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6 Degrees of Freedom Motion Simulation and Hexapod Driver using LabVIEW

The Requirements

The purpose of this project was to develop a computer model, build a user-friendly LabVIEW API, derive a robust NI hardware solution, and to design and fabricate a large hexapod motion table (Figure 1). This table reproduces large complex displacements and rotations with six degrees of freedom (surge, heave, sway, pitch, roll, yaw or 6DOF) for hours at a time. Added requirements are that all drive functions and sensor signals needed to be time synced to the atomic clock at NIST and streamed in real time in order to coordinate with related but separate data acquisition systems.

Background

High accuracy hexapods with large motions are rare and, when available, can be used in a multitude of studies. Such systems can be used to study the effect of ship motion on navigation and communication electronics, simulate loads on ship cargo to evaluate restraint systems that prevent cargo shifting, and to develop fast acting feedback algorithms that compensate for sea motions such as those used for LIDAR atmospheric measurement systems. The primary purpose of Hexapods is to be able to accurately reproduce varying sea states with realistic amplitudes and frequencies. Because of their unique abilities those platforms can also be used to reproduce specific triaxial earthquake motions and the effect they have on high speed GPS systems. In the past different designs have been made to accommodate payloads from a few hundred pounds to up to 2 tons. Lastly, fast acting and reliable safety routines with automatic shutdown protocols needed to be integrated in the software.

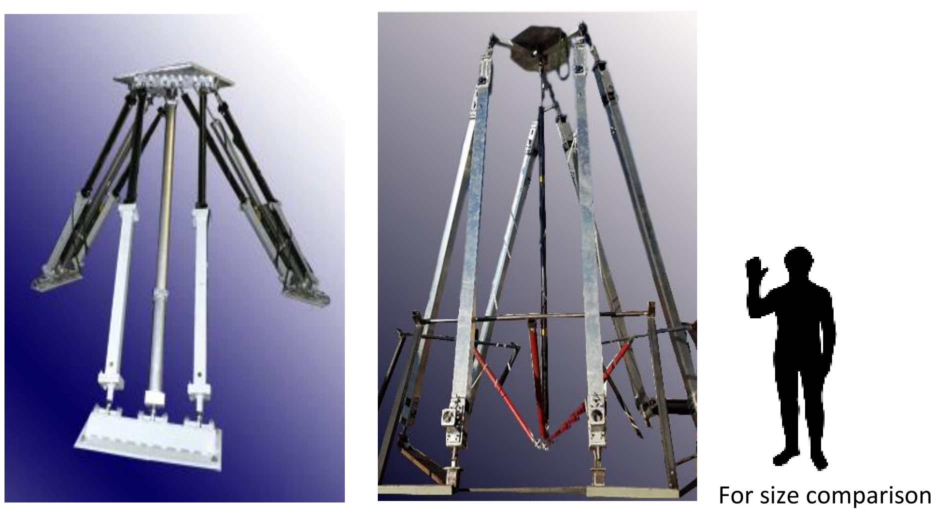


Figure 1) Full sized hexapod (hydraulic 2-ton payload left, electric 200lb payload right)

The Solutions

Using native and custom LabVIEW VI's for matrix and vector math, ANCO Engineers, Inc. (ANCO) produced a three-dimensional LabVIEW model to derive six independent actuator drive functions. These actuator drive functions were created using a non-linear transfer function acting on the desired surge/heave/sway/pitch/roll/yaw motions. The actuators were configured as a modified Stewart platform

(Figure 2) with three sets of parallel legs, angled slightly inward, connected to the single table top, with 120° separation. The height of this custom hexapod at full extension was 20 ft. The maximum vertical dynamic extension was ±30 in. The motion capability in surge and sway was ±15 in. Deflection in roll and pitch was ±50 Deg and yaw was ± 30 Deg. The table was approximately 24 x24 in. Table motions were produced using servo motor, belt drive, electric actuators with stroke capability of ±45 in. The frequency range of operation of this hexapod was 0-1½ Hz.

