Sarnicola Simulation Systems, Inc.

APPLICATION NOTES

for the

Hexad 3000H
Six Degree-of-Freedom Motion Platform

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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 is six degrees of freedom.

The platform is controlled by a standard PC-type computer running Microsoft Windows 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, the ability to produce a variety of motion profiles, the ability to store and replay customer-produced motion profiles, and the ability to interface to a host computer for realtime motion control. The internally generated profiles include a versatile, user-configurable sum-of-sines algorithm. 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 makes automated performance testing possible, and the test software includes an automated test facility.

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, the *Hexad Universal Motion Controller* (UMC) 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 motion control computer is by way of a USB interface. The UMC connects to the platform valves via a single DB-25 type cable. The controller also includes sixteen bits of

TTL-compatible input and output, two channels each of auxiliary analog input and output, and an Emergency Stop system.

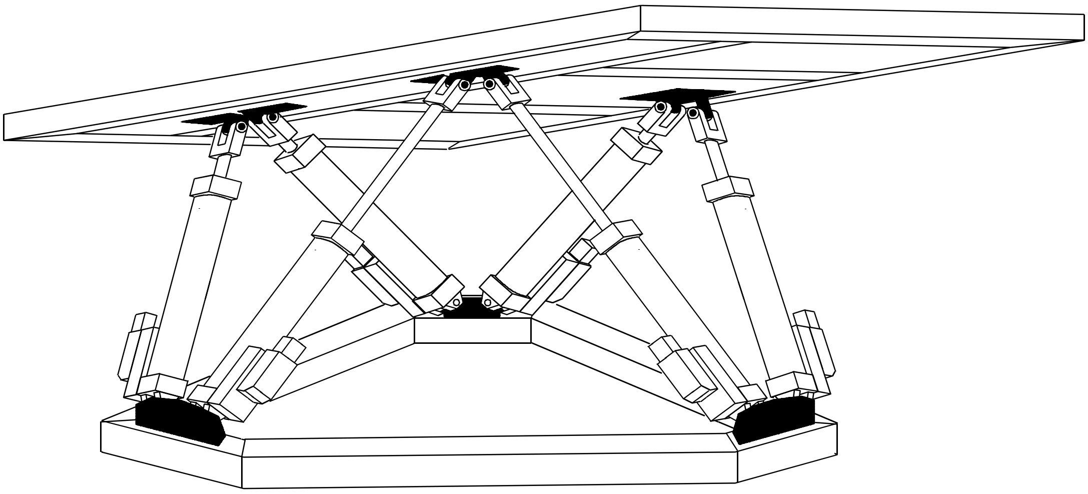

Figure 2-1. The Sarnicola Hexad-3000 Six-Degree-of-Freedom Motion Platform.

3.0 CONTROL SOFTWARE

The Hexad 3000H is controlled by a PC-type computer running Microsoft Windows 98, 2000, or XP, and running a proprietary control application called *HexTest*. 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 thirteen items including all executables and sample profile parameter files. In addition, the user may generate numerous profile parameter files and up to 9999 saved data files. The components are described in Table 3-1.

Installation of *HexTest* 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 Drivers directory of the distribution disk. The installer will place all components in Program Files unless a different directory is selected during installation. The control computer for each system ships with *HexTest* installed.

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.

Table 3-1. HexTest and HexView Software Components.

Item	Description
HexTest.exe	Primary Application
HexView.exe	Data Viewer accessory
HexTest.ini	Initialization File
Sample.cmp	Sample parameter file for computed profile
Sample.fpb	Sample file playback computed profile
Sample.xls	Excel file for making Sample.fpb
iont.dll	I/O support library
hexad.dll	Geometrical computations library
ftd2xx.dll	USB support library
DataLog.txt	Log file of all data runs
TestLog.txt	Latest report from auto test
Data*nnnn*.txt	HexView-compatible data file number *nnnn*
Data*nnnn*.xls	Excel-compatible data file number *nnnn*

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.

