Supplemental data

Tables

	Unloaded	Abdominal Phantom (5.4 kg)
Range of motion (cm)	13.8	13.8
Maximum Velocity (cm/s)	47.7	38.1
Maximum Acceleration (cm/s²)	445	286.1
Spatial Precision (high speed) (mm)	±0.16	±0.095
Spatial Precision (low speed) (mm)	±0.013	±0.013

Supporting Table S1: Platform specifications measured with and without an abdominal phantom load.

1.0 Revision history

Date	Review description	Signature
15 Jun 2015	Rev 1.0 of the MRI-compatible Motion pack (RC1309-V1)	Rajiv Chopra

2.0 File/Technical Document locations

Title	Software/ Manufacturer	Location
HR4 Motors	Nanomotion	Data Sheets http://www.nanomotion.com/wp-content/uploads/2014/05/HR-specs-Catalog621599844.pdf Mounting Instructions http://www.nanomotion.com/wp-content/uploads/2014/05/Application_Note_2-mounting_and_operating.pdf Product Manual (Motors and Ceramic drive strips) http://www.nanomotion.com/wp-content/uploads/2015/01/HR00458000-00-HR-Motor-User-Manual.pdf
AB2 Motor Driver	Nanomotion	Data Sheets http://www.nanomotion.com/wp-content/uploads/2014/05/AB2_Driver_Amplifier_datasheet.pdf Product Manual http://www.nanomotion.com/wp-content/uploads/2014/05/AB2-driver-user-manual.pdf
Linear Encoder		Encoder http://www.downloads-numerikjena.de/sheets/DS_LIA_eng.pdf Glass Strip http://www.downloads-numerikjena.de/sheets/DS_scale_tape_eng.pdf
Non-magnetic linear slides	Deltron Precision, Inc.	Catalog http://www.deltron.com/Downloadable_Catalogs.html#

Control Software	Labview, National Instruments	The software for this system was written in Labiew 2013. The software is freely available by contacting Rajiv.chopra@utsouthwestern.edu.
Motion Controller	National Instruments/ PCI-7344	Data Sheet http://www.ni.com/pdf/products/us/4mo636-637.pdf User Manual http://www.ni.com/pdf/manuals/370838b.pdf Interface cable (SHC68-C68-S) http://www.ni.com/pdf/products/us/4mo645.pdf Motion Interface box (UMI-7764) http://www.ni.com/pdf/products/us/4mo640-641.pdf
Abdominal Phantom	CIRS Inc, Model 057A	Data Sheet http://cirsinc.com/file/Products/057/057A%20DS%20101614.pdf

3.0 Overview

The RC1309-V1 is a non-magnetic motorized linear stage that can be used to generate arbitrary linear motion in a magnetic field. The system is MRI-compatible and can be used during imaging with a clinical scanner to study the influence of linear motion on image-quality and artifacts. The accompanying manuscript describes the characterization performed with this system in a clinical MRI for motion management studies.

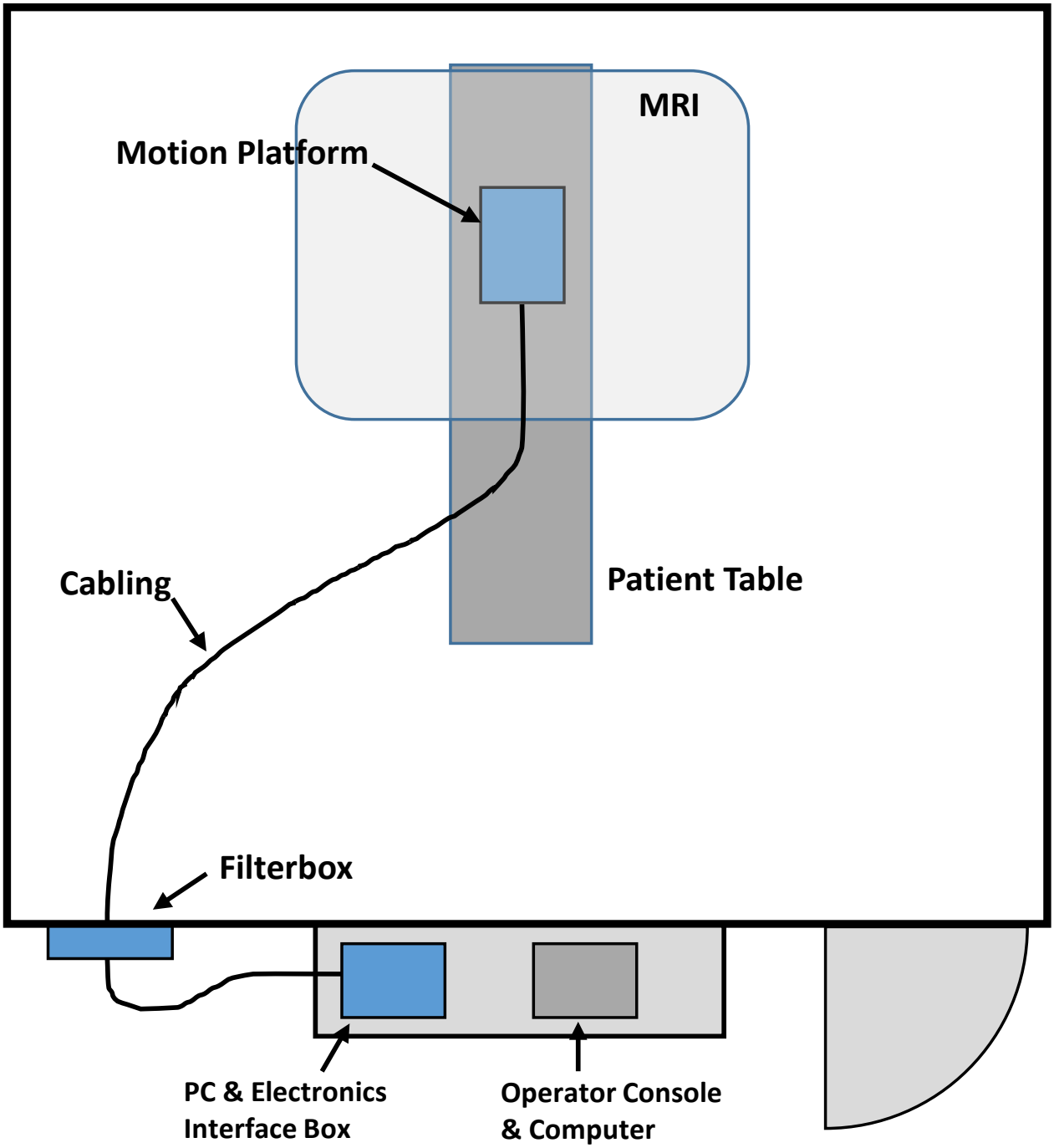
The system consists of the following components:

1. Non-Magnetic Linear stage: This stage is constructed from plastics and other non-magnetic materials. Linear motion is achieved using three non-magnetic linear ball slides. Piezoceramic motors are used to drive the linear stages, and an optical encoder measures position. The unit operates as a servo system and is controlled by a computer with a motion controller.
2. Filter-box: A shielded enclosure is mounted onto the RF shield of the magnet room and acts as a connection point for cables to enter and exit the room. It also houses low-pass filters and electronics necessary to ensure no RF interference with the MRI.
3. Computer and electronics interface box: A personal computer with a motion controller is used to drive the linear stage and to program arbitrary trajectories. The version described in this document utilizes a motion controller from National Instruments, with software written in Labview and Matlab. The electronics interface box includes the amplifiers for the motors, as well as the connection terminals to interface all the electrical cables associated with the motors and encoders with the motion controller. A DC power supply for the motor amplifier and encoders is also located in this box.
4. Abdominal Phantom: An MRI-compatible abdominal phantom was purchased from CIRS Inc (Model 057A, CIRS Inc) for initial studies with the platform. The phantom contains a series of abdominal organs (liver, kidneys) with different MRI contrast and with embedded lesions, as well as simulated subcutaneous fat, and bones (vertebrae & ribs). The phantom is in a self-contained container.

This document and the accompanying supplementary files provide information on the parts and CAD drawings necessary to reproduce the system. **Please note that there is considerable experience required with the components listed in order to achieve the performance described in this paper.** The tolerances on the machined components are important and there is a process of tuning the motors and encoders that is necessary to get the desired motion performance. This document does not go into detail on these steps, however, all interested users are encouraged to contact the corresponding author Rajiv Chopra (Rajiv.chopra@utsouthwestern.edu) for more details and/or assistance with fabrication of this system. Furthermore, the software written in Labview for the platform is not included in the supplementary files, but can be made freely available by contacting Rajiv Chopra. We emphasize that this is not a plug-and-play type of system and want to avoid users investing significant resources and not realizing the performance due to insufficient experience with the technology. We recommend collaborating with our group for the best possible results.

Assistance is available for individuals interested in the manufacturing of this system. All of the programs for CNC machining and fabrication of the parts have been implemented and replication of the system is relatively straightforward. Please contact Rajiv Chopra for more details.

4.0 Block Diagram of System



The above figure shows the overall layout and arrangement for the system. The motion platform is placed on the patient table of the MRI and advanced into the center of the bore. Electrical cabling extends from the platform to a filterbox mounted onto the RF shield of the magnet room. The cabling extends to a PC and electronics interface box located in the operator console area.

Some important notes about the installation/layout of the sytem:

- Since the platform moves during use, it is important to mount it firmly to the patient table. In the accompanying manuscript, a custom mount was made for the Philips Ingenia 3T patient table such that the platform was rigidly fixed to the table.
- All the hardware used in the motion platform should be non-magnetic such as plastic, brass, or aluminum. The HR4 motors should be ordered in the non-magnetic configuration, as should the encoder. The encoder strip should be glass or any other of the non-magnetic options available.
- Consideration should be taken to ensure appropriate coils can be used with the system. In the accompanying manuscript, a standard riser intended for pediatric imaging was used to separate the anterior torso coils from the phantom and platform. This enabled these components to move freely during imaging with these coils
- The filterbox must be attached to the RF shield to ensure proper grounding of the cables and shields to avoid RF interference. This can be done by mounting the box to an existing panel on the shield if one exists. Alternatively, if only a waveguide is present for a particular MRI, a custom metallic insert for the waveguide can be made which serves to create a mounting point for the cables and filters. The feasibility of this approach depends on the size of the waveguide available on the scanner.
- The PC and electronics interface box are located outside the magnet room in the operator console area. In the accompanying manuscript, these were mounted on a movable cart to enable use of the motion platform outside the MRI, however, this is optional.
- The cabling for the system is important and should be non-magnetic cables inside the magnet room. Further, the encoders and motors have specific requirements on the shielding for these cables. In general, the motors and encoders can be ordered with cables sufficiently long to reach the inner wall of the magnet room. The cabling outside of the MRI does not need to be non-magnetic, but should still obey the shielding requirements of the motors and encoders. Suitable connectors should be included on the filterbox to enable connection of the cables to it.
- The filterbox includes a low-pass capacitive D-sub filter for the motors. The capacitance of this filter should be chosen carefully as it adds to the capacitive load required for the motor amplifier to drive (since the piezomotors are essentially a capacitive load). Further, the capacitance of the length of cables used should be considered as well, to ensure the overall capacitance seen by the amplifiers is not beyond their specifications. The encoder includes the electronics to convert the sin/cos signals produced at the read-head into standard quadrature encoder signals. A capacitive low-pass D-sub filter is also included on the encoder line to avoid any potential interference.

