0.01–0.8	1–30	1–18°	M0, M1, M2
TP 115	Pitch	0.01–0.8	1–30	1–21°	M0, M1, M2
TP 116	Yaw	0.01–0.8	1–30	1–18°	M0, M1, M2

To begin to understand DOF interactions, two 2-DOF, one 3-DOF, and one 6-DOF test profiles were created. The 2-DOF and 3-DOF test profiles were created by combining test profiles from Table 2 and therefore has 10 discrete amplitude steps where the frequency continuously increases within each step. These test profiles are listed in Table 4. The 6-DOF test profile (TP 600) is a 200-s test profile created by Sandia National Laboratories to test the Pioneer Array WEC on LAMP using a pink noise signal frequency range of 0.1–0.25 Hz (Coe et al. 2024). The commanded position for each DOF for TP 600 can be found in Appendix A. All test masses (M0, M1, and M2) were tested with TP 600. The last column in Table 2, Table 3, and Table 4 list the payloads that were tested for each test profile. Note that not all tests tested M2 due to time constraints. All test profiles used (and data collected) in this work can be found on MHKDR at: https://mhkdr.openei.org/submissions/602.

Table 4. Multiple DOF Test Profiles With 10 Ramping Amplitude Steps and Continuous Frequency

Each amplitude step is 180 s, with 10 s of static time at the start and end of each test, yielding a total test length of 2,000 s. These test profiles are different combinations of TP 101–TP 106 (provided in Table 2).

Test Profile Name	DOF	Frequency Range at Minimum Amplitude (Hz)	Frequency Range at Maximum Amplitude (Hz)	Amplitude Range	Tested Masses
TP 206	Surge	0.01–0.5	0.01–0.2	0.1–1.8 m	M0, M1
	Yaw	0.01–0.8	0.01–0.5	1–30°	
TP 207	Sway	0.01–0.5	0.01–0.2	0.1–1.5 m	M0, M1
	Roll	0.01–0.8	0.01–0.5	1–30°	
TP 306	Surge	0.01–0.5	0.01–0.2	0.1–1.8 m	M0, M1
	Heave	0.01–0.5	0.01–0.2	0.1–1.3 m	
	Pitch	0.01–0.8	0.01–0.5	1–35°	

3 Data Acquisition and Instrumentation

Data were collected through two systems: the LAMP control system and the NREL developed EtherCAT data acquisition system (EDAS).

3.1 LAMP Control System

The LAMP real-time controller requires .dat and .header files as input defining the PVA. A sampling rate of 100 Hz was used for each of the 6 DOF. The system outputs .dat and .header files, including (but not limited to) controlled and response values for PVA, controlled and response actuator positions, actuator current, and actuator temperature. Prior to running test profiles on LAMP, test profiles were run through LAMP's emulator to verify that the files were output correctly and did not produce any errors or warnings in the emulator.

MATLAB code developed by E2M was used to converted 6-DOF PVA test profile csv files generated by Python into .dat and .header files. These 6-DOF PVA .dat/.header files were input into LAMP, and LAMP's software used inverse kinematics to convert the 6-DOF PVA into individual actuator positions. While running, LAMP measures the actuator positions and then uses forward kinematics to provide the user with LAMP's actual 6-DOF PVA during and after running of the test profile.

3.2 EDAS

Three strain gauges were attached to the LAMP frame (gray in Figure 2a), and seven strain gauges were attached to the adaptor frame (red in Figure 2a). The strain gauges were used to confirm the applied load was within LAMP and the added frames' limits and for material health monitoring over the long term. The three gauges mounted on the LAMP frame are HBM 1-LY13-10/305A bondable strain gauges, and the other seven gauges are Micro Measurements CEA-06-W250A-350 weldable strain gauges.

A 6-DOF EtherCAT inertial measurement unit (IMU) (Gable One Series SE7 IMU equipped with XSens Mti-7, GNSS, and INS) has been purchased and will be mounted to the center of the hex frame in the future. The IMU will be used to track the acceleration and rotational velocity (gyroscope) of the platform about the platform origin. Due to manufacturing/production delays from Gable One, the IMU was not used in this work.

4 Inverse Kinematics

LAMP is physically limited in each DOF by the stroke length of all the actuators. To better understand these position limits, an inverse kinematics model was created. Inverse kinematics refers to the operation of taking a desired payload position and orientation (pose) in Cartesian space and back-calculating what actuator lengths are needed to achieve that pose. Inverse kinematics is a fundamental calculation in Stewart platform control, as it allows the system to be controlled with Cartesian position and orientation, which is much more applicable to marine energy device testing and general robotic control. This process is always running in real time on the industrial controller, with several control processes monitoring the outcome to ensure the LAMP does not exceed any system or safety limits.

Because we know the actuator minimum and maximum achievable lengths by design, we can use an inverse kinematics solver to verify if a desired pose is achievable by the LAMP actuators. This is very useful because the LAMP pose limits are neither straightforward nor easily described, but the actuator limits are.

4.1 Methodology

The LAMP and most 6-DOF Stewart platforms have six variable length actuators, which means there are six spherical joints on both the base and top frames of the system. We can fully define a 6-DOF Stewart platform by knowing the spatial layout of the six joints on the base, the six joints on the top, and the minimum and maximum lengths of the six actuators. These are displayed in Figure 4, where the blue lines indicate the base, the red lines indicate the top, and the green lines indicate the actuators.

