

Sarnicola Simulation Systems, Inc.

APPLICATION NOTES

for the

Hexad 3000H

Six Degree-of-Freedom Motion Platform

Sarnicola Simulation Systems, Inc.
PO Box 480
970 Conklin Rd.
Conklin, NY 13748 USA
(607)724-4021

Rev Draft.4x 9 April 2002
(preliminary based on SMMT draft 4a)

1.0 INTRODUCTION

The Hexad 3000H is a hydraulically actuated six-degree-of-freedom (6-DoF) motion platform capable of carrying a 3000 pound load. It is suitable for a wide variety of equipment test and simulation applications. The platform itself uses the classic “hexapod” or “Stewart” configuration of six hydraulic legs to provide controlled motion in six degrees of freedom.

The platform is controlled by a standard PC-type computer running Microsoft Windows 98 and equipped with custom control software and a USB enabled outboard controller in a separate cabinet. The software provides a means of manual control of the platform as well as the ability to store and replay motion profiles generated from user-configurable sum-of-sines algorithms. The controller is also equipped with a data acquisition unit (ADC) that permits simultaneous logging of actual and commanded platform instantaneous position. The ADC system also allows the software to detect and respond to excessive velocities and accelerations.

2.0 DESCRIPTION OF THE PLATFORM

The Hexad 3000H is a standard implementation of the Sarnicola Hexad motion platform. It uses six hydraulic actuators arranged in a hexapod configuration to achieve controlled motion in all six motional degrees of freedom. The platform (shown with a rectangular deck frame and triangular base frame) is shown in Figure 2-1. The base of the platform may be built to customer specifications, but in its simplest form is a triangular steel frame with two joints at each vertex. Similarly, the moving deck may also be constructed to customer requirements, but in its simplest form comprises a triangular frame with two joints at each vertex, supported above the base frame by hydraulic actuators, and oriented oppositely to the base frame. The two actuators, or legs, connected to the two joints at each base vertex each connect to the adjacent two vertices on the moving frame. By separately controlling the six leg extensions, the platform can produce motion in any combination of the six spatial axes: surge, sway, heave, yaw, pitch, and roll.

The hydraulic cylinders are controlled by high bandwidth servo valves. Cylinder design has been optimized for smooth operation, particularly at low extension rates. The piston seals remain hydrostatic down to zero extension rate, thus minimizing the "turn-around bump" effect.

The system is powered by a hydraulic pumping unit (HPU) sized to meet the customer's requirements. A separate manual is provided for the HPU.

Leg position is controlled by a proprietary servo controller housed in a separate cabinet and connected to the control computer and the platform by cables. Leg extension is read by a linear potentiometer integrated into each leg assembly. Communication with the user's host computer is by way of a USB interface. The motion controller integrates with the computer via USB, and with the platform valves via a single DB-25 type cable. The controller also includes sixteen bits of TTL compatible input and output, and an Emergency Stop system.

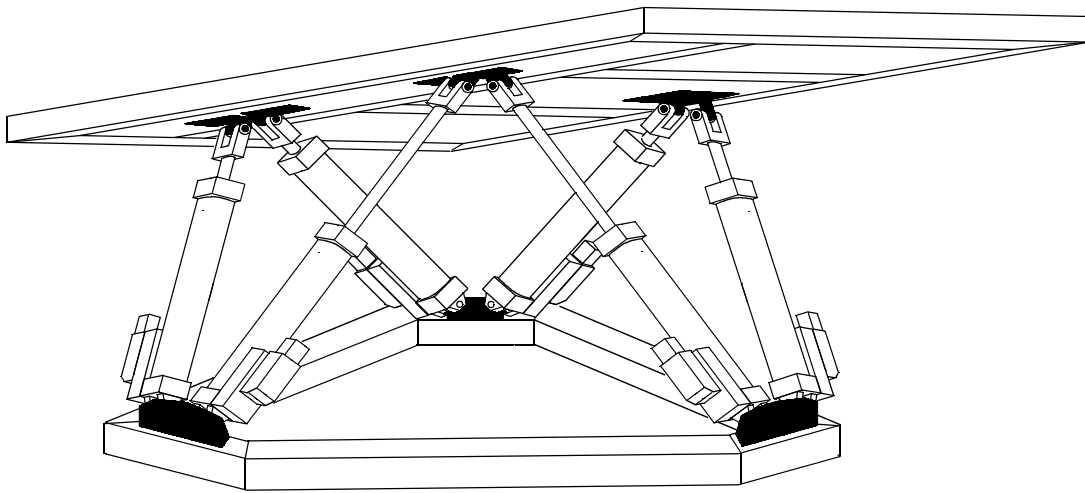


Figure 1-1. The Sarnicola Hexad-3000 Six-Degree-of-Freedom Motion Platform.

3.0 CONTROL SOFTWARE

The Hexad 200H is controlled by a PC-type computer running Microsoft Windows 98. The control software package allows for manual control of the platform for test, alignment, and demonstration purposes, as well as the ability to create, edit, and execute stored motion profiles. In addition the program provides the ability to log commanded and actual leg position data.

3.1 Installation and Operation

The initial software package comprises fourteen items including all executables and profile data files. In addition, the user may generate up to 9999 saved data files. The components are described in Table 3-1. All components reside in a single user-created directory. (The control computer was shipped with all components in c:\SSS\ with a shortcut to HexTest.exe on the Desktop.)