2. *Profile Mode.* In profile mode, the program commands a specific motion profile to the platform. There are six types of profiles:

- ***Standard Profiles***. The standard profiles are simple sinusoidal oscillations in each of the six motional degrees of freedom. The standard profiles are listed on the left side of the Profiles frame.
- ***Computed Profiles***. The computed profiles are complex motions generated by computing a 30-term sum-of-sines for each motional degree of freedom. The parameters of each computed profile are saved in a file; the computer computes the instantaneous state vector in real time using the stored parameters. The parameters are stored in a files with the .cmp extension.
- ***File Play***. In File Play, the program reads a user-created time-series motion profile saved in a file with the .fpb extension.
- ***Realtime***. In Realtime mode, the motion control computer interfaces to a customer-supplied host computer via RS-232. The host sends motion control data to the motion control computer in real

time, and the motion control computer sends back instantaneous position data.

- ***Auto Test***. In autotest mode, the software plays back a specific motion profile while comparing the commanded motion to the actual motion. It gives a pass/fail result for each leg in each motion determined by fidelity to the command.
- ***Step Test***. The step test commands a step input to all legs simultaneously. This maneuver is particularly useful for tuning and troubleshooting.

To select a profile, simply click the appropriate radio button in the Profiles frame. The three buttons in the Profiles frame change function depending on the profile type selected. They allow for selecting a specific file, editing the profile, and starting and stopping the selected profile. Clicking the Start button takes the system out of manual mode and into profile mode with the selected profile active. Clicking the Stop button, stops the running profile and returns the system to manual 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 clicking the Stop button. When running a computed or file play profile, the program automatically logs up to 250,000 frames of data (83 minutes at 50 frames/sec.). 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 clicked, 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--the number of times per second the platform position is updated. Iteration rate is sometimes called the frame rate. Editing the update rate changes the update rate for the manual mode as well as standard profile mode.

If one of the computed profiles is selected when the Edit button is clicked, 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. Use of the computed profile editor is described in detail in section 3.1.1.

3.1.1 Constructing Sum-of-Sines Computed Profiles

A computed 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

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

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 3.2.1. 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 computed profile by clicking its option button, then click the Select button. In the selection window, select the file to be edited and click Edit. To create a new computed profile, click New. In either case, 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_1, 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. Before saving, be sure to enter the desired filename in the FileName field. The program will automatically add the extension .cmp to the filename specified.

> ***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 Computed Profiles

Whenever a computed 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 other 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 computed, file play, or step test 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 either to ignore the data or to save it by clicking the Save button in the Data Logger frame. Before saving, you 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. (Valve null offset is the chief source of error.) The DAC is a twelve-bit device, so its range is from 0 to 4,095 counts. The ADC is actually a ten-bit device, but the software scales its output to match twelve-bit resolution. Full retraction is a small number; full extension is a large number. The exact values depend upon the precise configuration of the platform.

Saved data may be retained in two formats: a convenient text format for human analysis, and a text format that can be read directly into an Excel spreadsheet.

The data files named Data*nnnn*.txt are ASCII files laid out in a form suitable for human analysis in a text editing program. In order to provide a convenient method of viewing these 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. The format of the files is shown if Table 3-2.

Table 3-2. Format of human-readable 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 named Data*nnnn.*xls are also ASCII files, but are laid out in a form suitable for importation into many data analysis or spreadsheet programs. They import directly to Microsoft Excel. (If opened from within Excel, the Text Import Wizard will appear. Just click Finish.)
.
By default, Data*nnnn*.txt and Data*nnnn*.xls files are saved in the same directory as the executable file. You may specify an alternate save path by editing the initialization file, HexTest.ini.

The data logger can store up to 250,000 data points (each a 6-component vector) for each profile run. This capacity is sufficient to record 83 minutes of data at an iteration rate of 50 Hz. The data format is shown if Table 3-2.

3.1.4 Using File Play Profiles

The File Play feature allows the user to control the platform with a time-series recorded as a file. The file play profile is a file with extension .fpb. These files must be saved in the same directory with the executable (c:\Program Files\HexTest by default). A file play file is an ASCII file laid out in a format that is reasonably convenient for human reading, editing and interpretation. The format is shown in Table 3-3.