5.0 Parts List

Parts & Materials

The tables below list the parts required to manufacture the linear motion platform and associated components. The key parts are listed with their source and approximate cost. However, many of the cables/connectors are not listed since there are many options available and these can be selected based on user preference as well as the specifications of the motors and encoders.

Item	Qty	Cost	Details
Motion Platform			
Motors	2	$2,000	Non-magnetic HR4 motors from Nanomotion Ltd, driven in parallel. Order with the length of cabling required to reach the filterbox in the magnet room.
Ceramic Strip	2	$200	A ceramic strip is required for each motor. The strip is attached to the linear slide and must be sized to the length and height of the slide. The strips can be purchased from Nanomotion.
Encoder	1	$1,500	LIA20 (non-magnetic) optical encoder with a glass strip. Order the encoder with the desired length of cable required to reach the filterbox in the magnet room
Plastic/Hardware		~$2,000	
Linear Slides	3	$450	Non-magnetic linear ball slides from Deltron Inc
Abdominal Phantom	1	$2,500	Model 057 A from CIRS Inc. Optional for the system
Electronics Interface Box			
Power supply	1	$150	Require a dual output DC power supply to power the motor amplifier, and the encoder. Please make sure the current handling of the motor output is sufficient for the amplifiers.
UMI Interface box	1	$400	Interface box from National Instruments to enable signal routing from the motor and encoder wires to the motion controller
Motor Amplifier	1	$1,200	AB2 piezo driver from Nanomotion
Encoder electronics	1	~$500	Electronics required to convert sin/cos signals into quadrature output. Obtained directly from the encoder manufacturer

Connectors, Enclosure, Misc		~$1,500	Parts required to make a suitable shielded enclosure for all the components of the system
Filter Box			
Housing	1	~$300	Suitable enclosure and hardware for mounting onto RF shield
D-sub filters	2	$150	Low-pass capacitive d-sub filters for motors and encoders
Computer			
PC	1	$1,800	Rack mount PC with PCI slots to enable installation of motion controller
Mobile cart	1	$250	Portable cart to transport system to and from MRI
Cabling	1	$250	NI cable to connect motion controller to electronics interface box
Motion controller	1	$3,000	4 axis servo controller (PCI-7344) from National Instruments
Labview/Matlab			Cost depends on software license agreements between vendors and users
Cabling/Connectors		$750	Miscellaneous cabling/connectors between filter box and electronics interface box and PC
Total Cost of Materials		~19,000	Includes cost of phantom. Does not include cost of software. Savings with respect to cabling/hardware may be possible depending on available supplies.

Labour Estimates:

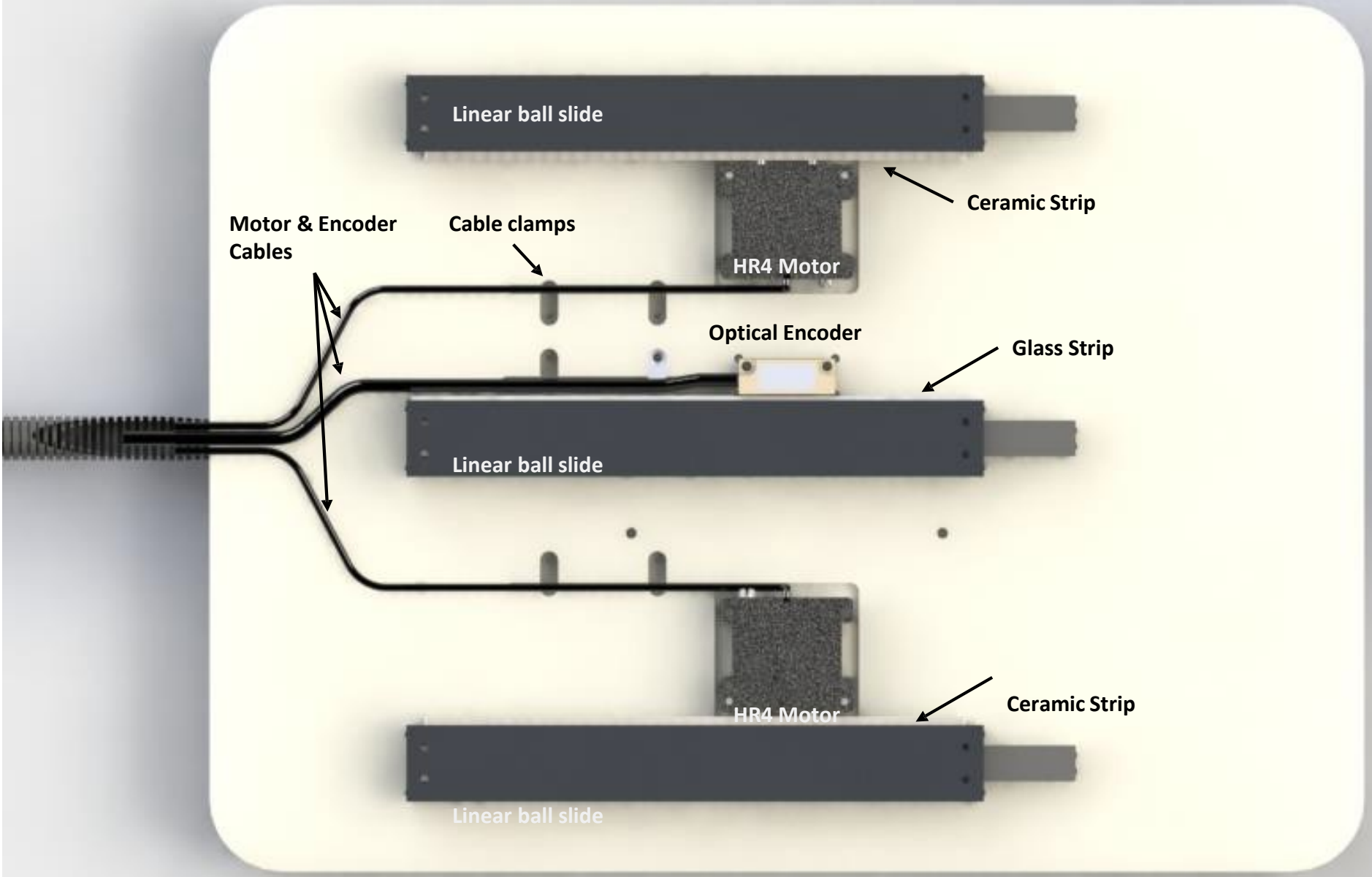
The time required to develop the system depends strongly on the available local resources and expertise in electro-mechanical manufacturing, assembly, and testing. The estimates below represent the time required for our group to assemble a system. The significant investment in development of this system is not included.