Installation is by way of the familiar setup.exe from a distribution CD. On initial installation, when the USB cable is first plugged in, Windows will detect the USB hardware and the New Hardware Wizard will ask for the associated system software. The necessary files are in the root directory of the distribution disk.

Operation of the software should be straightforward. Although no help system has been provided, there are ToolTips associated with each command button and data item to remind the user of conventions and definitions.

The program operates in three main modes:

1. **Manual Mode.** In manual mode, the user controls the state of the platform by manually entering

the desired state, either with the scroll buttons on each state vector and configuration parameter, or by typing the parameters in directly. *Note that the new parameter does not take effect until the Enter key is pressed.* If the focus changes without pressing Enter, the previous parameter value is retained. Note also that changes take effect slowly, in order to prevent dangerously large accelerations of the platform. Double-clicking the State Vector frame opens a diagnostic window.

2. Profile Mode. Selecting a profile and pressing the Run button places the platform in Profile Mode, giving control to the selected profile. Return to Manual Mode by pressing Stop. When running a custom profile, the program automatically logs up to 60 minutes of data. After returning to Manual Mode the Data Logger frame is active, allowing the user to enter comments and decide whether or not to save the logged data. The data file name is incremented automatically and saved with the time and date stamps shown.

3. Edit Mode. When the Edit button is pressed, a window opens to allow editing of the selected profile. If one of the standard profiles is selected, the only adjustable parameters are Amplitude, Form Frequency and Iteration Rate. The standard profiles are simply sinusoidal oscillations on the axis selected. Amplitude is percent of maximum for that axis; form frequency is the frequency of oscillation; and iteration rate is the update rate of the state vector. If one of the custom profiles is selected when the Edit button is pressed, the a window opens which allows the user to configure a sum-of-sines profile using all six axes and with a prescribed offset and Earth orientation.

Table 3-1. HexTest and HexView Software Components.

| Item | Description |
|--------------|-------------------------------------|
| HexTest.exe | Primary Application |
| HexView.exe | Data Viewer accessory |
| PlatData.txt | Initialization File |
| CustomA.txt | Parameter file for custom profile A |
| CustomB.txt | Parameter file for custom profile B |
| CustomC.txt | Parameter file for custom profile C |
| CustomD.txt | Parameter file for custom profile D |
| CustomE.txt | Parameter file for custom profile E |
| CustomF.txt | Parameter file for custom profile F |
| InpOut32.dll | I/O support library |
| Hexad.dll | Geometrical computations library |
| tmwin32.dll | USB communications library |
| DataLog.txt | Log file of all data runs |
| Datannnn | Raw data file number <i>nnnn</i> |

3.1.1 Constructing Custom Profiles

A custom profile is a profile in the form of a separate sum-of-sines function for each axis of the platform. The profile function for each axis may have up to 30 individual terms, with the amplitude a_n , frequency f_n , and phase ϕ_n independently adjustable. Specifically, the functional form is

$$g(t) = \sum_{n=1}^{30} a_n \sin(2\pi f_n t + \phi_n)$$

A custom profile also includes a user-specified vector setting the position of the center of rotation of the payload relative to the deck joint plane, and a set of parameters specifying the orientation of the Earth coordinate system. Definitions of the coordinate systems are given in section 3.21. The offset vector is given by its three coordinates CRX, CRY, and CRZ. These are the coordinates (in inches) of the desired center of rotation of the payload relative to the deck frame--a coordinate system fixed in the deck. The Earth orientation is given by the three parameters Azimuth, Elevation, and Tilt. These are the Euler angles for the rotation of the Earth Frame relative to the Base Frame.

To enter the profile editor, first select the desired profile by clicking its option button, then click the Edit button. The window which appears allows editing of all 90 parameters associated with one axis of motion. To select the axis to be edited, click the associated option button. The offset and Earth orientation parameters may be edited from any selected axis and are common to all six axes. The ‘Harmonic Frequency’ check box enables a feature that automatically sets the frequencies to be harmonics of f_j , a feature useful in synthesizing periodic waveforms.

Note that new data will not be accepted into a field until the Enter key is pressed. Clicking Quit will abandon all editing on all axes without saving. Clicking Save will save current edits, but does not revert to manual. To exit with saving, click Save, then Quit. The Clear button simply sets all data to zero in the selected axis only.

Caution! The Hexad 3000H platform is quite capable of generating extreme accelerations that could damage equipment and injure personnel. A sum-of-sines profile containing combinations of high frequencies and high amplitudes can easily exceed the force limits of equipment and mountings. A ‘high frequency’ in this context could be as low as 1 Hz. Note also that thirty sine waves of small amplitude may add to a large displacement or acceleration when their phases align. *Always test your profile thoroughly, with the platform de-energized (pump turned off), before attempting a live run.*

3.1.2 Testing Profiles

Whenever a profile is edited, the program flags the new version as untested. The first time the profile is run, the program assumes that the operator intends to be testing the profile, and therefore does not send motion commands to the physical platform. All other features, including the view window and the data logger are fully functional. By observing the platform in the view window, the

operator can study the behavior of the profile. The operator may also save the logged data from the test run and study it using more analytical tools.

Good judgement will be necessary to devise suitable tests that insure that a profile is both operationally valid and safe for the system. A simple profile may require only verification; a more complex profile may require extensive analysis.