Table 3-3. Format of File Play Profile files.

Sample	<--------------------------------*Name*					
20May04		This is a sample File Play profile.<-----*Date and Caption*				
ItRate	Az	El	Tilt	CRX	CRY	CRZ
40	5	2	0	0	0	-1
Frame	Yaw	Pit	Roll	Srg	Swy	Hev
1	0	0	10	0	0	0
2	0	0	10	0	0	0
3	0	2	9	1	-1	-1
4	0	4	8	2	-1	-2
5	0	6	7	3	-1	-2
etc.						

When creating file play profiles, be sure to follow this format exactly, taking note that the data is tab-delimited. You must separate data items with a Tab character (ASCII 009). Each distribution of *HexTest* includes an example file play profile called Sample.fpb that you can use as a guide or template for creating new files. Also included is Sample.xls, an Excel spreadsheet file that contains the same data as Sample.fpb.

Excel is very useful for creating file play profiles. Start with Sample.xls, and save a copy of it under a new name. Then open the copy in Excel. Use the features of Excel to create the desired profile and save the final version as a “Text (Tab-delimited) (.txt)” file. Excel may insist on appending the

.txt file extension on your filename, but you can rename the file with the .fpb extension.

Some pointers:

1. Put something in every field.
2. Be sure to include all the header information and column headings.
3. Choose and iteration rate between 20 and 100 Hz.
4. Keep the Excel version of the file for future editing.

3.1.5 Using Auto Test

When the Auto Test profile is selected and run, a window appears which allows the user to follow the progress of the test. The commanded and actual leg extension for each leg is shown in a "strip-chart" display, and the pass-fail result of each phase of the test is shown textually for each leg. When the test is complete, log information is also displayed.

The results of the test are always logged to the file TestLog.txt. Previous log files are overwritten. If you need an archival record, be sure to copy TestLog.txt before running Auto Test again.

The pass-fail criteria are based on comparison of actual to commanded leg extensions. A mistuned or malfunctioning leg will fail the test because it will not follow its commands to within the required tolerance.

3.1.6 Using Step Test

The Step Test profile moves the platform smoothly to a level position above home, waits five seconds, steps it to home, waits five seconds and ends. The data logger is active so that a record of the profile will be available after the test. The amplitude of the step command can be set in the initialization file. The default is 5 inches. To change the direction of the step, change the sign of the step amplitude.

3.1.7 Using Realtime

In the Realtime profile, the motion control computer provides an interface to a customer-supplied host computer that commands the instantaneous state of the platform. The communication with the host is provided by a three-wire RS-232 link running at 9600 bps (no parity, 8-bits, 1 stop bit). Communication is bidirectional and includes all leg commands, DOs and AOs on the Host-to-Motion channel, and all leg actuals, DIs, and AIs on the Motion-to-Host channel.

With the Realtime profile is selected, when you click Start, the motion computer homes the platform, enters the Handshake phase and begins looking for a valid data string from the host. When a valid string arrives, the motion control returns a reply data string and enters its Online phase. While online, the motion computer listens for a valid 46-byte data string from the host, receives it, processes it, acts on it, and then passes back to the host a 37-byte reply. The motion computer then waits for the next valid 46-byte data string from the host. Pacing is the host's responsibility. The host must wait at least 4 milliseconds after transmitting a packet before transmitting another. When online, the host must receive the return packet before transmitting the next outgoing packet.

If the motion computer should receive a malformed packet, or if the com line goes silent for more than one second, the motion computer goes offline.

The host-to-motion packet is a 46 byte string of ASCII characters. It must be exactly in the format shown in Table 3-4. The motion-to-host packet is a 37-byte string of ASCII characters in the format shown in Table 3-5.