Detail	Estimate
Manufacturing of Components & parts	30-40 hours
Electrical Wiring and cabling	30-40 hours
Assembly, system testing, and tuning	30-40 hours

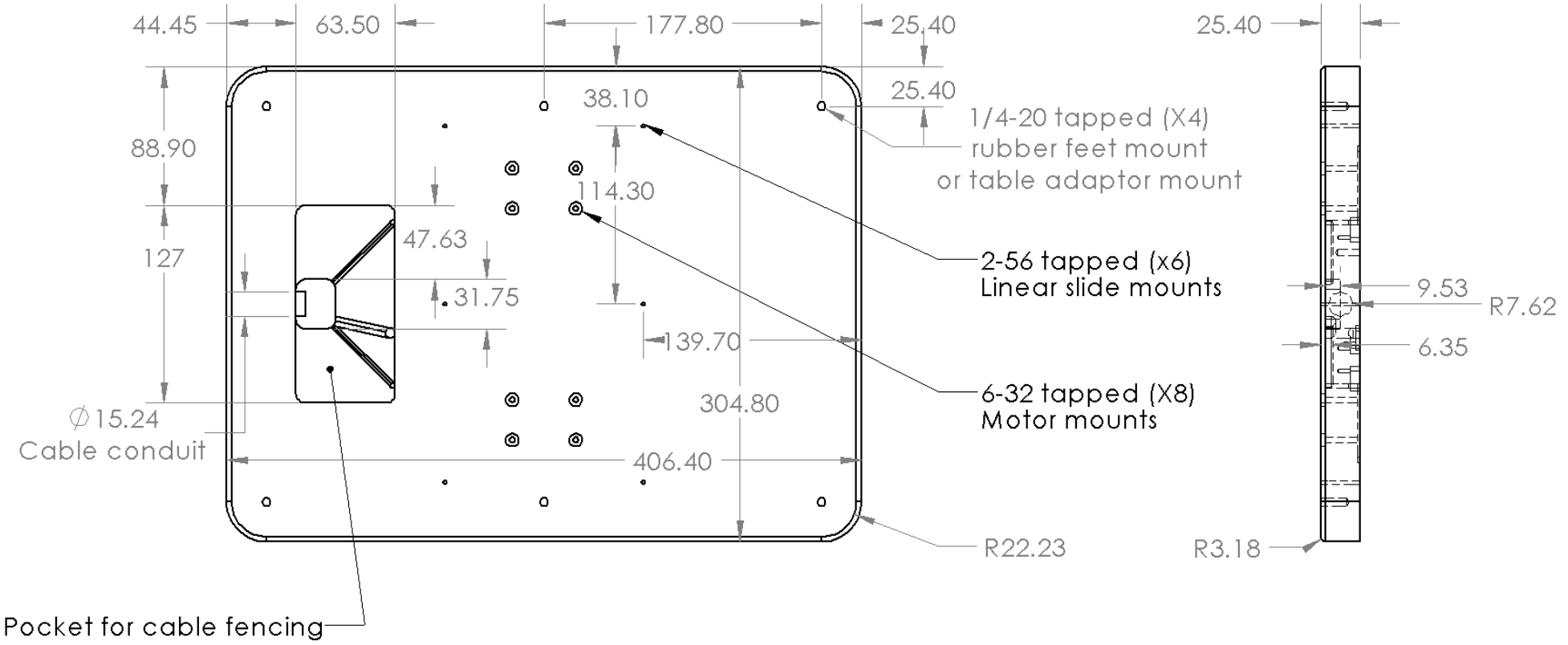
Appendix

Supplementary files have been included with this document including:

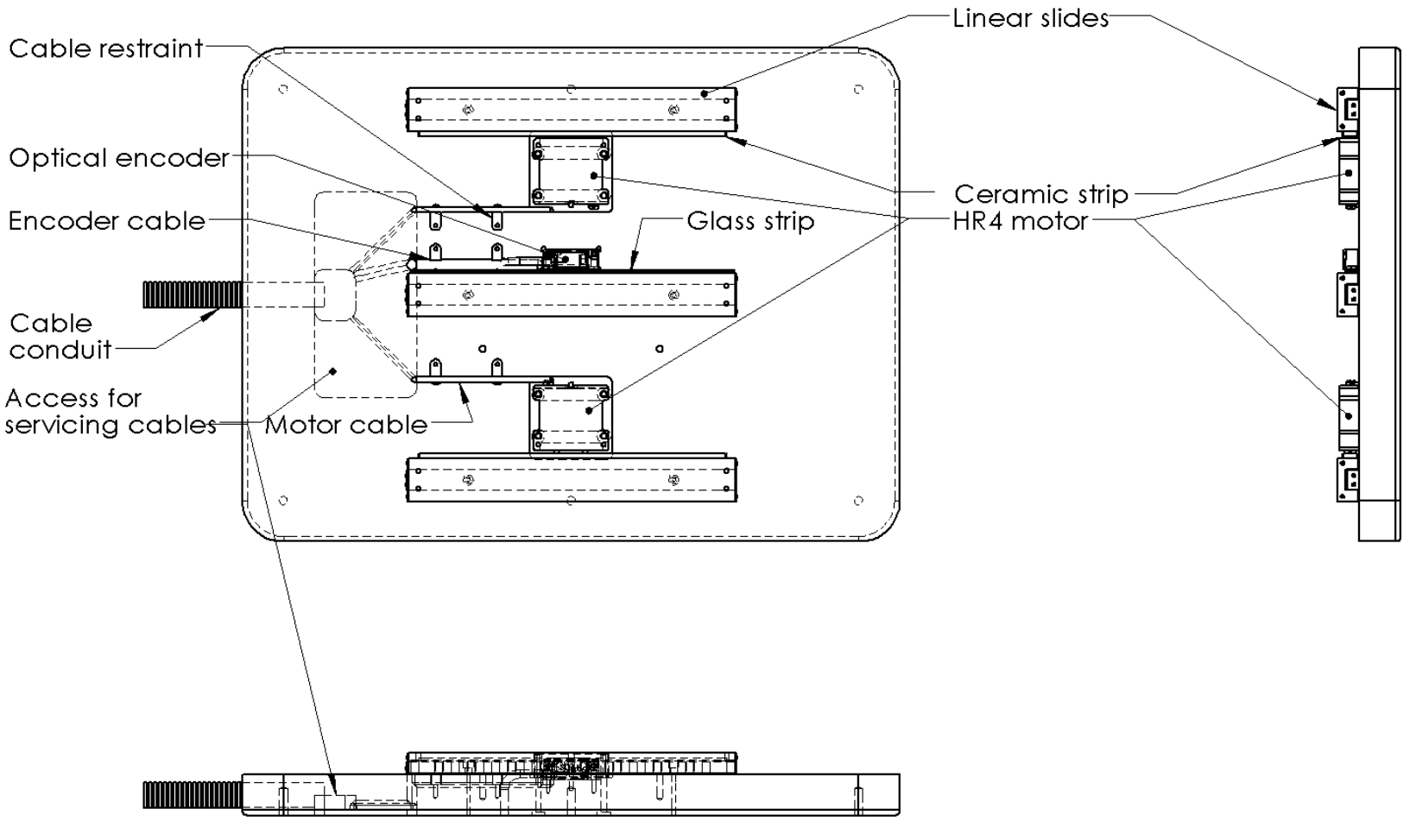
1. Shop drawings (pdf) have been included for the motion platform and relevant components.
2. A software manual has been included that outlines the features of the software developed in Labview to control the platform. Please contact Rajiv Chopra if you are interested in the software.
3. An assembly manual for the version of the platform used on the Philips Ingenia 3T, as described in the accompanying paper, is included.
4. The physiological motion trajectories obtained from a volunteer, are included as text files. The files include the position of the organ in 50 ms time steps. The duration of the motion is approximately 2 minutes and can be repeated as necessary.