3.1.3 Using the Data Logger

Each time a custom profile is run, the program automatically begins logging data for that run. When the profile is stopped, the data is stored in memory but not saved. At this time, the user has the opportunity to either ignore the data or save it by pressing the **Save** button in the Data Logger frame. Before saving, the user may enter a short identifying comment in the text box provided for that purpose. The program saves recorded data to a file with the name shown in the Data Logger frame, and makes an entry in the file DataLog.txt. The file DataLog.txt is an ASCII file containing a log of all the saved data runs. Each entry includes the data file name, time and date stamps, and the comments entered when the data was saved. If a new profile is run without first saving, all data from the previous (unsaved) run is lost.

The saved data is in the form of the commanded leg extension DAC number and the recorded leg extension ADC count. Nominally, these two integers are equivalent, and at steady state they should be equal to within instrumental errors and offsets. The DAC is a twelve-bit device, so its range is from 0 to 4,095 counts. The ADC is actually an eight-bit device, but the software scales its output to match twelve-bit resolution. The home position is defined as 2048 counts. Full retraction is a small number; full extension is a large number. The exact values depend upon the precise configuration of the platform.

Table 3-2. Format of data log files.

| | | |
|-------------------------------|--------|-------------------------------------|
| 09Apr99 | <----- | Date Stamp |
| 1357 | <----- | Time Stamp |
| 70 | <----- | Number of data points |
| 3.5 | <----- | Duration (sec) |
| Evaluation and test | <----- | Comment text |
| .05 | <----- | Time of first sample (sec) |
| 1720 1706 1692 1724 1713 1734 | <--- | Commanded leg extensions (legs 1-6) |
| 1727 1718 1701 1729 1720 1740 | <--- | Measured leg extensions |
| .1 | <----- | Time of second sample |
| 1725 1697 1670 1733 1711 1753 | | |
| 1733 1705 1678 1740 1719 1748 | | |
| etc. | | |

The data files (Data~~nnnn~~.txt) are ASCII files laid out in a form suitable for importation into any data analysis or spreadsheet program. The data logger can store up to 108,000 data points (each a 6-component vector) for each custom profile run. This capacity is sufficient to record one hour of data at an iteration rate of 30 Hz. The data format is shown in Table 3-2.

Since the data files are in ASCII format, they may be viewed (and edited) directly using any word processing program. The WordPad program provided with Windows 98 is suitable for this purpose. In order to provide a convenient method of viewing the data files in graphical form, a data file viewing program called HexView is provided as part of the software distribution. Use of HexView is straightforward.

3.1.4 Safety Features

The HPU and the control software include several safety features intended to reduce the risk of damage to equipment due to excessive accelerations. Despite these features it is still important that the user exercise good judgement in the use of the platform and vigilance against failures and anomalous system conditions. Even in normal operation, the platform can generate accelerations that may be capable of damaging mounted equipment.

1. Emergency Stop. The Motion Controller includes a two-terminal interface for an E-Stop signal. The interface is a 4N25 opto-isolator with a 510 ohm resistor in series with the LED input. The E-Stop system must supply a 3-10 volt signal capable of 10 mA. A TTL-level signal is acceptable.

The connector for the E-Stop signal is a DB-25F located at the center of the back panel of the Motion Controller. Pin 13 is plus and pin 25 is minus. (The other pins on this connector are used for DI.)

The E-Stop signal is active low, that is, it is present during normal operation and goes low to indicate an E-Stop condition.

On receipt of an E-Stop (low), the Motion Controller will ignore commands from the Motion Computer and settle the platform under hardware control, ignoring further signals from the computer.

The Motion Controller accepts digital signals from the Motion Computer via USB. These signals are used to control a DAC which generates analog command voltages for the six servo controllers. Since there is only one DAC, its output is distributed to the six controllers by way of a six-channel multiplexer with a sample-and-hold on each channel. The E-Stop signal is ANDed with a computer control signal to the Inhibit line on the multiplexer so that when the E-Stop signal drops, the multiplexer is inhibited, effectively cutting off signals from the computer and leaving the sample-and-hold circuits connected to a high impedance. As the hold capacitors droop, the controllers are commanded to settle the platform legs.

In most applications, an E-Stop will be accompanied by shut down of the HPU, and a consequent loss of operating pressure. As pressure drops and the hold capacitors droop, the leg control valves will open allowing smooth settling of the platform in about 15 seconds. If the HPU does not shut

down, the settling will proceed more slowly, but will still complete in under a minute.

2. *HPU Interlock.* [Not implemented in the standard configuration.] The Emergency Stop circuit includes a solid state relay under the control of the control computer. The control terminals of the relay are activated by digital control signal that requires receipt of a 7-bit digital code from the control computer in order to close the relay and enable the HPU. Thus the computer can enable and disable the HPU, and effect an Emergency Stop.

The interlock circuitry also sends a digital signal back to the controller to indicate the state of the HPU. If this signal goes low, indicating Emergency Stop, the controller enters its Emergency Stop mode.

The HPU Interlock relay and associated circuitry are housed in the control room Emergency Stop switch box.

3. *Software Emergency Stop.* [Not implemented in the standard configuration.] The software can control the enabling of the HPU by way of the HPU Interlock system. The control software display includes a green button labeled HPUEnable. When this button is clicked it enables the HPU Interlock by transmitting the required code. The button then changes color to red and changes its label to EStop. Clicking this button initiates an Emergency Stop by disabling the HPU Interlock. The button then reverts to the green HPUEnable label.