Table 3-4. Host-to-Motion packet format

Element	Length (Bytes)	Format	Remarks
Header	2	XX	Two digit number incremented each frame
Surge	5	±XXXX	Value of surge in 100ths of an inch
Sway	5	±XXXX	Value of sway in 100ths of an inch
Heave	5	±XXXX	Value of heave in 100ths of an inch
Yaw	5	±XXXX	Value of yaw in 100ths of a degree
Pitch	5	±XXXX	Value of pitch in 100ths of a degree
Roll	5	±XXXX	Value of roll in 100ths of a degree
AO0	4	XXXX	Value of Analog Out 0 in thousandths of a volt Max value 5000 (5.000 volt)
AO1	4	XXXX	Value of Analog Out 1 in thousandths of a volt Max value 5000 (5.000 volt)
DOMSB	2	XX	Digital Out MSB in Hex (00-FF)
DOLSB	2	XX	Digital Out LSB in Hex(00-FF)
CRLF	2	<CRLF>	ASCII 13, 10

Table 3-5. Motion-to-Host packet format

Element	Length (Bytes)	Format	Remarks
Header	2	XX	As received from host
Leg 1	4	XXXX	Value of Leg 1 ADC number
Leg 2	4	XXXX	Value of Leg 2 ADC number
Leg 3	4	XXXX	Value of Leg 3 ADC number
Leg 4	4	XXXX	Value of Leg 4 ADC number
Leg 5	4	XXXX	Value of Leg 5 ADC number
Leg 6	4	XXXX	Value of Leg 6 ADC number
AI0	4	XXXX	Value of AI0 ADC number
AI1	4	XXXX	Value of AI1 ADC number
DIMSB	2	XX	Digital In MSB in Hex (00-FF)
DILSB	2	XX	Digital In LSB in Hex(00-FF)
CRLF	2	<CRLF>	ASCII 13, 10

3.1.8 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 Universal 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 CPC-17 located on the back panel of the Universal Motion Controller. Pin 13 is plus and pin 25 is minus. (The other pins on this connector are used for DI.) If no external E-Stop is provided, the E-Stop system may be bypassed by jumpering pins on the CPC DO connector:

DO-1 (+5VDC) jumps to DO-13 (E-Stop+)
DO-2 (Ground) jumps to DO-25 (E-Stop-)

If the external DIO connectors are not wired, the E-stop may be bypassed by jumpering pins on the DIO header strip J5 inside the case of the UMC:

J5-47 (+5VDC) jumps to J5-43 (E-Stop+)
J5-34 (Ground) jumps to J5-44 (E-Stop-)

The E-Stop signal is active low, that is, it is present during normal operation and goes low to indicate an E-Stop condition. When the E-Stop signal is present, the green SysOK lamp on the front panel of the UMC lights to indicate that the external E-Stop system is ready. When the E-Stop signal is absent, the green SysOK lamp extinguishes and the red E-Stop lamp illuminates.

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.

After an E-Stop event, prudent practice dictates that the system should be shut down and the cause of the fault determined before continuing to operate the system. However, it may sometimes be convenient (in a test procedure, for instance) to reset the E-Stop system immediately. This may be accomplished by clicking the Reset E-Stop button on the diagnostics page. This button is only enabled in manual mode, and it settles the software before actually issuing a reset to the UMC.

The Universal Motion Controller accepts digital signals from the Motion Computer via USB. These signals are used to control an array of DACs which generates analog command voltages for the six servo controllers. The first stage in each servo controller channel is a low-pass filter to smooth the steps of the digital commands. The DAC and the low-pass filter of each channel are connected through an analog switch controlled by the E-Stop system. When the E-Stop signal drops, all the analog switches open, cutting off signals from the computer and leaving the low-pass filter circuits connected to a high impedance. In this configuration, the time constant of the filter is several seconds so that its output declines gradually to zero commanding its associated servo to retract smoothly. The result is that on E-Stop the platform settles gracefully over the course of about five seconds.

In many applications, an E-Stop will be accompanied by shut down of the HPU, and a consequent loss of operating pressure. The hydraulic system is equipped with an accumulator that will provide operating pressure to complete the E-Stop settle under control. If the HPU does not shut down, the settling will proceed just as if it had. The "settle on E-Stop" strategy is superior to "freeze on E-Stop" because a system without hydraulic pressure will settle erratically, possibly over the course of several minutes. In an emergency situation that calls for freezing, just activate Freeze from the control computer, by clicking the Freeze button, or pressing spacebar.