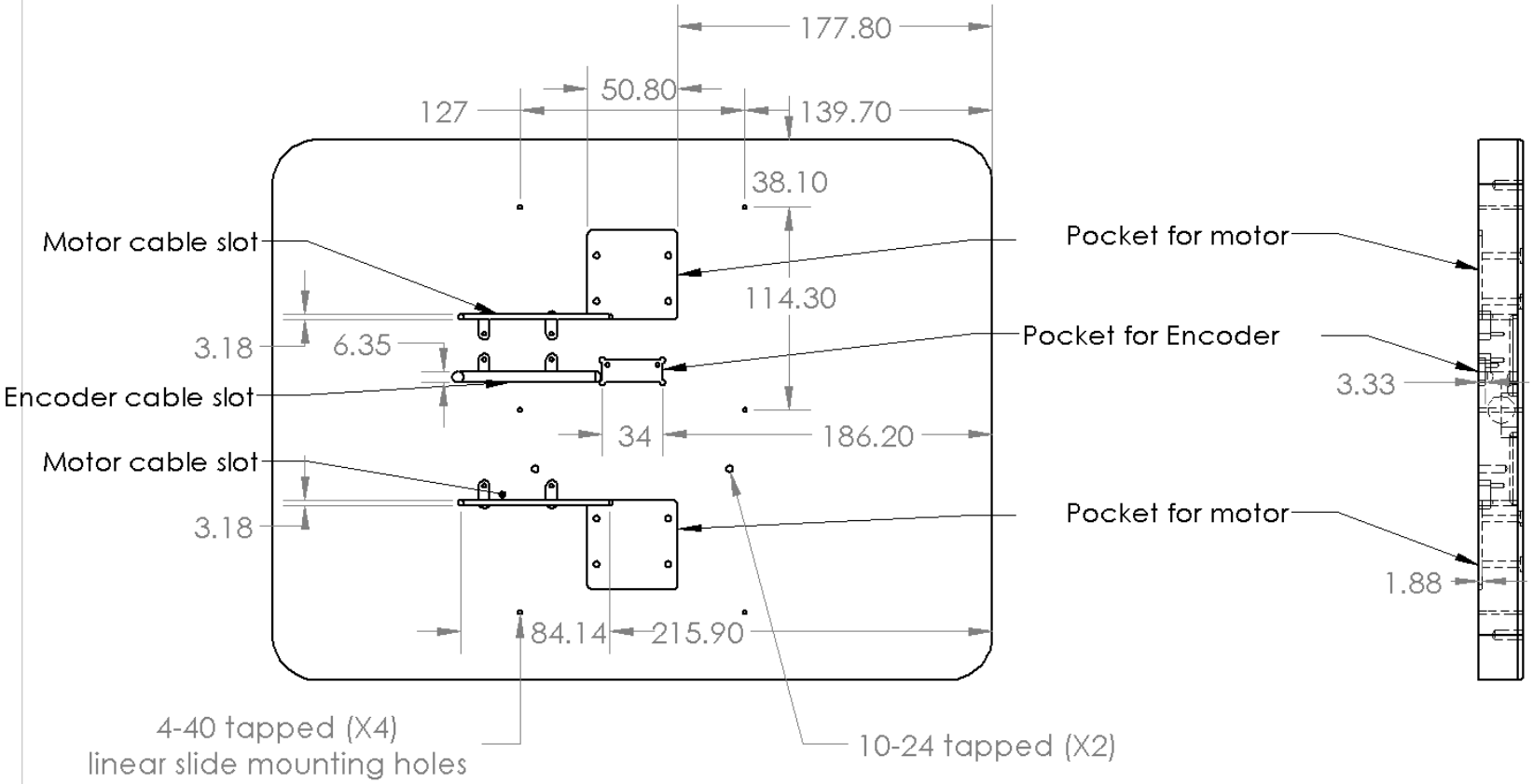
Bottom Plate



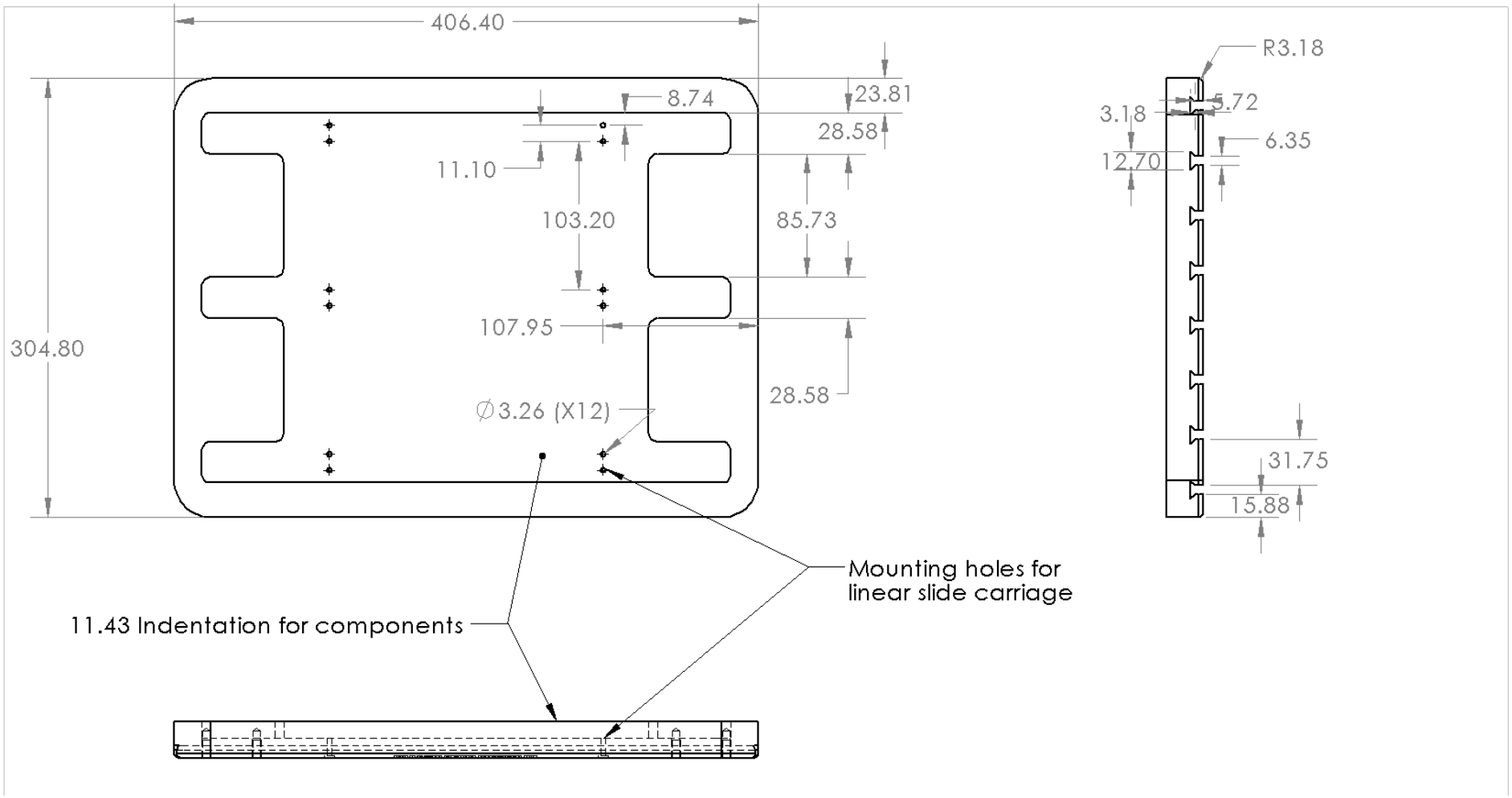
Bottom Plate – bottom view



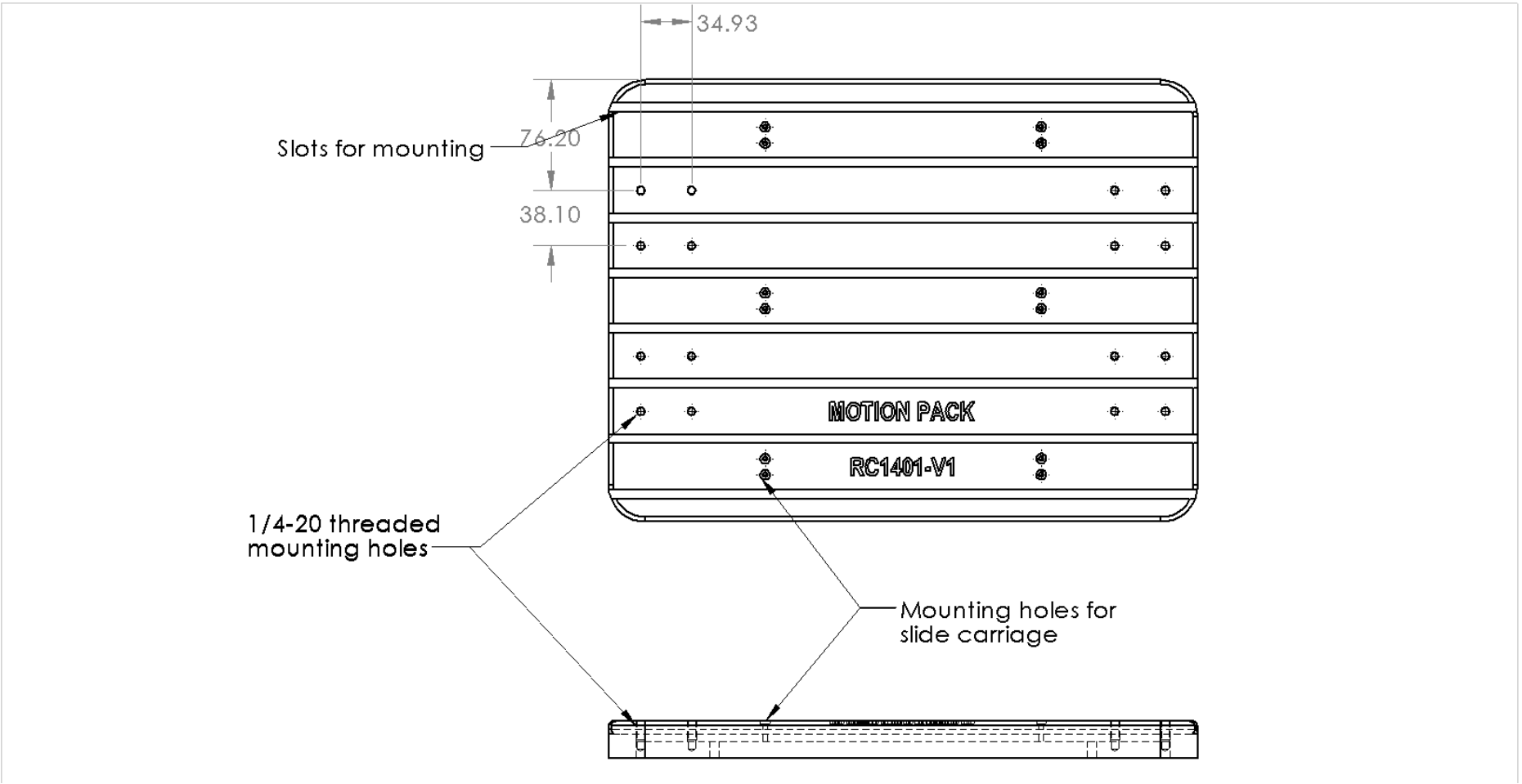
Base Plate – component view



Base Plate – top view



Top Plate – bottom view

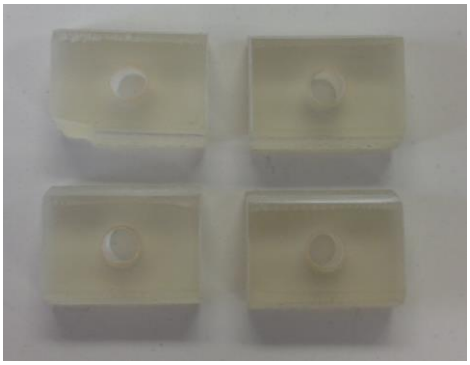


Top Plate – top view

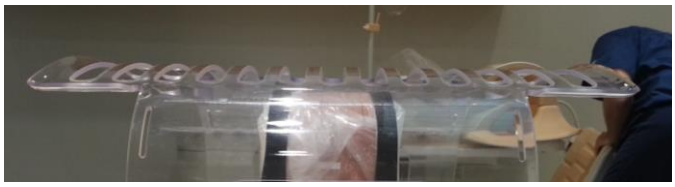
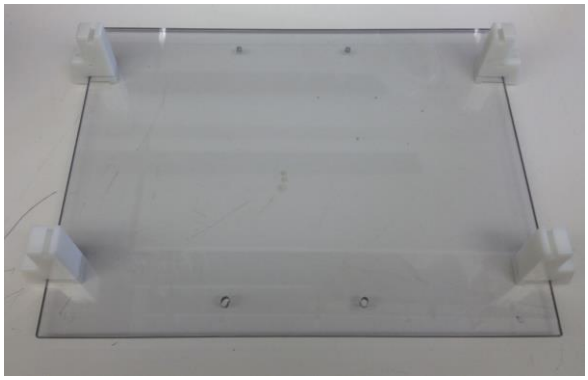
MRI Motion Platform Assembly

System Components:

Quantity	Item	Visual
4	1” Plastic thumb screw	
4	3/4” Plastic thumb screw	
4	2” Plastic thumb screw	

2	Rubber strap	
2	Velcro strap	
4	Slide-in table insert	
4	Slide-in velcro strap holder	

1	Motion pack and attached cable	
1	Filter box	
1	Phantom	
1	Pelvic Coil Receiver	

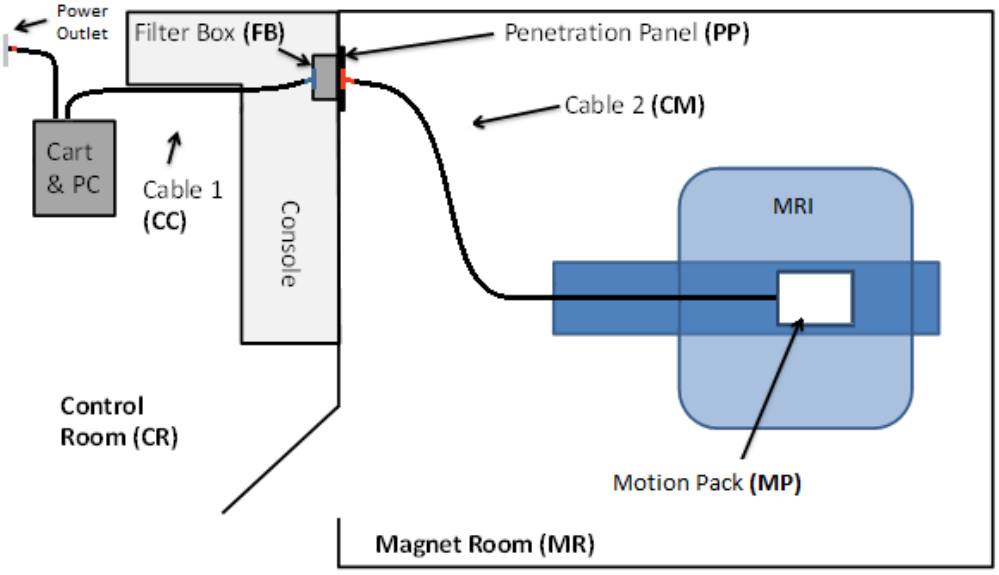
1	Plastic cover	
1	MRI soft strap for RF Receiver	
2	Slide-in soft strap holder	
1	Base plate	