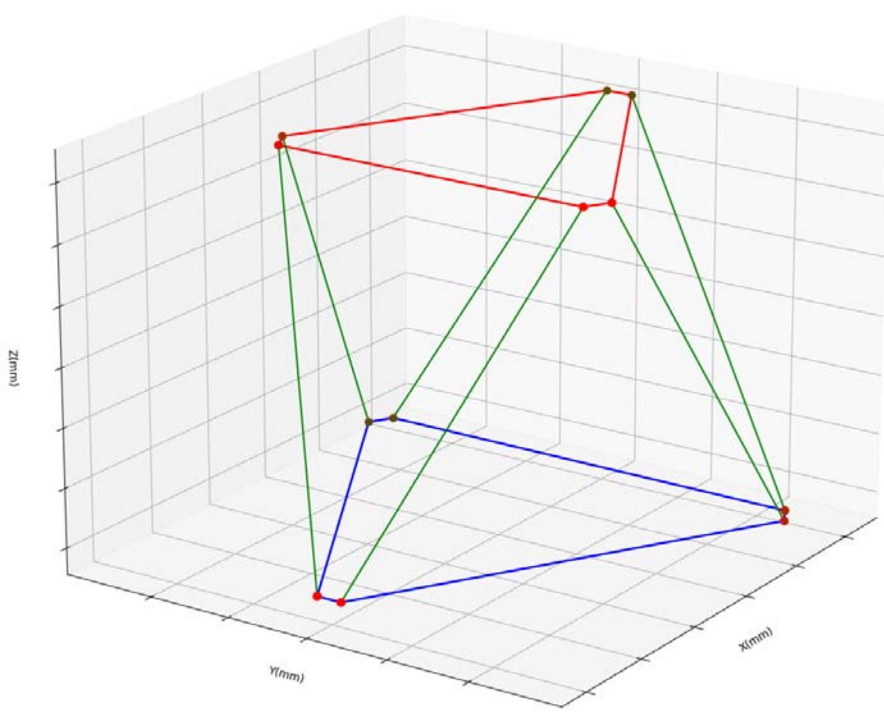


Figure 4. 3D plot of the LAMP base, top, and actuators

The pose of the system is essentially the location of the top in relationship to some reference point. For inverse kinematics, the reference point is usually the origin of the base. Thus, the pose of the top consists of a translation vector (surge, sway, heave) and a rotation vector (roll, pitch, yaw) from the origin of the base to the origin of the top. We can determine the new location of the top joints with the translation and rotation vector by applying a coordinate transformation to the original location of the top joints. Knowing the location of the transformed top joints, we can simply calculate the distance between the corresponding base joints and top joints to know the actuator lengths. This process is described in more detail in Liu et al. 1993).

An additional complexity with the LAMP is that the system is controlled by issuing a pose relative to two modifiable reference points: the neutral position and the rotational reference point (RRP). The translational component of the commanded pose is relative to the top frame in its neutral position, which is defined by having all the actuators at mid-length. The rotational component of the commanded pose is relative to a custom point, which is defined by a translation offset from the origin of the top frame (also called moving platform centroid). The location of RRP greatly affects the resultant actuator lengths from a commanded pose. In practice, the RRP should be set to the centroid of the device under test so commanded orientations can result in the direct orientation of the device under test and will not need to be pre-processed or post-processed.

4.2 LAMP Kinematics Python Library

NREL has developed a tool in Python called LAMPKinematics, which allows staff members to evaluate a desired motion trajectory and understand if it is within the pose/actuator limits of the LAMP. The library is currently not publicly available because it contains information considered to be intellectual property of E2M.

The main functionality of this library is to input a desired pose relative to the neutral position translationally and the RRP rotationally and receive the resultant actuator lengths as well as a Boolean that indicates that the actuators are within their working range. In its current state, the neutral position and RRP are not easily modifiable; this is intentional, as determining new neutral positions and RRPs should be done with support from test engineering staff. Example code can be found in Appendix B.

4.3 Validation

This code was validated by comparing the LAMPKinematics library’s performance modeling the actuator lengths to the data collected during actual LAMP tests. Figure 5 shows that the simulated (LAMPKinematics library) aligns with a maximum absolute error of 0.02% of the actuator span to the real-world behavior of the LAMP, proving that the model can calculate the actuator lengths that result from a commanded pose with a sufficient level of accuracy for most use cases.

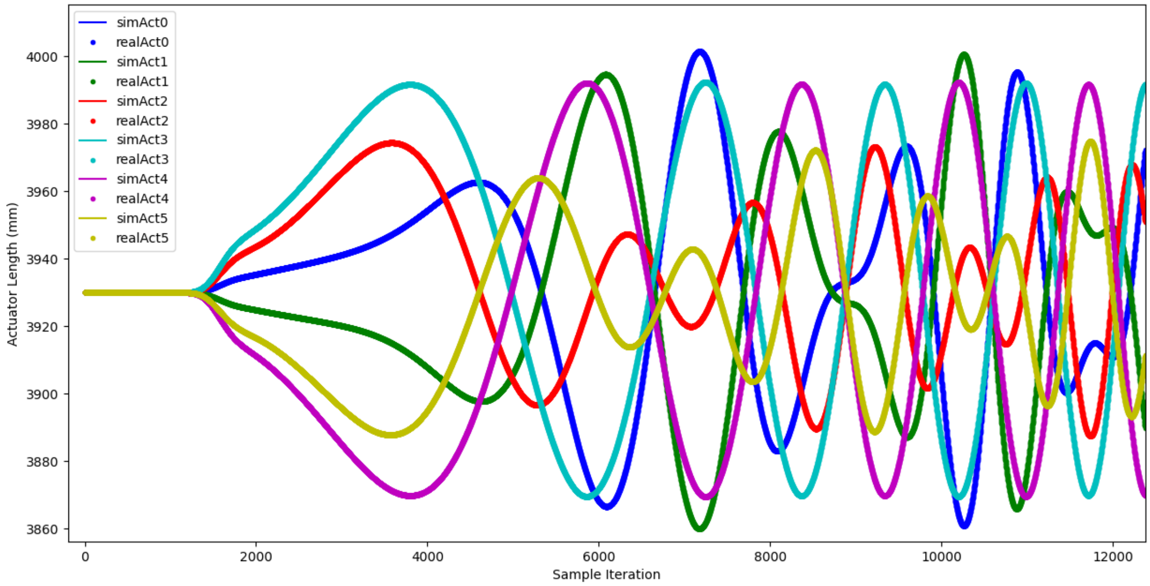


Figure 5. Validation of LAMPKinematics model with LAMP testing data by comparing actuator length. The real data (dots) collected from LAMP testing match the modeled kinematics with maximum absolute error of 0.02% of the actuator span (line).

4.4 Limitations

The inverse kinematic solver is currently only useful for determining if a desired pose is possible with the LAMP system. It does not currently include the ability to determine if a desired pose velocity is possible, and it does not account for the mass effects of larger payloads; however, these could be estimated by solving the inverse dynamics with a physics-based simulation.

5 Quality Control

As the LAMP controller is effectively a black box to operators due to its proprietary nature, it is important to verify the output data match expectations. There are many variables that influence the output of any control system, and these variables may trickle down into resultant analysis on the LAMP data. A common method of quality control (QC) is clipping, which sets values beyond predetermined thresholds to null values. In a typical measurement system, these values would be set based on the specifications of the instrument and digital-to-analog converter specifications. Given that the LAMP system does not provide such specifications, other methods must be used to determine the QC min and QC max values for each channel. This project implements a method that uses all available data to determine the absolute min/max values and the 0.01 and 99.99 percentile values. If the difference between the respective percentile value and the min/max is greater than 1 standard deviation (σ), the percentile value is used as the QC value; otherwise, we use the absolute found value.

Quality Control Minimum

$$QC_{\min} = \begin{cases} Q_{0.01} & \text{if } |(Q_{0.01} - \text{Min})| > \sigma \\ \text{Min} & \text{otherwise} \end{cases}$$

Where:

- $QC_{\min}$ is the calculated quality control minimum.
- $Q_{0.01}$ is the 0.01 percentile value of the data.
- Min is the minimum value of the data.
- σ is the population standard deviation.