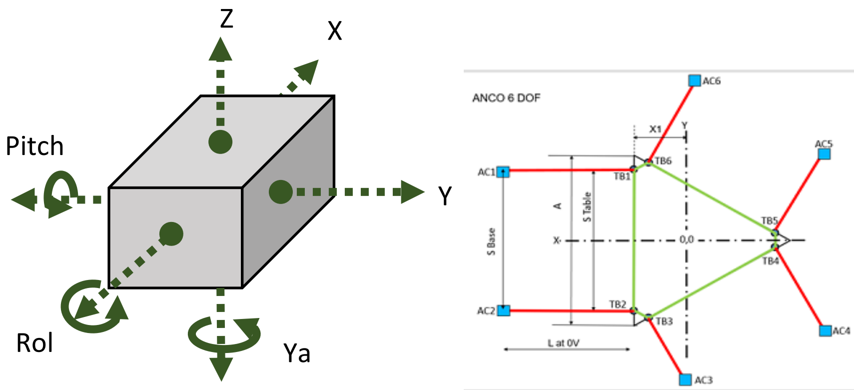


Figure 2) Six degrees of freedoms with modified Steward platform geometric constants

The Challenges

Given the hexapod's great height this table was assembled in the parking lot of ANCO's laboratory. The design of the actuators had to be optimized for weight, speed, displacement, and payload specifications. The allowable payload was up to 60 lbs. The electric actuator force rating was up to 200 lbs. Continuous tests on the hexapod sometimes exceeded several hours in duration. Therefore, LabVIEW code needed to be stable and developed to handle real time processing of complex rotational and translational six degrees of freedom motions. Due to the test payload's sensitivities to high frequency vibrations (>5 Hz) all actuator motions had to be executed with extreme smoothness. Given the length of the actuators (about 16 ft at center position), it was critical to eliminate any high frequency vibrations that could incite transverse resonances of the actuators. There was also a requirement to verify achieved table motion fidelities for all six degrees of table motion. To accomplish this, a drive function required a timestep of at least 100 samples per second. Further smoothing needed to be added using cubic spline computations for each drive function. Using creative programming, CPU loads were kept below 15%. Additional challenges included the design and implementation of a very fast safety monitoring protocol. Systems with such large aspect ratios can become kinematically unstable in a matter of seconds if even small discrepancies in displacement or velocity response are present. A total of 32 analog data channels were monitored and required to be time locked with all drive functions and synchronized to the NIST atomic clock. Data was streamed in real time to a local solid-state storage device, often producing data files of the order of gigabytes.

Using LabVIEW for Complex Simulations

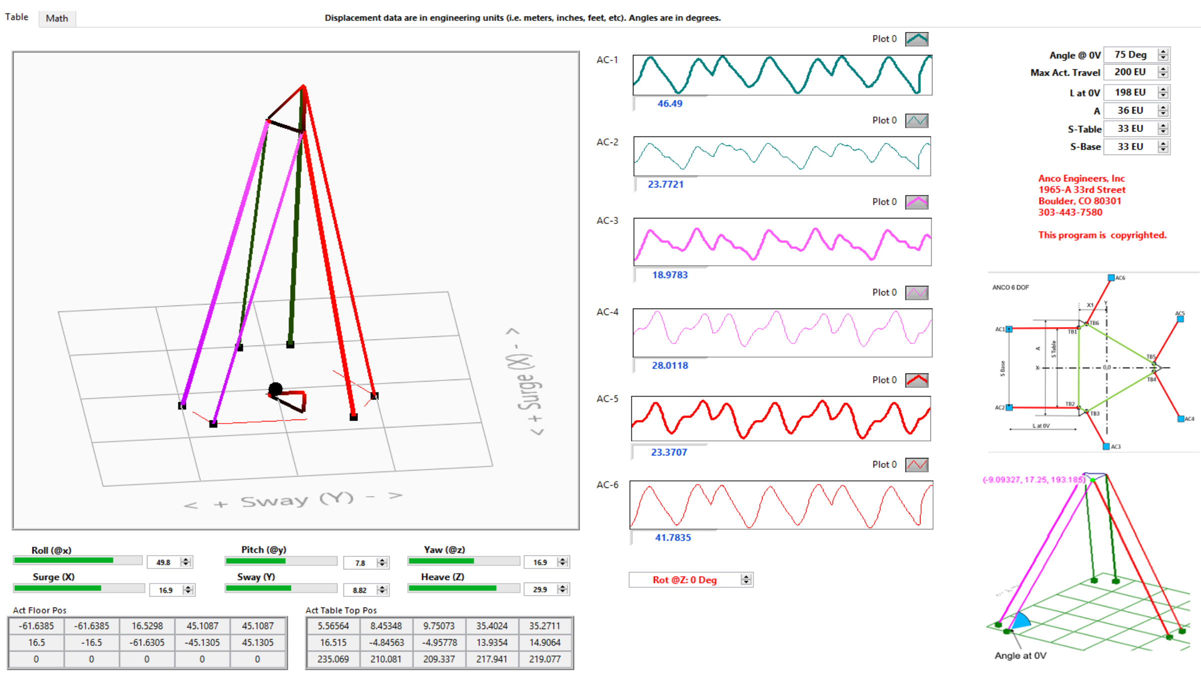
A custom LabVIEW API (Animation 1) was developed that simulated all mathematically possible motions for surge, sway, heave, roll, pitch, and yaw. For example, the mathematical basis for rotating 3D bodies is given as:

$$\text{Rot}(X, \alpha) \quad \begin{vmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & -\sin(\alpha) \\ 0 & \sin(\alpha) & \cos(\alpha) \end{vmatrix}$$

$$\text{Rot}(Y, \alpha) \quad \begin{vmatrix} \cos(\alpha) & 0 & \sin(\alpha) \\ 0 & 1 & 0 \\ -\sin(\alpha) & 0 & \cos(\alpha) \end{vmatrix}$$

$$\text{Rot}(Z, \alpha) \quad \begin{vmatrix} \cos(\alpha) & -\sin(\alpha) & 0 \\ \sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 1 \end{vmatrix}$$

LabVIEW native VI's and 3D graphs elements were used to help with simulating and investigating motions and kinematic instabilities in the hexapod.



Animation 1. Simulation of Hexapod motions using LabVIEW ActiveX for visualization

https://youtu.be/FIncYRi1NOk

Using LabVIEW API and National Instruments PXI Hardware

During software development and table check-out it quickly became clear that smooth drive functions were needed to avoid transverse excitation of the long, flexible actuators. This smoothing was enhanced by using "S" ramps. This was particularly useful when sudden transitions, such as E-stops, were demanded. The use of a custom developed cubic spline between data points allowed smooth operations in almost all conditions. Hence, it was possible to execute very complex geometric static and dynamic states as can be seen in the video below:

https://youtu.be/fAT9qLeDKCw

A user-friendly LabVIEW program (Figure 3) was written that allowed the input, pre/post processing of drive functions, and test items sensor data recording. The program is designed to handle all interfaces with a PXI controller which was chosen as a reliable platform to drive the hexapod and its safety features. For this a NI-PXI-1036 PXI chassis populated with a NI-PXI-8820 controller, a PXI-6733 output, and a PXI-6284 input card is the preferred hardware architecture. Analogue sensor signals were passed through an anti-aliasing filter and fed through a series of NI-BNC 2090A panels. Using this configuration, most motions could be repeated with 0.1 in. accuracy. Additional encoder feedback signals showed overall drive fidelities of nearly 5%.