Deliberately quitting the control program (clicking on Quit) will induce an Emergency Stop. Complete failure of the computer (e.g., power loss) will also induce an Emergency Stop.

4. *Profile Test Detection.* When the user creates or edits a custom profile, the software flags the profile as untested. The first time the user attempts to run this profile, the software displays a warning and then permits the profile to run without sending commands to the platform. See section 3.2.1 above.

5. *Excessive Acceleration Detection.* [Not currently implemented.] The control computer is equipped with an analog-to-digital converter card (ADC) intended primarily to allow logging of actual platform motion. The control software monitors these inputs, continuously computing the velocity and acceleration of each leg. If a velocity or acceleration exceeds a preset maximum, the system initiates an Emergency Stop and displays a message describing the event. [E-Stop initiation not included in the standard configuration.] The acceleration and velocity trip point values are included in the initialization file (PlatData.txt) and may not be changed from within the control program or while the program is running. See section 3.1.5 for instructions on editing setpoints.

3.1.5 The Initialization File

Initialization parameters, platform geometrical constants, and controller electrical parameters reside in the initialization file PlatData.txt. The contents of the supplied version of the file are shown in Table 3-3. Most of the items in the initialization file should never be changed by the user. Nevertheless, editing is possible. The file is in ASCII format and may be edited using any word

processing utility such as NotePad or WordPad. When editing PlatData.txt, take care to maintain the format exactly. Do not insert punctuation into the headings. Be sure to delimit data entries with commas. The only entries that should ever be changed are those for PosnMax, AttMax, OffsetMax, OrientMax, and VelMax AccelMax. Notations in the table indicate the meaning of each of these entries.

Table 3-3. Contents of the Initialization File PlatData.txt.

| | |
|----------------------------------|--|
| Zsettled and DZ | |
| -24.63, 28.36 | |
| PosnMax <----- | <i>Maximum values of Surge (X), Sway (Y),</i> |
| 17, 18, 14.2 | <i>And Heave (Y) in inches</i> |
| AttMax <----- | <i>Maximum values of Yaw (), Pitch (),</i> |
| 45, 30, 32 | <i>And Roll () in degrees</i> |
| OffsetMax <----- | <i>Maximum values of Earth Frame Origin Offset</i> |
| 5, 5, 5 | <i>CRX, CRY, CRZ in inches</i> |
| OrientMax <----- | <i>Maximum values of Earth Frame Orientation</i> |
| 180, 20, 20 | <i>Azimuth, Elevation, Tilt in degrees</i> |
| VelMax AccelMax <----- | <i>Setpoints for Excessive Velocity and Acceleration</i> |
| 60, 1000 | <i>Detection. VelMax in in/sec; AccelMax in in/sec²</i> |
| Rmin StrokeLen StopTubeLen RHome | |
| 36.37, 23, 0, 47.15 | |
| BridgeRange BridgeGain | |
| 10.00, 1.96 | |
| PotLen, PotRes, PadRes (total) | |
| 24.0, 5000, 19000 | |
| Base Points | |
| 16.939, 26.500, 38.82 | |
| 14.479, 27.920, 38.82 | |
| -31.419, 1.42, 38.82 | |
| -31.419, -1.42, 38.82 | |
| 14.479, -27.920, 38.82 | |
| 16.939, -26.500, 38.82 | |
| Deck Points | |
| 26.367, 1.42, 0 | |
| -11.954, 23.545, 0 | |
| -14.414, 22.125, 0 | |
| -14.414, -22.125, 0 | |
| -11.954, -23.545, 0 | |
| 26.367, -1.42, 0 | |

3.2 Computational Details

The basic computational problem for the control software is to transform a commanded state vector in the form of the desired position and attitude of the simulation payload into the form of the extensions of the six legs. Once the leg extensions are known, it is a straightforward matter of scaling to convert to leg length control voltages, and to command the DAC to produce those voltages. The controller box controls the hydraulics to extend the legs to the desired lengths.

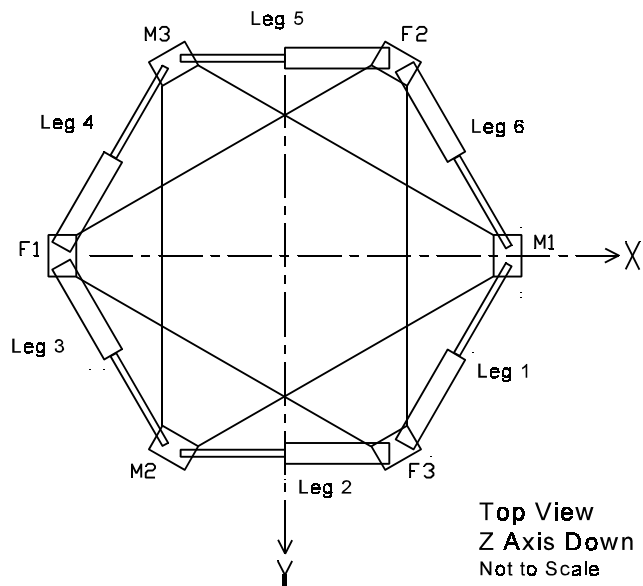


Figure 3-1. Leg Layout and Nominal Coordinate System Orientation. Legs are numbered clockwise from the nominal x-axis. M1-M3 are the moving leg endpoints in some convenient (deck) joints; F1-F3 are the fixed (base) joints.