Quality Control Maximum

$$QC_{\max} = \begin{cases} Q_{99.99} & \text{if } |(\text{Max} - Q_{99.99})| > \sigma \\ \text{Max} & \text{otherwise} \end{cases}$$

Where:

- $QC_{\max}$ is the calculated quality control maximum.
- $Q_{99.99}$ is the 99.99th percentile value of the data.
- Max is the maximum value of the data.
- σ is the population standard deviation.

The output from these calculations yields a classification for each data point. For further processing, data that failed the QC check are set to null, removing outliers from further calculations. With continued operations, the QC values should be continually recalculated and eventually solidified. Any outputs from the LAMP should utilize these values to verify that the LAMP is operating nominally.

6 Test Mass Comparisons

All of the test profiles were run with multiple test masses (listed in the last column of Table 2, Table 3 and Table 4). The same test profiles were run under different test masses to compare the effect payload mass has on LAMP's operational abilities. To quantify this effect, the mean absolute error (MAE) was calculated for each test, comparing LAMP's response to what was commanded. For a single test profile, the MAE for each test mass was compared. For all position comparisons, the MAE was the same for each test mass; as an example, Figure 6 shows the MAE for each test mass at each DOF for TP 600. From the test mass position comparisons, we determined that LAMP's movement over time for any test profile is the same for M2 as for M0. More testing and analysis need to be completed to understand if test masses greater than 1,047 kg (M2) would yield the same movement as no weight for a given test profile.

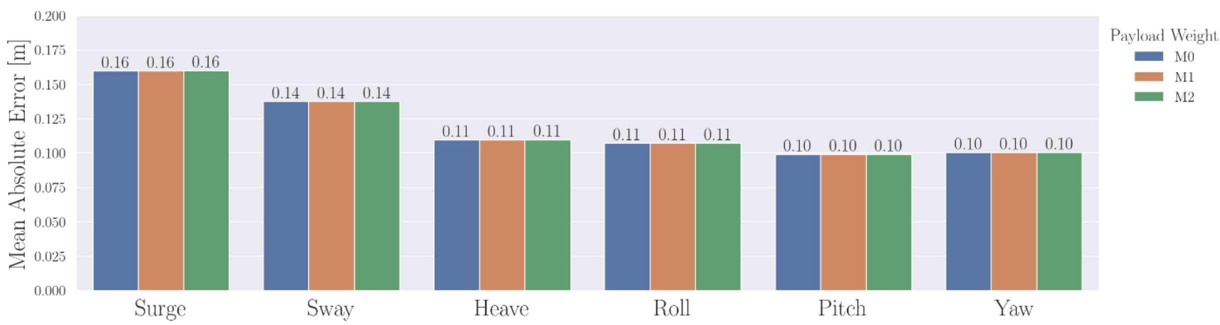


Figure 6. TP 600 response position MAE for each test mass (M0 blue, M1 orange, and M2 green) at each DOF. All three test masses have the same MAE at all DOF.

Other metrics beyond PVA were compared between test masses, including measured actuator motor current. In Figure 7 the measured motor current is compared using the same test profile (TP 600) across different test masses, observing that there are increases in the current usage as the weight increases. The rest of this report focuses on characterizing LAMP's PVA limits. For this reason, the test masses are not differentiated for the rest of this report, and all further conclusions drawn are for any payload between 0 and 1,047 kg.

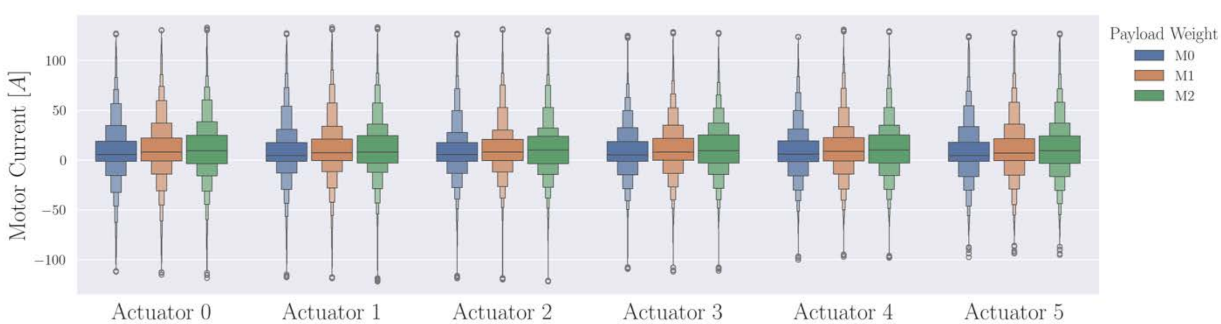


Figure 7. TP 600 motor current for each test mass (M0 blue, M1 orange, and M2 green) for each actuator. The magnitude of the motor current for each actuator increases with payload.

7 1-DOF PVA Limits

Instantaneous PVA data from the 1-DOF test profiles at all test masses were compared to the provided manufacturer specifications shown in Table 1. Tables 5–7 provide this comparison across single degrees of freedoms for position, velocity, and acceleration, respectively. This assessment demonstrates that the manufacturer-provided PVA ranges tend to be conservative estimates of the platform's performance limits (all percentage increases are positive values). The LAMP response was determined by moving the system in 1-DOF starting from the neutral position where the actuators are at mid-span. Table 8 provides a summary of the measured instantaneous PVA limits.

Table 5. 1-DOF Position Limits From the Manufacturer Specification vs. LAMP's Response With a Given Command*

DOF	Manufacturer Position Range (±)	Response Position Range (±)	Percentage Increase (%)
Surge	1.25 m	1.45 m	16.00
Sway	1.15 m	1.26 m	9.57
Heave	0.90 m	1.01 m	12.78
Roll	25.50°	27.74°	8.80
Pitch	30.00°	31.73°	5.77
Yaw	26.00°	28.34°	9.00

Table 6. 1-DOF Velocity Limits From the Manufacture Specification vs. LAMP's Response With a Given Command*

DOF	Manufacturer Velocity Max	Response Velocity Max	Percentage Increase (%)
Surge	1.25 m/s	1.71 m/s	36.80
Sway	1.25 m/s	1.66 m/s	32.80
Heave	1.00 m/s	1.09 m/s	9.00
Roll	28.00°/s	33.92°/s	21.14
Pitch	30.00°/s	36.76°/s	22.53
Yaw	None	32.87°/s	None

Table 7. 1-DOF Acceleration Limits From the Manufacture Specification vs. LAMP's Response With a Given Command*