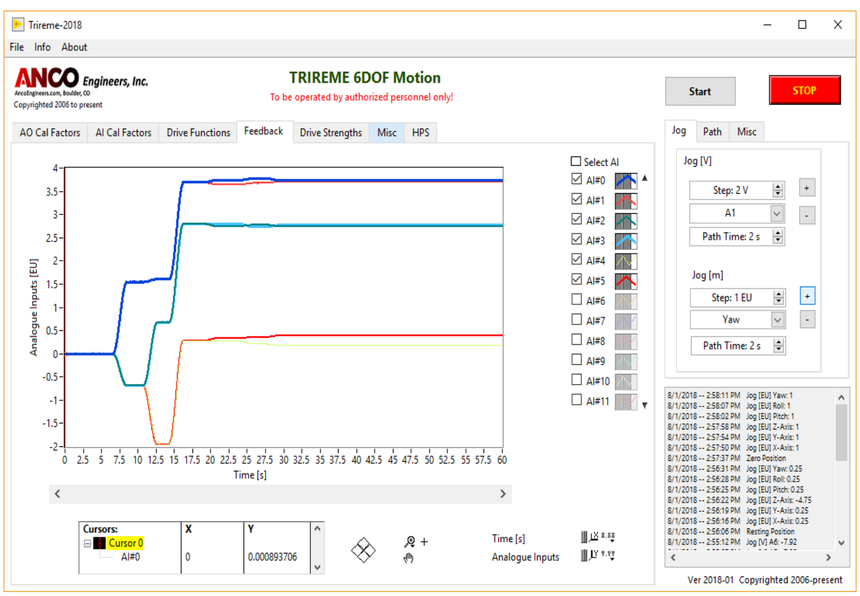
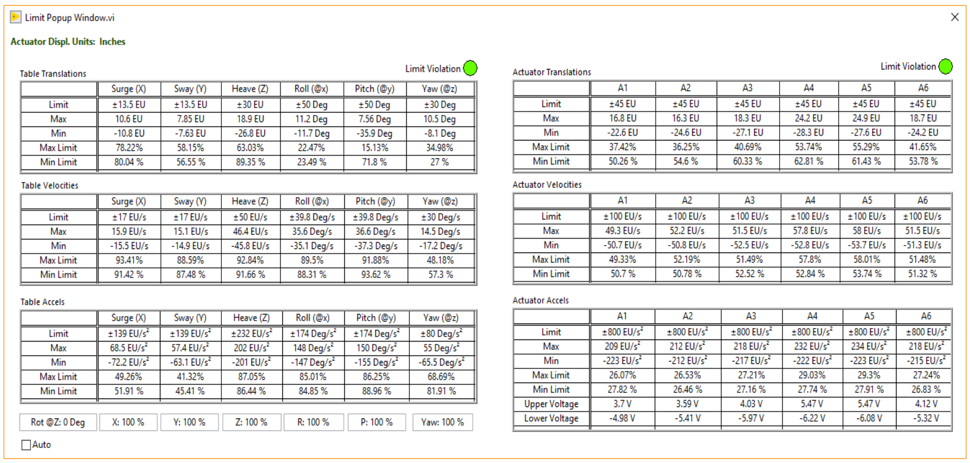


Figure 3) User Interface of the Hexapod Driver called Trireme

For such a large, expensive, and critical system, including its payload, safety is paramount. A mechanical hardware failure can put such a complex system into a potentially dangerous knuckle position in less than five seconds. Such events often require extensive external devices and manual, post event correction for recovery. For that purpose, several interlocks and monitors on the displacement encoder feedback signals were implemented in real time using the PXI-6733 card. With a 10-millisecond reaction time, fast and real time shut down sequences could interrupt all motions immediately and combat such undesirable scenarios. Furthermore, all drive functions are extensively examined/interrogated to ensure a successful test prior to execution (Figure 4). That is, one does not want the requested motion signals to exceed the allowable and safe operating range of the hexapod.



Limit Popup Window.vi

Actuator Displ. Units: Inches

Table Translations — Limit Violation

	Surge (X)	Sway (Y)	Heave (Z)	Roll (@x)	Pitch (@y)	Yaw (@z)
Limit	±13.5 EU	±13.5 EU	±30 EU	±50 Deg	±50 Deg	±30 Deg
Max	10.6 EU	7.85 EU	18.9 EU	11.2 Deg	7.56 Deg	10.5 Deg
Min	-10.8 EU	-7.63 EU	-26.8 EU	-11.7 Deg	-35.9 Deg	-8.1 Deg
Max Limit	78.22%	58.15%	63.03%	22.47%	15.13%	34.98%
Min Limit	80.04 %	56.55 %	89.35 %	23.49 %	71.8 %	27 %

Table Velocities

	Surge (X)	Sway (Y)	Heave (Z)	Roll (@x)	Pitch (@y)	Yaw (@z)
Limit	±17 EU/s	±17 EU/s	±50 EU/s	±39.8 Deg/s	±39.8 Deg/s	±30 Deg/s
Max	15.9 EU/s	15.1 EU/s	46.4 EU/s	35.6 Deg/s	36.6 Deg/s	14.5 Deg/s
Min	-15.5 EU/s	-14.9 EU/s	-45.8 EU/s	-35.1 Deg/s	-37.3 Deg/s	-17.2 Deg/s
Max Limit	93.41%	88.59%	92.84%	89.5%	91.88%	48.18%
Min Limit	91.42 %	87.48 %	91.66 %	88.31 %	93.62 %	57.3 %