3.2.1 Coordinate Systems

The Hexad leg extension vector computations require the use of four distinct coordinate systems.

1. The Deck Frame is a coordinate system fixed in the physical deck structure of the motion platform and moving with it. Figure 3-1 shows a schematic plan view of the platform illustrating the leg numbering system and the nominal orientation of the coordinate systems. The origin is at the center of the circle on which the upper leg joints lie. The x-axis lies in the plane of the upper joints and proceeds out the “front” of the deck, towards a point midway between the upper ends of legs 1 and 6. The y-axis lies in the same plane and proceeds out the “right” side of the platform, forward of the tops of legs 2 and 3. The z-axis points down to make the system right handed. In the Deck Frame, the coordinates of the six upper joints of the legs are constants (and the z-coordinates are all zero).

2. The Base Frame is a coordinate system fixed in the physical base structure of the motion platform, and therefore stationary. The Base Frame is coincident with the Deck Frame when the platform is homed. Thus the z-coordinates of all the lower joints (the base points) are all equal constants, with positive value equal to the homed height of the platform (+38.82 inch).

3. The Moving Frame is a coordinate system fixed in the simulation payload. The origin of the Moving Frame is offset from the origin of the Deck Frame by a vector called the *Offset*. The offset is specified by the user as the coordinates of the Center of Rotation, XCR, YCR, and ZCR in the

Deck Frame. The Moving Frame is parallel to the Earth Frame when the platform state has its yaw, pitch, and roll parameters all zero (its nominal state), but it is fixed relative to the Deck Frame (although not necessarily parallel to it) because the payload is physically connected to the deck.

4. The Earth Frame is a coordinate system fixed in the *simulated* Earth. For convenience in specifying the state of the payload, the Earth frame must be coincident with the Moving Frame when the payload is in its nominal state. Consequently, the Earth frame is offset from the Base Frame by the same offset vector that specifies the position of the center of rotation relative to the deck. Nominally, the Earth Frame is coincident with the Base Frame (which is fixed in the *real* Earth), but offset from it by the same amount as the Moving Frame is offset from the Deck Frame. The origin of the Earth Frame is fixed by specifying the position of the origin of the Moving Frame; the orientation of the Earth frame is set by specifying *Azimuth*, *Elevation* and *Tilt* of the Earth x-y plane relative to the x-y plane of the Base Frame. Azimuth is the amount of rotation of the Earth Frame about its z-axis (i.e. the Euler yaw angle), elevation is rotation about its y-axis (i.e. the Euler pitch angle), and tilt is its rotation about its x-axis (i.e. the Euler roll angle). Note that the view window in the control program is fixed in the Earth Frame, its line of sight being along the Earth y-axis. Since the Moving Frame is coincident with the Earth Frame when the platform is in its normal position, the Earth orientation parameters also specify the orientation of the Moving Frame relative to the Deck Frame.

When the platform is homed (level and positioned at the center of its range of motion), all four coordinate systems are coincident with their x-y planes in the plane of the upper joints and their z-axes pointing down. Specifying a non-zero offset (CRX, CRY, and CRZ) moves the center of rotation away from the centroid of the deck. The deck and base frames are still coincident, and the Earth and moving frames are still coincident, but their origins are at the center of rotation. Specifying non-zero Earth orientation parameters (azimuth, elevation, and tilt) changes the attitudes of the Earth and moving frames rotating them relative to the base and deck frames. The base and deck frames are still coincident; the Earth and moving frames are still coincident. The deck is still in its nominal position; although the viewpoint in the view window has changed.

The *State Vector* of the platform is the combination of the position and orientation of the Moving Frame (that is, the payload) relative to the Earth Frame. The position vector has coordinates given by Surge (x), Sway (y), and Heave (z); the orientation Euler angles are given by Yaw (ψ), Pitch (θ), and Roll (ϕ). The order of rotation is yaw, pitch, roll. Commanding a non-zero state separates the moving and Earth frames by moving the origin of the moving frame an amount (x, y, z) and rotating it to a new attitude (ψ, θ, ϕ). The Earth Frame remains stationary as long as the offset and Earth orientation parameters are fixed.

The state vector of the platform is always given in Earth coordinates. Thus, when the platform is homed, all six state vector coordinates (surge, sway, heave, yaw, pitch, and roll) are zero. When the platform is settled, the deck moves down by half its total heave excursion to a heave value of $z = +14.2$ in. When extended, it moves up to a heave value of $z = -14.2$ in. Clicking the Home, Settle, or Extend command buttons automatically sets the Offset (CRX, CRY, and CRZ) vector and the Earth orientation parameters (Azimuth, Elevation, and Tilt) to zero. Changing the State Vector by adjusting the parameters individually, or by running a profile retains the set values of Offset and

Earth orientation. The platform deck must move so as to cause the Moving Frame to reproduce the commanded motions.

3.2.2 Computation of Leg Extensions

Starting with a knowledge of the geometric constants describing the physical platform, the adjustable parameters fixing the center of rotation and the Earth orientation, and the desired payload state vector, the strategy will be to convert all the coordinates specifying joint positions to Earth coordinates, and then find the distances between each pair of leg joints.