DOF	Manufacturer Acceleration "Up to"	Response Acceleration Max	Percentage Increase (%)
Surge	4.5 m/s^2	10.09 m/s^2	124.22
Sway	4.5 m/s^2	8.26 m/s^2	83.56
Heave	4.5 m/s^2	7.77 m/s^2	72.67
Roll	120.0°/s^2	265.49°/s^2	121.24
Pitch	120.0°/s^2	305.22°/s^2	154.35
Yaw	120.01°/s^2	285.16°/s^2	137.63

Table 8. LAMP 1-DOF Position, Velocity, and Acceleration Limits Measured During This Work*

DOF	Position Range (±)	Absolute Max Velocity	Absolute Max Acceleration
Surge	1.45 m	1.71 m/s	10.09 m/s^2
Sway	1.26 m	1.66 m/s	8.26 m/s^2
Heave	1.01 m	1.09 m/s	7.77 m/s^2
Roll	27.74°	33.92°/s	265.49°/s^2
Pitch	31.73°	36.76°/s	305.22°/s^2
Yaw	28.34°	32.87°/s	285.16°/s^2

***Note that although this testing found larger limits than provided by the manufacturer, LAMP may still be constrained prior to hitting its limits as needed for system health and longevity. The operating range and capabilities of LAMP will be evaluated on a case-by-case basis, and single-DOF position, velocity, and acceleration values presented in Tables 5–8 should be taken as instantaneous absolute maximum values. Future use of LAMP will likely be limited to smaller values.**

8 Position Correlation

To better understand LAMP's PVA limits and quantify the relationship between the commanded and response position, the correlation between the command and the response for a given frequency and amplitude was evaluated. To do this, a binning method was used to calculate the rolling correlation within distinct frequency and amplitude bins. The bins were derived from the instantaneous frequency and amplitude of the specific test cases, derived from the test profile specifications.

Specifically, the continuous data for frequency and amplitude were discretized into bins, enabling a localized examination of the system's performance. Within each bin, a 100-sample (1 s) rolling correlation was calculated between the commanded and response position data. Instead of utilizing the average rolling correlation, the 5th percentile was retained as the correlation estimate, ensuring a conservative assessment of LAMP's limits under varied conditions. A confidence interval was derived for each bin, and bins with insufficient data were excluded to maintain the reliability of results.

8.1 Position Correlation Equation

A single LAMP position correlation matrix provides a measure of the linear correlation between the commanded (`Motion.KinematicsFwd->ComPose<DOF>`) and response (*`Motion.KinematicsBwd->Pose<DOF>`*) position across all payloads within specific frequency and amplitude bins, filtered by the number of degrees of freedom that are in motion. Pearson correlation provides a unitless value between 1 and -1, allowing for comparison between measures of different units. In correlation analysis, 1 represents a perfect linear relationship, 0 represents no linear relationship, and -1 represents an inverse or negative linear relationship.

To quantify the relationship between the commanded and response positions over time, a rolling window method calculates the Pearson correlation coefficient over a window of 100 samples (equivalent to 1 s), capturing a moving window of the relationship between command and response.

The rolling correlation at time t for commanded position $x_c(t)$ and response position $x_r(t)$ is defined as:

$$\rho(t) = \frac{\mathbb{E}\left[\left(x_c(t) - \mu_{x_c}\right)\left(x_r(t) - \mu_{x_r}\right)\right]}{\sigma_{x_c}\sigma_{x_r}}$$

Where:

- μ_{x_c} and μ_{x_r} are the means of the commanded and response positions, respectively, over the rolling window.
- σ_{x_c} and σ_{x_r} are the standard deviations of the commanded and response positions, respectively, within the rolling window.
- $\mathbb{E}$ represents the expected value (average) within the window.

This rolling correlation is computed across multiple time points, resulting in a vector of correlation values:

$$\vec{\rho} = \left[\rho\left((x_c, x_r)_{t_1}, \ldots, (x_c, x_r)_{t_{100}}\right), \ldots, \rho\left((x_c, x_r)_{t_{n-100}}, \ldots, (x_c, x_r)_{t_n}\right)\right]$$

Where:

- $\rho\left((x_c, x_r)_{t_1}, \ldots, (x_c, x_r)_{t_{100}}\right)$ is a 100-sample correlation calculation.

From this vector of correlation values, the 5th percentile is computed as the bin correlation value, defined as:

$$\rho_{5th} = \text{Percentile}(\vec{\rho}, 5)$$

8.2 Command and Response Time-Series Correlation

To better understand LAMP's ability to reproduce commanded motion, the correlation of the command and response position time series of individual test profiles were determined. In the following visualizations (Figure 8 and Figure 9), the figure on the left is a time series from one step of a test profile, and the figure on the right is the 100-sample rolling correlation between the command and response position (ρ).

In cases where the command and response relationship are highly linear, a strong correlation is observed. In cases where either the frequency or amplitude are limited by position, velocity, or acceleration limits imposed by the LAMP controller, the correlation decreases. A rolling correlation threshold of 0.95 is marked as a blue dotted line and denotes the recommended boundary between the linear and nonlinear response of the LAMP.

Figure 8 visualizes three steps of TP 101, a single-DOF ramping frequency, constant amplitude surge test profile. As shown in Figure 8a (first step), the rolling correlation is 1 for the entire step, indicating the test profile is within LAMP's linear operating range. In Figure 8b (fifth step), as the test profile increases in frequency, the correlation decreases, but the decrease is not constant. The rolling correlation captures the change in the linear relationship over time.

Figure 9 visualizes three steps of TP 111, a single-DOF ramping amplitude, constant frequency surge test profile. In these profiles, the rolling correlation captures the amplitude limitations in all three test cases. Based on the correlation coefficient and the test profile specifications, the cause of decrease in correlation is due to the increased amplitude of the test profile.