2. Computer Failure Emergency Stop. If the motion computer should stop issuing correct commands for more than ten seconds, or if the USB interface should fail, the green On Line lamp on the controller will extinguish, the red Off Line lamp will illuminate, and the controller will enter Emergency Stop. If communications with the computer is restored, the On Line lamp will return, and the Off Line lamp will exgtinguish, but the controller will remain in Emergency Stop until the Reset Emergency Stop button (in the Diagnostics window) is clicked.

Note: *The Windows operating system suspends execution of the program, and therefore suspends communication with the controller, while the user moves or resizes windows. Manipulating windows for more than ten seconds will mimic a computer failure and precipitate an Emergency Stop.*

3. Software Fault Detection. When the Fault Detect checkbox in the Diagnostics window is checked, the program is capable of detecting deviations from the commanded leg extensions. The control software monitors the actual leg extension values returned by the controller, and when it detects a discrepancy larger than a threshold amount that persists for larger than a threshold time interval, it freezes platform motion and displays the word "Fault" in red in the View window. The program then waits for a predetermined interval, commands the platform to settle, and recovers to normal operation. If the fault occurred in Profile Mode, the system reverts to Manual Mode. The default settings for the Fault Enabled checkbox, and for the Fault Error Size, Fault Initiation Time, and Fault Recovery Time may all be set in the initialization file. See section 3.1.6 for instructions on editing default values.

4. Profile Test Detection. When the user creates or edits a computed profile, the software flags the profile as untested. The first time the user attempts to run this profile, the software displays a warning and them permits the profile to run without sending commands to the platform. See section 3.1.2 above.

5. Excessive Acceleration Detection. [Not implemented in the standard configuration. Not recommended for most applications.] The control software monitors the leg extension values returned by the controller, and continuously computes 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 (HexTest.ini) and may not be changed from within the control program or while the program is running. See section 3.1.6 for instructions on editing setpoints.

3.1.6 The Initialization File

Initialization parameters, platform geometrical constants, and controller electrical parameters reside in the initialization file HexTest.ini. The contents of the supplied version of the file are shown in Table 3-6. Many 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 HexTest.ini, take care to maintain the format exactly. Be sure to delimit data entries with commas.

Table 3-6. Contents of the initialization file HexTest.ini.

Title = Hexad 3000H	; Max 20 characters
Make XLS = yes	; yes or no
Make TXT = yes	; yes or no
XLS Path = c:\motiondata\	; local for default or full path such as c:\motiondata\
TXT Path = local	; local for default or full path such as c:\motiondata\
Default ItRate = 50	; Hz
Default FormFreq = 0.25	; Hz
Default Profile Amplitude = 50	; percent
Default Step Amplitude = 5	; inches
Bridge Exitation Hi = 5.00	; volts
Bridge Exitation Lo = 0.00	; volts
Bridge Gain = 1	; volts/volt
Pot Length = 24.0	; inches
Pot Resistance = 5000	; Ohms
Pad Resistance = 0	; Ohms (total, both ends)
OffsetMax = 5, 5, 5	; x, y, z inches
OrientMax = 180, 20, 20	; w, p, r degeees
Default Fault Detect = off	; off or on
Fault Initiate Time = 3	; sec
Fault Recovery Time = 10	; sec
Fault Error = 1	; inches
VelMax = 60	; in/sec
AccelMax = 1000	; in/sec2
AmberWarnThreshold = 90	; percent of full extension of retraction
RedWarnThreshold = 95	; percent of full extension or retraction
CylLen = 33.625	; inches

```
StrokeLen = 23                  ; inches including stop tube
StopTubeLen = 0                 ; inches
DeckRadius = 26.406             ; inches true radius to bearing points [sqr(x^2+y^2)]
DeckAxleSpacing = 2.84          ; inches
DeckAxleRadius = 1.375          ; inches
BaseRadius = 31.451             ; inches
BaseAxleSpacing = 2.84          ; inches
BaseAxleRadius = 1.375          ; inches
```

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 controls the hydraulics to extend the legs to the desired lengths.