The deck joint positions (or deck points) in deck coordinates are given by six vectors \mathbf{D}_{Dj} , where the D subscript indicates deck coordinates and the j subscript indicates leg number. The \mathbf{D}_{Dj} are constants set at initialization. Similarly, the base joint positions (or base points) in base coordinates are given by six vectors \mathbf{B}_{Bj} . Ultimately, the leg extensions L_j will be computed as the lengths of the vector differences of these two vectors. That is,

$$L_j = |\mathbf{D}_{Dj} - \mathbf{B}_{Bj}|$$

or (in Earth coordinates),

$$L_j = [(D_{xj} - B_{xj})^2 + (D_{yj} - B_{yj})^2 + (D_{zj} - B_{zj})^2]^{1/2}$$

The immediate computational issue, therefore, is to compute convert the deck and base points to the Earth Frame.

The position and orientation of the payload relative to its mounting on the platform deck will generally be a matter of physical convenience, whereas the test design will generally demand that the payload be moved relative to a specific center of rotation with axes oriented in a specific way. Consequently, the user may specify the desired center of rotation as the vector \mathbf{C}_D in deck coordinates. Its coordinates are the parameters CRX, CRY, and CRZ specified by the user. This vector specifies the position of the origin of the moving frame relative to the deck frame. The user may also specify the orientation of the Earth Frame such that the axes of motion are aligned with the payload in the desired way. The user specifies the orientation of the Earth Frame by setting the parameters Azimuth (w), Elevation (p), and Tilt (r).

The rotation matrix $\mathbf{B}(w,p,r)$ constructed from the Earth orientation angles serves to rotate the Base Frame into the Earth Frame and the Deck Frame into the Moving Frame. Specifically, the Base-to-Earth and Deck-to-Moving rotation matrix is

$$\mathbf{B} = \begin{matrix} \begin{matrix} \cos p \cos w & \cos p \sin w & -\sin p \\ -\sin w \cos r + \sin r \sin p \cos w & \cos w \cos r + \sin r \sin p \sin w & \sin r \cos p \\ \sin r \sin w + \cos r \sin p \cos w & -\sin r \cos w + \cos r \sin p \sin w & \cos p \cos r \end{matrix} \end{matrix}$$

The deck points expressed in the Moving Frame are therefore

$$\underline{D}_M = \underline{B}(\underline{D}_D - \underline{C}_D)$$

The rotation matrix $\underline{A}(\psi, \theta, \phi)$, constructed from the Euler angles of the platform state rotate the Moving Frame into the Earth Frame. Specifically, the Moving-to-Earth rotation matrix is

$$\underline{A} = \begin{bmatrix} \cos \theta \cos \phi & -\sin \psi \cos \phi + \sin \phi \sin \theta \cos \psi & \sin \phi \sin \psi + \cos \phi \sin \theta \cos \psi \\ \cos \theta \sin \phi & \cos \psi \cos \phi + \sin \phi \sin \theta \sin \psi & -\sin \phi \cos \psi + \cos \phi \sin \theta \sin \psi \\ -\sin \theta & \sin \phi \cos \theta & \cos \theta \cos \phi \end{bmatrix}$$

The position of the center of rotation is commanded by the user as a vector \underline{P}_E in the Earth Frame. The coordinates of the position vector are simply the commanded values of surge, sway, and heave (x, y, and z). The deck points expressed in the Earth Frame are then

$$\underline{D}_E = \underline{P}_E + \underline{A} \underline{D}_M$$

Now the Earth Frame is offset from the Base Frame by the same amount as Moving Frame is from the Deck Frame, that is, by the vector \underline{C} . Note that the numerical values of the components of \underline{C} (CRX, CRY, and CRZ) are equal in both the deck and base frames. Consequently, the base points may be expressed in the Earth frame as.

$$\underline{B}_E = \underline{B}(\underline{B}_B - \underline{C}_B)$$

Knowing both the base points and the deck points in the Earth frame, the leg lengths (that is, the joint-to-joint distances) are easily computed as shown above.

3.2.3 Leg Command Voltages

Each leg of the platform is equipped with a sensor that continuously measures the extension of the leg, producing a dc voltage proportional to leg the extension of the hydraulic cylinder. The output is nominally -1.2 volts for full retraction and +1.1 volts for full extension (23 inches). The controller box includes a ± 5 VDC power supply for the leg sensors and signal conditioning circuitry for their signals. The actual values of the extremum voltages depends upon the selection of padding resistors and the internal gain settings on the controller. The asymmetry arises because the travel of each ram is mechanically limited to only 23 inches while the sensors (linear pots) have a 24-inch, and because the cylinder extension is a non-linear function of heave.

The controller circuit completes a position feedback loop that drives the hydraulic servovalves to adjust leg extension until the leg sensor voltage matches the commanded leg position voltage provided by the DAC as controlled by the software.

Calculation of the required DAC output voltage requires accounting for the retracted leg length, the fact that the midpoint of leg extension does *not* correspond to home position (midpoint of range of motion), and that the zero of the command voltage does not correspond to the midpoint of leg extension. The computation proceeds in the following way.

[Insert Analysis.]

4.0 CONTROL HARDWARE

4.1 System Overview

The Hexad 3000H control system produces the required attitude of the motion platform by individually controlling the lengths of its six legs. The software computes the required leg lengths and transmits them as commands to the controller. The controller, in its turn, implements a second-order control system which commands the servo valve on each leg to open until the leg reaches its commanded extension. Each leg is equipped with a linear potentiometer which measures leg extension and completes the servo loop by transmitting the leg length signal back to the controller. Figure 4-1 shows the physical configuration of the Hexad 3000H control system and also illustrates the functional relationships of the major components. Pinouts for the connectors and cables are given in Table 4-1.