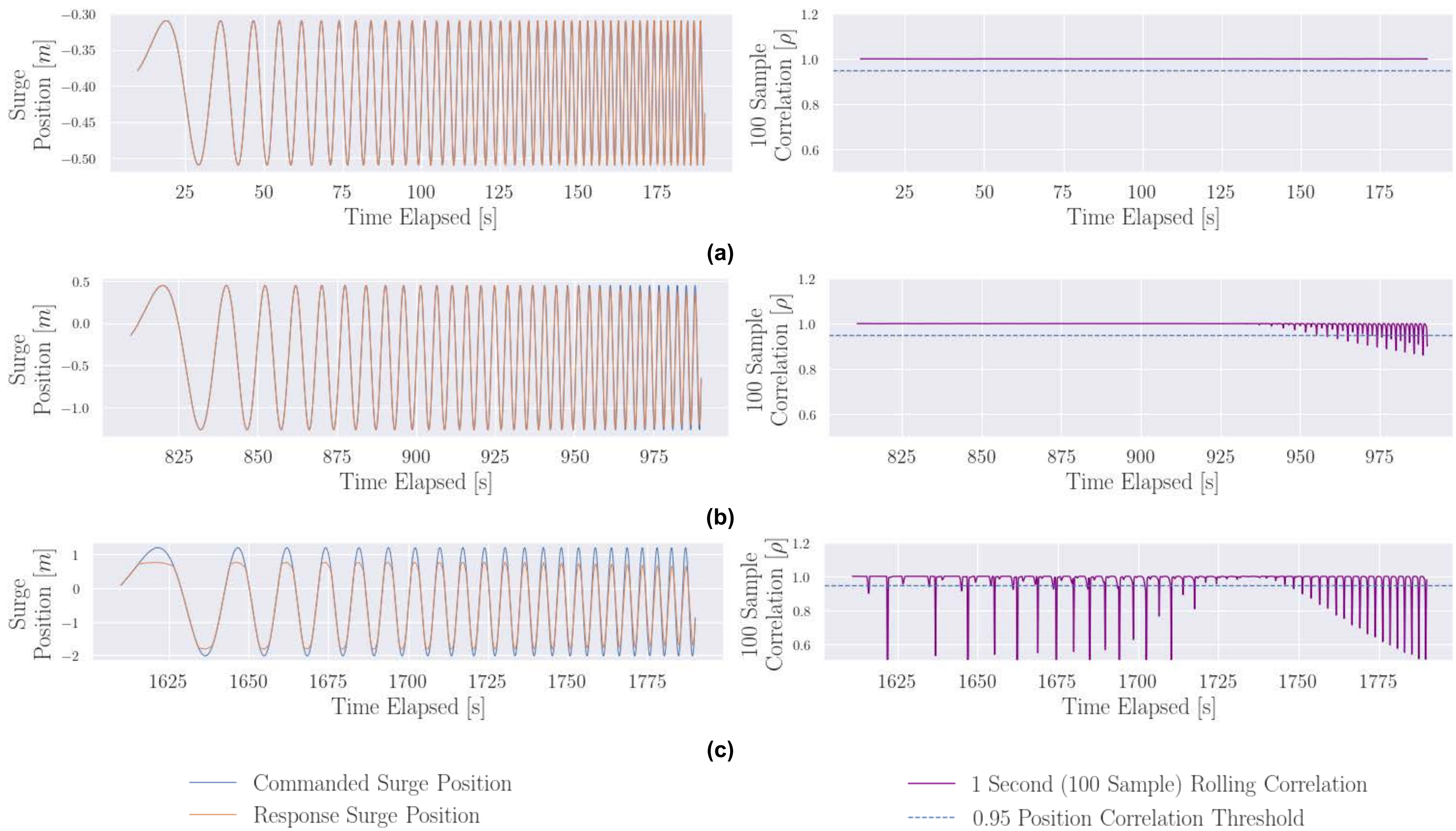


Figure 8. The commanded surge position (blue) vs. the response surge position (orange) and the rolling correlation between the command and response over time of three different amplitude steps for TP 101: (a) 0.10 m, 0.01–0.50 Hz; (b) 0.86 m, 0.01–0.37 Hz; and (c) 1.61 m, 0.01–0.23 Hz

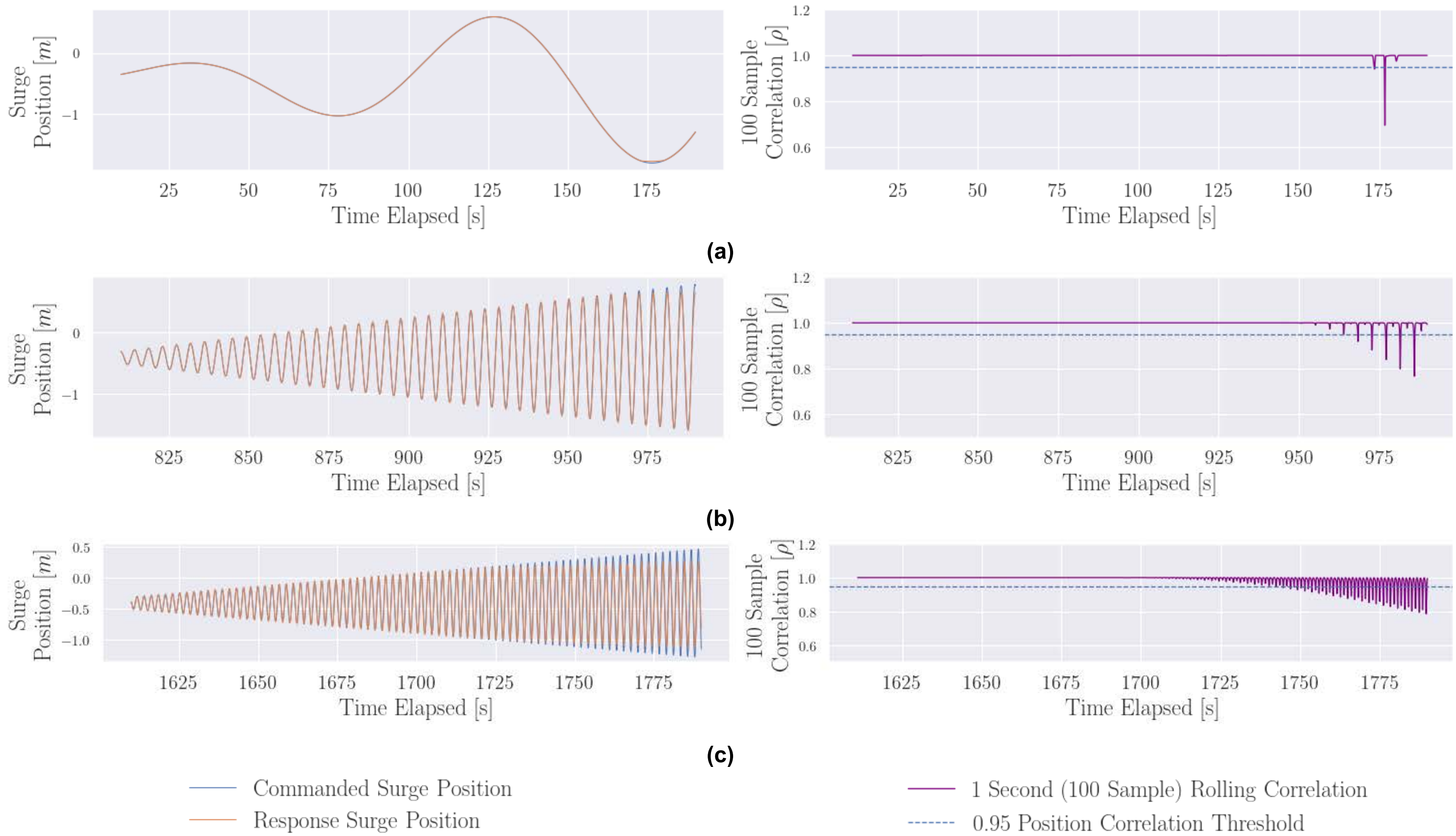


Figure 9. The commanded surge position (blue) vs. the response surge position (orange) and the rolling correlation between the command and response over time of three different frequency steps for TP 111: (a) 0.01 Hz, 0.10–1.5 m; (b) 0.23 Hz, 0.10–1.19 m; and (c) 0.45 Hz, 0.10–0.88 m