Table Accels

	Surge (X)	Sway (Y)	Heave (Z)	Roll (@x)	Pitch (@y)	Yaw (@z)
Limit	±139 EU/s^2	±139 EU/s^2	±232 EU/s^2	±174 Deg/s^2	±174 Deg/s^2	±80 Deg/s^2
Max	68.5 EU/s^2	57.4 EU/s^2	202 EU/s^2	148 Deg/s^2	150 Deg/s^2	55 Deg/s^2
Min	-72.2 EU/s^2	-63.1 EU/s^2	-201 EU/s^2	-147 Deg/s^2	-155 Deg/s^2	-65.5 Deg/s^2
Max Limit	49.26%	41.32%	87.05%	85.01%	86.25%	68.69%
Min Limit	51.91 %	45.41 %	86.44 %	84.85 %	88.96 %	81.91 %

Rot @Z: 0 Deg | X: 100 % | Y: 100 % | Z: 100 % | R: 100 % | P: 100 % | Yaw: 100 %

Auto

Actuator Translations — Limit Violation

	A1	A2	A3	A4	A5	A6
Limit	±45 EU	±45 EU	±45 EU	±45 EU	±45 EU	±45 EU
Max	16.8 EU	16.3 EU	18.3 EU	24.2 EU	24.9 EU	18.7 EU
Min	-22.6 EU	-24.6 EU	-27.1 EU	-28.3 EU	-27.6 EU	-24.2 EU
Max Limit	37.42%	36.25%	40.69%	53.74%	55.29%	41.65%
Min Limit	50.26 %	54.6 %	60.33 %	62.81 %	61.43 %	53.78 %

Actuator Velocities

	A1	A2	A3	A4	A5	A6
Limit	±100 EU/s	±100 EU/s	±100 EU/s	±100 EU/s	±100 EU/s	±100 EU/s
Max	49.3 EU/s	52.2 EU/s	51.5 EU/s	57.8 EU/s	58 EU/s	51.5 EU/s
Min	-50.7 EU/s	-50.8 EU/s	-52.5 EU/s	-52.8 EU/s	-53.7 EU/s	-51.3 EU/s
Max Limit	49.33%	52.19%	51.49%	57.8%	58.01%	51.48%
Min Limit	50.7 %	50.78 %	52.52 %	52.84 %	53.74 %	51.32 %

Actuator Accels

	A1	A2	A3	A4	A5	A6
Limit	±800 EU/s^2	±800 EU/s^2	±800 EU/s^2	±800 EU/s^2	±800 EU/s^2	±800 EU/s^2
Max	209 EU/s^2	212 EU/s^2	218 EU/s^2	232 EU/s^2	234 EU/s^2	218 EU/s^2
Min	-223 EU/s^2	-212 EU/s^2	-217 EU/s^2	-222 EU/s^2	-223 EU/s^2	-215 EU/s^2
Max Limit	26.07%	26.53%	27.21%	29.03%	29.3%	27.24%
Min Limit	27.82 %	26.46 %	27.16 %	27.74 %	27.91 %	26.83 %
Upper Voltage	3.7 V	3.59 V	4.03 V	5.47 V	5.47 V	4.12 V
Lower Voltage	-4.98 V	-5.41 V	-5.97 V	-6.22 V	-6.08 V	-5.32 V

Figure 4) Drive function interrogation table

Benefits of using LabVIEW and NI Hardware

ANCO has a long history of developing code in LabVIEW and is very familiar with NI-hardware. With a clear mathematical approach in mind, building a fast acting and responsive simulation in LabVIEW turned out to be very effective. The use of 3D graph elements allowed ANCO to show clients complex motions and to interrogate and avoid drive functions that may or may not be unrealizable. LabVIEW helped streamline the entire project from project conception, through the various design phases, to the successful execution of tests.

LabVIEW's native mathematical functions for complex matrix and vector operations were extremely effective in reducing programing and computation time. ANCO could build simulation API's in a matter of hours, and with minute to minute code modifications made the client interaction cycle significantly more reactive and fluid. The smooth integration of DAQmx drivers ensured a flawless and accurate operation of the PXI system and all attached hardware.

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