Computing the leg length vector is a matter of computing the positions of the leg endpoints in some convenient coordinate system and then using the distance formula to compute the extension of each leg as the distance between its endpoints.

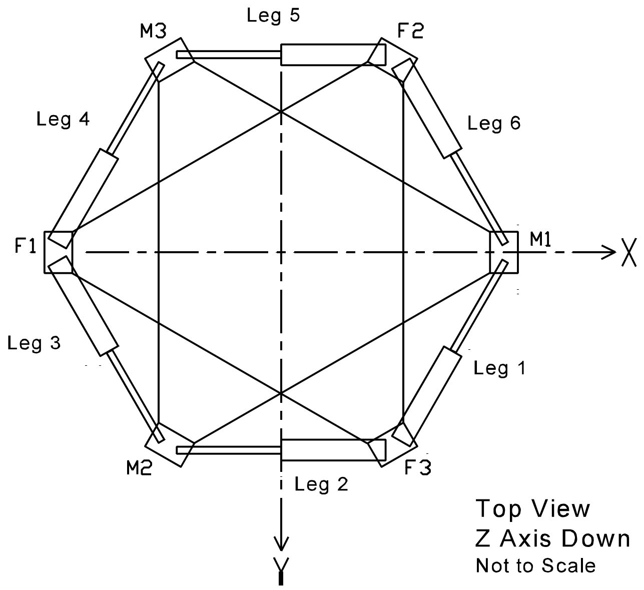

Figure 3-1. Leg Layout and Nominal Coordinate System Orientation. Legs are numbered clockwise from the nominal x-axis. M1-M3 are the moving (deck) joints; F1-F3 are the fixed (base) joints.

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 form 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 (z = +14.2 in for the standard geometry). When extended, it moves up to its maximum heave value (z = -14.2 in for the standard geometry). 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 $\mathbf{D}_{\mathrm{Dj}}$, where the D subscript indicates deck coordinates and the j subscript indicates leg number. The $\mathbf{D}_{\mathrm{Dj}}$ are constants set at initialization. Similarly, the base joint positions (or base points) in base coordinates are given by six vectors $\mathbf{B}_{\mathrm{Bj}}$. Ultimately, the leg extensions Lj will be computed as the lengths of the vector differences of these two vectors. That is,

$$L_j = |\boldsymbol{D}_{\boldsymbol{Ej}} - \boldsymbol{B}_{\boldsymbol{Ej}}|$$

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 use specifies the orientation of the Earth Frame by setting the parameters Azimuth (*w*), Elevation (*p*), and Tilt (*r*).

The rotation matrix $\underline{\boldsymbol{B}}(w,p,r)$ 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

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

The deck points expressed in the Moving Frame are therefore

$$\boldsymbol{D_M} = \underline{\boldsymbol{B}}\,(\boldsymbol{D_D} - \boldsymbol{C_D})$$

The rotation matrix $\underline{\boldsymbol{A}}(\psi,\theta,\varphi)$, 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

$$\underline{\boldsymbol{A}} = \begin{matrix} \cos\theta \cos\varphi & -\sin\psi \cos\varphi + \sin\varphi \sin\theta \cos\psi & \sin\varphi \sin\psi + \cos\varphi \sin\theta \cos\psi \\ \cos\theta \sin\psi & \cos\psi \cos\varphi + \sin\varphi \sin\theta \sin\psi & -\sin\varphi \cos\psi + \cos\varphi \sin\theta \sin\psi \\ -\sin\theta & \sin\varphi \cos\theta & \cos\theta \cos\varphi \end{matrix}$$

The position of the center of rotation is commanded by the user as a vector $\mathbf{P}_E$ 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

$$\boldsymbol{D_E} = \boldsymbol{P_E} + \underline{\boldsymbol{A}}\,\boldsymbol{D_M}$$

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 **C**. Note that the numerical values of the components of 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.

$$\boldsymbol{B_E} = \underline{\boldsymbol{B}} (\boldsymbol{B_B} - \boldsymbol{C_B})$$

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 the extension of the hydraulic cylinder. The commanded voltages may be read from the Diagnostics window of *HexTest*. Note that the leg position sensors and the leg cylinders have different stroke lengths, so the leg command voltages do not range from exactly 0 to exactly 5 volts. Note also that at mid-stroke, the commanded voltage is 2.5 volts, but at the home position the command voltage is not 2.5 volts. Home is not at mid-stroke; rather it is at the mid-point of the heave range.