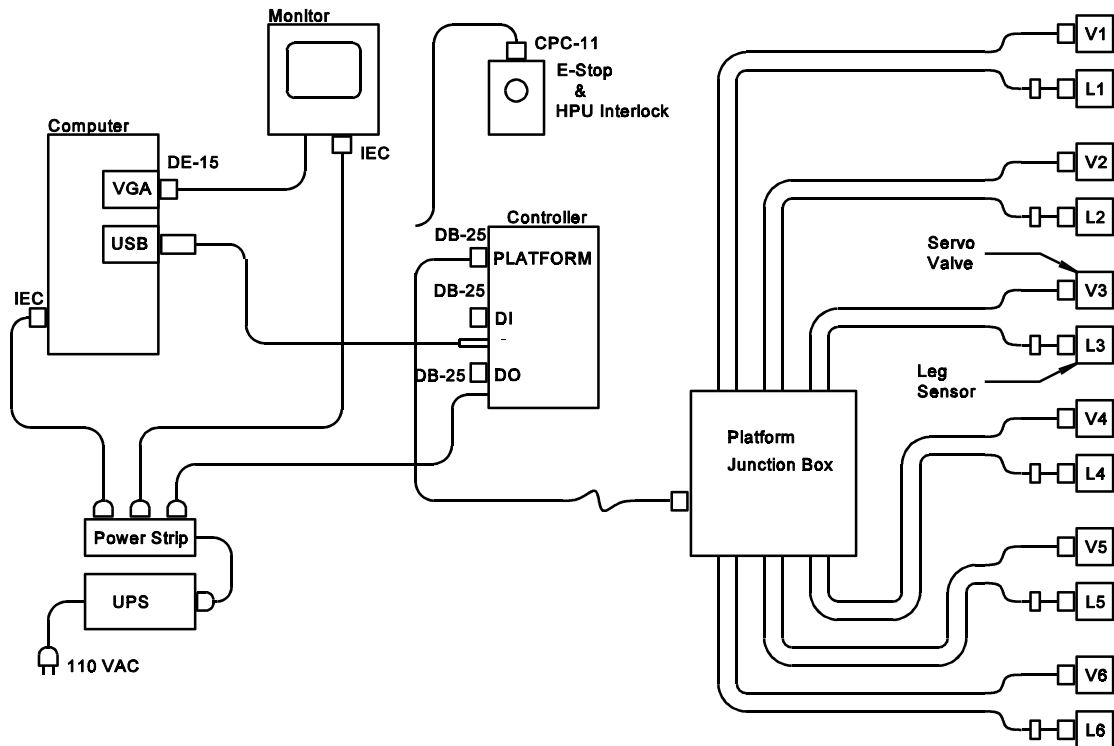


Figure 4-1. System Interconnect Diagram. V1 through V6 are the six servo valves. L1 through L6 are the six leg sensors. The Platform Junction Box is located on the platform itself. The cable between the Platform Junction Box and the Controller is a 25-conductor cable with DB-25 connectors wired straight through; male on Controller end and female on PJB end.

4.2 Controller

4.2.1 Theory of Operation

[Insert analysis]

The equilibrium point of the system is set by adjusting the value of the Zero voltage. Trimmer potentiometers are provided on the controller circuit to adjust Gain, Damping, and Zero.

The performance of the system is determined by the tuning of the control system, that is, by the adjustment of the Gain and Damping controls. The Gain control sets the natural frequency ω_0 , which determines the “stiffness” of the system, while damping controls the tendency to overshoot or “ring”. For accurate, smooth response, the damping should be set at critical damping, $\zeta = 1$. Gain is determined by the natural frequency required to produce the required accuracy at the maximum

specified operating frequency.

4.2.2 Design Implementation

The controller is housed in a single plastic cabinet. Pinouts for connectors and cabling relevant to the controller are given in Table 4-1.

Table 4-1. Platform to Controller Wiring Color Code and Pinout.

This cable connects the Controller (DB-25 connector) to the platform at the main junction box. Wire numbers indicate pinouts of the header connectors on the controller circuit board.

| DB-25 | Wire | Platform | D0 | DI |
|-------|------|-----------|--------|-------|
| 1 | 1 | Pot 1 | +5V | +5V |
| 14 | 2 | Pot 2 | +5V | +5V |
| 2 | 3 | Pot 3 | GND | GND |
| 15 | 4 | Pot 4 | GND | GND |
| 3 | 5 | Pot 5 | Bit0 | Bit0 |
| 16 | 6 | Pot 6 | Bit1 | Bit1 |
| 4 | 7 | Ret 3 | Bit2 | Bit2 |
| 17 | 8 | Ret 2 | Bit3 | Bit3 |
| 5 | 9 | Ret 1 | Bit4 | Bit4 |
| 18 | 10 | Valve 1 | Bit5 | Bit5 |
| 6 | 11 | Valve 2 | Bit6 | Bit6 |
| 19 | 12 | Valve 3 | Bit7 | Bit7 |
| 7 | 13 | -12V | Bit8 | Bit9 |
| 20 | 14 | +12V | Bit10 | Bit10 |
| 8 | 15 | -5V* | Bit11 | Bit11 |
| 21 | 16 | +5V* | Bit12 | Bit12 |
| 9 | 17 | Valve 4 | Bit13 | Bit13 |
| 22 | 18 | Valve 5 | Bit14 | Bit14 |
| 10 | 19 | Valve 6 | Bit15 | Bit15 |
| 23 | 20 | Ret 4 | | +12V |
| 11 | 21 | Ret 5 | | +12V |
| 24 | 22 | Ret 6 | | GND |
| 12 | 23 | GND | | GND |
| 25 | 24 | Enable# | EStop- | -12V |
| 13 | 25 | Run/Stop# | EStop+ | -12V |