8.3 Command and Response Amplitude and Period Correlation

Correlation matrices were created to understand LAMP's abilities and communicate abilities with future users. The resulting matrices resemble a WEC power matrix, facilitating a comparative analysis of the strength of the relationship between the command and the response positions for each degree of freedom throughout the entire test campaign. This analysis aims to identify the expected worst-case relationship between the command and the response at specific frequencies and amplitudes by focusing on the 5th percentile of the rolling correlation values. This approach provides researchers and developers with valuable guidelines for selecting test profile parameters based on the measured data. The computed correlations were visualized in a heatmap, with axes representing frequency (converted to period) and amplitude. These heatmaps effectively visualize trends in expected positional accuracy across different operational conditions.

Correlation Matrix

For each amplitude/frequency bin (a, f), a correlation matrix is computed, capturing the pairwise correlations between multiple payloads. The correlation matrix for bin (a, f) is defined as:

$$\boldsymbol{\rho}_{a,f} = \begin{pmatrix} \rho_{5th}\left(a_{\text{bin}_n}, f_{\text{bin}_0}\right) & \cdots & \rho_{5th}\left(a_{\text{bin}_n}, f_{\text{bin}_n}\right) \\ \vdots & \ddots & \vdots \\ \rho_{5th}\left(a_{\text{bin}_0}, f_{\text{bin}_0}\right) & \cdots & \rho_{5th}\left(a_{\text{bin}_n}, f_{\text{bin}_n}\right) \end{pmatrix}$$

Where $\rho_{5th}\left(a_i, f_j\right))$ is the 5th percentile rolling Pearson correlation coefficient computed for each pair of payloads within the bin (i, j).

8.4 LAMP's Position Correlation Matrices

A correlation matrix was created for each DOF from all 1-DOF testing (TP 101–TP 106 and TP 111–TP 116, and all test masses). These matrices are shown in Figure 10. The matrices provide guidance on LAMP's capabilities for 1-DOF movement. As before, a correlation threshold of 0.95 is used in the following visualizations to denote the boundary between a strong and weak relationship between the commanded and response position. This value indicates that the LAMP is unable to maintain the expected position and may be performing some type of attenuation to maintain control. Blue cells denote frequency and amplitude bins where the linear relationship is strong, decreasing to red cells denoting a weak linear relationship.

For example, Figure 10a shows the correlation between the commanded and response surge position for surge-only test profiles (i.e., TP 101 and TP 111). From Figure 10a one can conclude that LAMP will perform a 1-m, 6-s command perfectly, but will perform poorly if commanded to move 1.2 m at 4 s. The six correlation matrices shown in Figure 10 are useful for understanding LAMP's single-DOF limits, but not its multi-DOF limits.

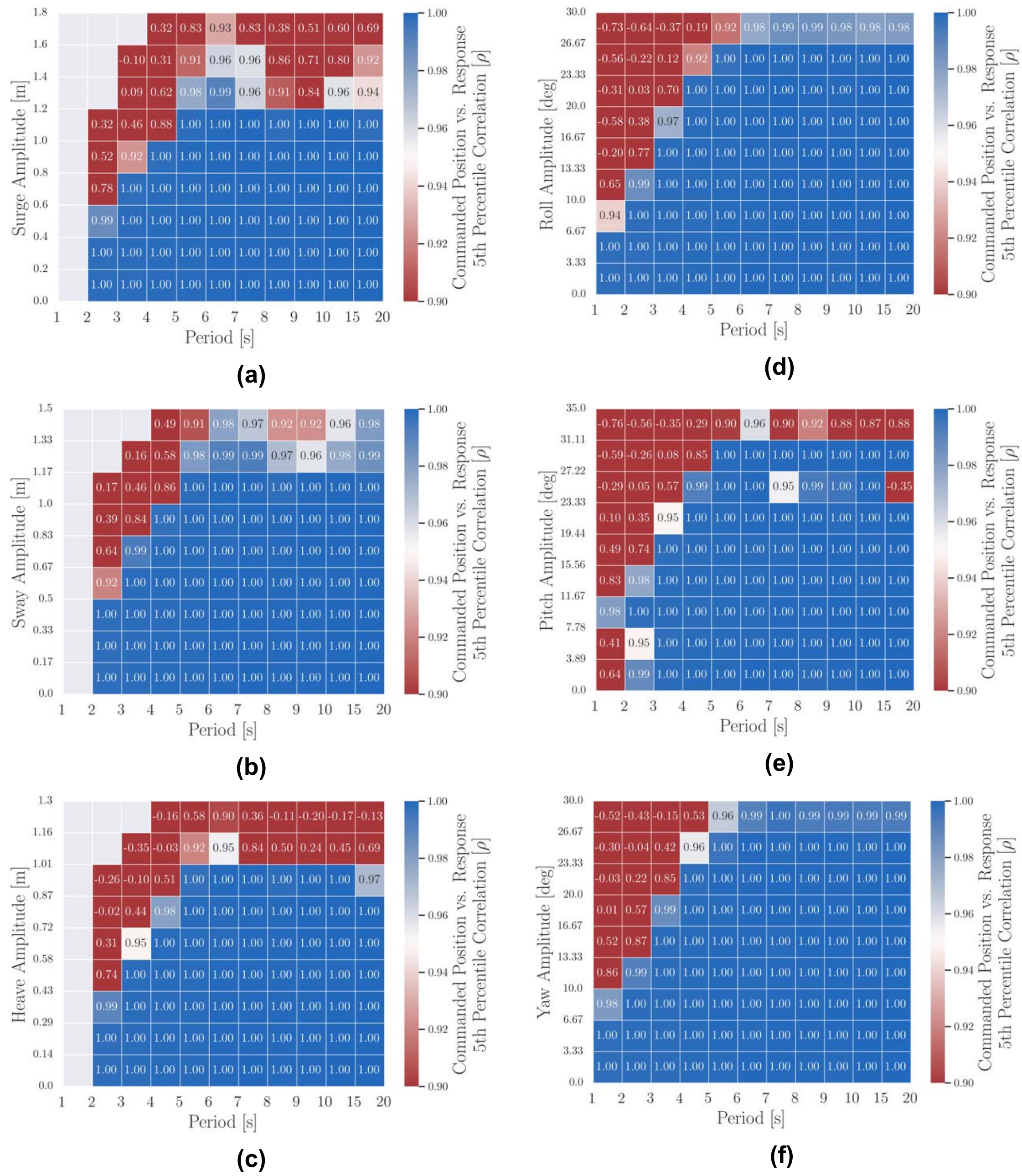
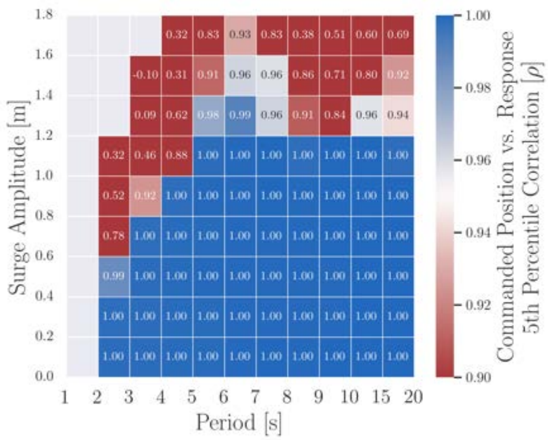