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. The leg sensor voltages are displayed on the Diagnostics window.

Calculation of the required DAC output voltage requires accounting for the retracted leg length, and the fact that the midpoint of leg extension does *not* correspond to home position (midpoint of range of motion).

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.

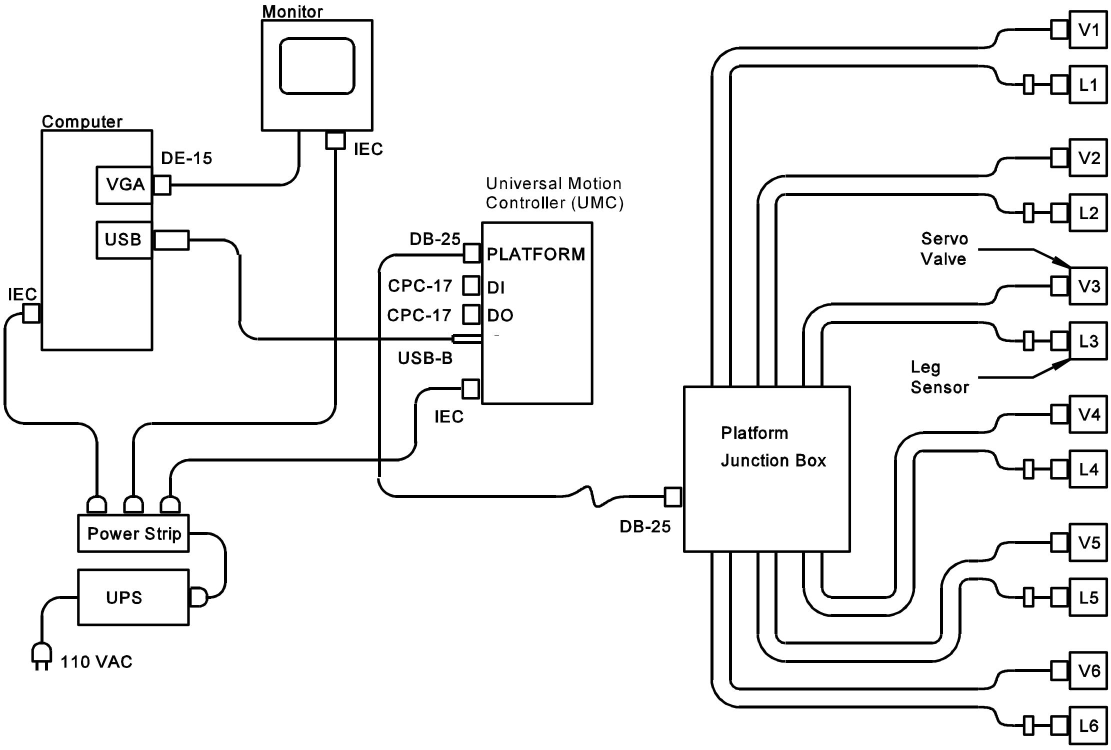

Figure 4-1. System Interconnect Diagram. V1 through V6 are the six servo valves. L1 through L6 are the six leg sensors. The Platform Junction Box is located on the platform itself. The cable between the Platform Junction Box and the Controller is a 25-conductor cable with DB-25 connectors wired straight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

4.2 Controller

4.2.1 Theory of Operation

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

The Span control allows calibration of the extension of each leg so that the commanded leg extensions matches the actual extension over the entire range.

4.2.2 Design Implementation

Packaging. Compact, portable, metal case. 2.25 x 13 x 11 (HxWxD). Custom packaging (eg, rackmount) is available.

Power. 100-230 VAC/DC, 50-60 Hz, 0.5 A Switch on power entry module.