*9V on DMAD Card

#DMAD Card only

4.3 HPU Interlock

The HPU Interlock system gives the control computer the ability to enable and disable the HPU and to initiate a software Emergency Stop. [Not Implemented]

5.0 BASIC OPERATIONAL PROCEDURES

5.1 Startup

1. Conduct daily readiness check.
 - 1.1 --- (to meet customer safety requirements)
 - 1.2 ---
 - 1.x Check for obvious oil leaks and physical damage.
 - 1.y Verify critical cabling:
 - a. USB to Controller
 - b. Controller to Platform
 - c. Controller Power Cable.
 - 1.z Retract all Emergency Stop Switches (if so equipped).
Verify green light illuminates.
2. Start computer and launch Hexad 3000H control program.
 - 2.1 Set Monitor Power Switch to ON.
Verify pilot light amber.
 - 2.2 Set Computer Power Switch to ON.
Verify Windows Operating System loaded.
 - 2.3 Double click the HexTest icon to launch control program.
3. Set Main Power Switch to ON.
4. Set HPU Power Switch to ON.
6. If HPU Enable feature implemented: Click HPU Enable to enable HPU.
Verify Enable HPU button turns red and reads E-Stop.
Verify green pilot on Controller illuminates.
7. Start HPU
 - 7.1 Depress HPU Motor Start Button.
Verify HPU starts.
Verify hoses energize and platform remains settled.
Verify sound of accumulators charging within 30 seconds.
Note: Platform may move slightly, but should remain in the settled position.
 - 7.2 Wait 30 seconds while pumps warm up.
Verify system pressure 1500 ± 50 psi
8. Click Home to move platform to home position.
Verify platform moves to home position smoothly.

Note: The system is now ready for operation. If this is the first start of the day, the oil will be cold and should be warmed by exercising the platform gently before commanding any abrupt moves. The Heave Standard Profile at 10%

amplitude and 0.1Hz frequency (default settings) for 3 minutes is suitable.

5.2 Shutdown

1. Click **Settle** to move the platform to its settled position.
Verify platform settles smoothly.
2. Shut down HPU.
 - 2.1 Depress HPU Motor Stop button.
Verify HPU stops.
Verify Accumulators dump immediately (30 seconds to complete).
 - 2.3 Set HPU Power Switch to OFF.
3. Shut down Controller and Computer
 - 3.1 Click **Quit** to terminate control program.
 - 3.2 Click **OK** on the HPU shutdown message.
 - 3.2 Click **Start|ShutDown|Okay** to shut down Windows.
Note: Other computer operations may be conducted before shutting Windows down.
 - 3.3 Set Monitor Power Switch to OFF.
Note: The Controller may be left plugged in and ON while the computer is in use for purposes other than platform control.

Note: At this point the system is shut down and safe for maintenance, payload reconfiguration, or storage.

5.3 Emergency Stop

[Not Implemented]

5.4 Tuning

1. Preset all tuning pots
Note: The pots are 25-turn units, with clicking end indicators. Clockwise rotation increases the relevant parameter. All turns counts are given in complete 360 degree rotations CW from full CCW.
 - 1.1 ZERO: 10 turns
 - 1.2 GAIN: Set all gains the same to a value determined theoretically or from previous experience. A good starting point is 20 turns.
 - 1.3 DAMP: Start with 4 turns
2. Start System
Note: The system should come up stable and near the settled position. If a leg is not stable, increase DAMP on that leg. If increasing damping does not stabilize the leg, decrease GAIN and try again.

Note: All legs should respond in very nearly the same manner.

3. Set Zero

3.1 Click Settle, to fully retract all legs.

3.2 Turn the ZERO control CCW to extend the leg a few inches, then CW to retract the leg until it is just off the stop. Make the adjustment slowly close to the stop.

4. Set GAIN

Note: Adjusting the gain changes the “stiffness” of the system. Increasing gain makes the system more responsive to inputs. Increased gain also makes instability more likely. In general there should be no reason to change the gain from its nominal setting of 20 turns. Instead, use damping to limit accelerations or to make the system more or less responsive.

4.1 Adjust the GAIN control to its desired setting.

5. Set DAMP

Note: Adjusting the damping changes the “responsiveness” of the system (for a given gain). Increasing damping limits the system’s acceleration. Decreasing damping makes the system more responsive, but also allows for oscillation. The most responsive damping setting (critical damping) is the lowest setting for which a sudden input produces no oscillation or overshoot.

Note: Paradoxically, excessive damping may create an unstable configuration with runaway oscillation.

5.1 Click Home to extend all legs to near mid-position.

5.2 Use the ZERO control to move the leg suddenly. Note the response.

5.3 Adjust the damping control in half-turn increments to the desired response.

5.4 Repeat as necessary.

5.5 Set ZERO so the platform appears level.

5.6 Click Settle to retract all legs.

5.7 Readjust ZERO (see step 3).