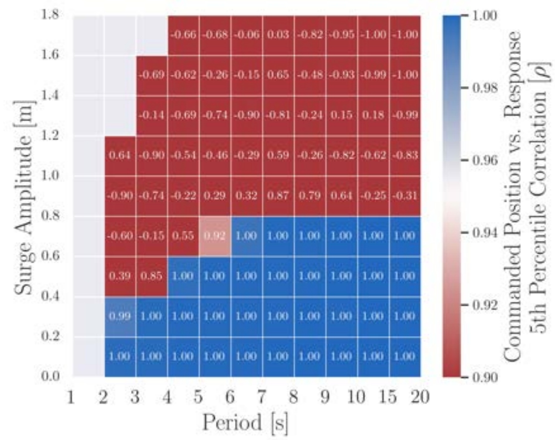
Figure 10. 1-DOF position correlation matrices between the command and the response of LAMP for different amplitude and period combinations for (a) surge, (b) sway, (c) heave, (d) roll, (e) pitch, and (f) yaw

To begin to understand multi-DOF limits, correlation matrices were created for 1-DOF (Figure 11a), 2-DOF (Figure 11b) and 3-DOF (Figure 11c) for surge movement only. These matrices were formed using data from TP 101 and TP 111 (1-DOF), TP 206 (2-DOF), and TP 306 (3-DOF). Comparing the three correlation matrices in Figure 11, it is clear that as LAMP moves in more DOF, LAMP's limits become greater. For example, as previously mentioned, LAMP will perform a 1-m, 6-s surge command perfectly when only commanded to move in surge, but if commanded to move in both surge and yaw (TP 206, Figure 11b), LAMP will poorly perform a 1-m, 6-s surge command. Although in both surge and yaw, LAMP will perfectly perform a 0.7-

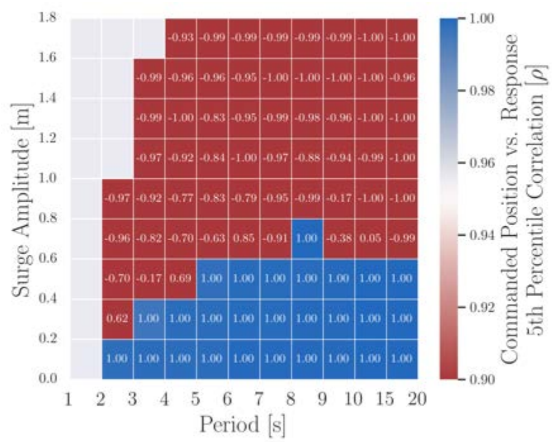
m, 6.5-s surge command, but if commanded to move in surge, sway, and heave (TP 306, Figure 11c), LAMP will poorly perform a 0.7-m, 6.5-s surge command. These data are useful for understanding LAMP's limits, but more data need to be collected and analyzed to provide a deeper understanding of multi-DOF limits. For example, how would Figure 11b change if instead of being derived from a surge, yaw test profile it was derived from a surge, heave profile or if surge and yaw were out of phase?



(a)



(b)



(c)

Figure 11. Surge position correlation matrices between the command and the response of LAMP for different amplitude and period combinations for (a) 1-DOF, (b) 2-DOF, (c) 3-DOF

9 Conclusions

This effort aimed to understand LAMP's amplitude and frequency limits for different applied payloads. Data from 16 different test profiles and multiple payloads were collected, and an inverse kinematics model was created. The inverse kinematics model was validated for relating the 6-DOF position (surge, sway, heave, roll, pitch, and yaw) to each of the six actuator positions to determine LAMP's physical position limitations.

LAMP's response to the test profiles was compared for three different test masses, and from this comparison, it was concluded that LAMP's PVA response is the same when under a payload of 0–1,047 kg. Other measurements, such as actuator motor current, vary with payload.

Using the command (input time series) and response (output time series) PVA datasets, position correlation matrices were computed to identify the level of correlation of input to output data. The correlation values were binned according to amplitude and period to describe LAMP's ability to successfully produce motion within the described range, which can be used to guide WEC testing on LAMP.

The team proposes further exploration of LAMP's capabilities using the emulator. The emulator predicts LAMP's response from a given PVA profile. After quantifying the relationship between LAMP's actual response and the emulator's outputs, LAMP motion data for all DOF could be used to better assess motion limitations prior to conducting physical experiments. Understanding LAMP's capabilities goes beyond PVA limitations to also include run time, which is hypothesized to be reliant on actuator servo temperature, and payload impact, including payloads with moving moments of inertia.

Lastly, with the addition of an EtherCAT-based IMU, it will become possible to verify the accuracy of the LAMP response data, which are fed back from the LAMP controller. By comparing data streams of PVA data from the LAMP controller with IMU data, measurement uncertainty can be reduced, thereby improving confidence in the LAMP dynamic model.