Controls. Main power switch. (All operational control is handled by the host computer.)

Indicators. Green Power Pilot LED
Green System OK LED
Red E-Stop LED
Green On Line LED
Red Off Line LED

Connectors. USB-B Jack for host computer interface.
DB-25S for interface to platform.
CPC-17 (26 pin standard sex) for Digital Output (16 bits TTL, +5VDC power out)
CPC-17 (26 pin standard sex) for Digital Input (16 bits TTL, +5VDC, ±12VDC power out.) and E-Stop
IEC Power Entry module (switched and fused)

Table 4-1. Controller to Platform Wiring Pinout.
The controller connects to the platform by way of a standard DB-25 cable. The DI and DO signals connect by way of CPC-17 connectors. Wire numbers indicate conductor position in a ribbon cable.

Pin Number	Wire Number	Platform (DB-25)	DO (CPC-17)	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	AO-0	AI-0
11	21	Ret 5	GND	GND
24	22	Ret 6	AO-1	AI-1
12	23	GND	GND	GND
25	24	Estop-	+12V	
13	25	Estop+	-12V	

* Pot Excitation

5.0 BASIC OPERATIONAL PROCEDURES

5.1 Startup

1.0 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)

2.0 Turn on controller.
- 2.1 Set controller power switch to on
- 2.2 Verify green Power LED is on
- 2.3 Verify green SysOK LED is on

3.0 Start computer and launch *HexTest* control program.
- 3.1 Press Monitor Power Switch.
  Verify pilot light amber.
- 3.2 Press Computer Power Switch.
  Verify Windows Operating System loaded.
- 3.3 Launch *HexTest* control program. (The controller must be ON for this step to work.)
  Verify green On Line LED on controller is on
  Verify *HexTest* shows settled platform

4.0 Enable HPU Power
- 4.1 Set Main Power Switch to ON.

5.0 Start HPU
- 5.1 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.
- 5.2 Wait 30 seconds while pumps warm up.
  Verify system pressure 1500 ±50 psi

6.0 Home Platform
- 6.1 Click Home to move platform to home position.
  Verify platform moves to home position smoothly.

Note: The system is now ready for operation.

5.2 Shutdown

1.0 Click Settle to move the platform to its settled position.
Verify platform settles smoothly.

2.0 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.

3.0 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|Turn Off Computer to shut down Windows and turn computer off.
  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. The control program (*HexTest*) may be used with the controller turned off or disconnected.

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

5.3 Emergency Stop

If an actual emergency stop occurs, the platform will settle and the red E-Stop lamp will illuminate. In the standard configuration, the motion computer software will not be aware that the E-Stop event has occurred. If the system enters the “Off Line” state because of too much Windows activity, there is no need to shut down the HPU. Start with step 2.2 and proceed.

1.0 Address any emergency concerns

2.0 Stop the control system
- 2.1 Press the HPU Motor Stop button.
  Verify HPU stops.
- 2.2 Stop any running profiles.

3.0 Recovery (after the cause of the E-Stop has been corrected)
- 3.1 Retract all Emergency Stop Switches (if so equipped).

Verify the green SysOK lamp is lit.
Verify the red E-Stop lamp is extinguished.

3.2 Open the diagnostics window (click the Diagnostics button)

3.3 Click the E-Stop Reset button
Verify the green On Line lamp is lit
Verify the red Off Line lamp is extinguished

3.4 Press the HPU Motor Start button
Verify the HPU starts

Note: At this point, the system is ready for use.

5.4 Tuning

1.0 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 5 turns

1.4 SPAN: 13 turns.

2.0 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.

3.0 Set Zero

3.1 Click Settle, to fully retract all legs.

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

4.0 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.

5.0 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).

6.0 Set SPAN

6.1 With the platform settled, set ZERO so each leg is 3/8 inch off the stop.
6.2 Click Extend to extend the platform.
6.3 Adjust SPAN until to set each leg 3/8 inch retracted off the stop.
6.4 Settle and readjust ZERO.
6.5 Repeat until consistent. There should be minimal interaction between SPAN and ZERO.