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Appendix A. TP 600 Position

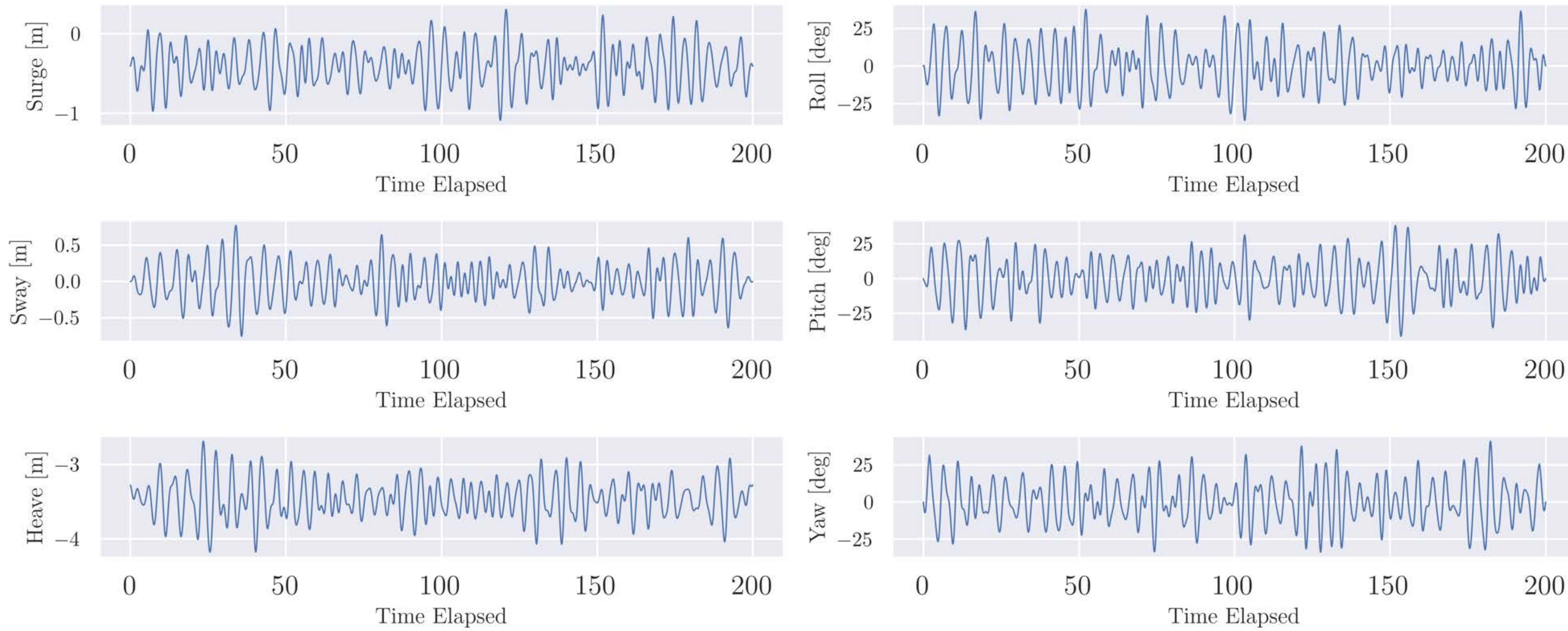

Figure A-1. TP 600 commanded position for each DOF

Appendix B. Inverse Kinematic Example Usage

```
import LAMPKinematics as LK
import matplotlib.pyplot as plt
import numpy as np
from scipy.spatial.transform import Rotation as R

# Example Usage
ActuatorSystem = LK.ActuatorSystem
ActuatorSystem.init_visualize()
ActuatorSystem.set_offsets(posOffset=[0, 0, 0], rotOffset=[0.0, 0.0, 0.0])
suc, len, pva = ActuatorSystem.check_actuators()

print("Resulting Actuator Lengths: ",len)
print("Actuators Within Limits? ", suc)

ActuatorSystem.visualize(500)
```

This code outputs the neutral position of the LAMP, which is displayed in Figure 4.

Translations can be applied in millimeters and rotations in radians to determine if the LAMP is able to achieve that position:

```
ActuatorSystem.set_offsets(posOffset=[500, 500, 250], rotOffset=[.20, .10,
0])
```

Figure B-1 shows the LAMP with translation and rotation applied, and the code returns a “True,” indicating that this pose is possible for LAMP.

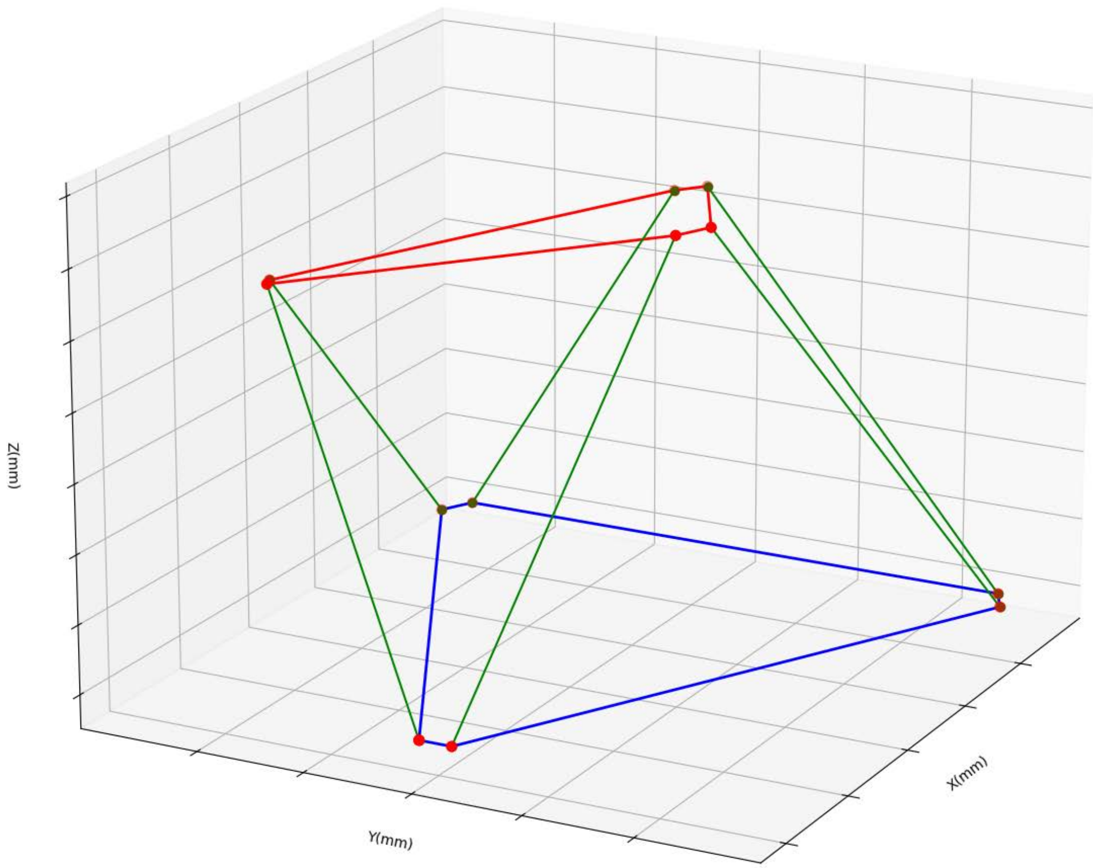

Figure B-1. LAMP with translation and rotation applied