1	Cart and PC	

Overview:

The MRI-compatible motion pack can be used in tandem with an anatomical phantom in order to produce quantifiable motion. Such motion can range from 1 mm to 12 cm displacements, represented by sinusoidal movement or custom waveforms, both manipulated by a program specifically designed for motion pack control. The cart and attached PC is used to manipulate the motion pack from within the control room. All motion pack control is done outside of the magnet room.

The motion pack controller works through a two-cable filter box system, in which signals are sent from the computer, to cable 1 (CC), through the filter box, to cable 2 (CM), and are ultimately translated into movement by the motion pack from within the MRI. In order to operate the motion pack, the cart should be plugged into a standard three-prong power outlet from within the control room, which will then power the entire system once the motion pack is connected. Pictured below is the setup of the entire motion pack system.



Control Room Connections:

1. Install the filter box (FB) onto the Penetration panel (PP). The FB contains electronics necessary to remove any electrical interference when the motion pack is operational. which might corrupt the MR images. It is attached to the penetration panel since this connection point for passing electrical signals into the MRI. First remove the blank plate on the penetration panel (unscrew the eighteen screws) and replace the plate with the FB. Attach it by screwing the eighteen screws necessary back into the penetration panel to hold it in place. **MAKE SURE THE SIDE OF THE FILTER BOX WITH ORANGE TAPE IS FACING THE MRI ONCE IT IS ATTACHED.**

2. Connect the cable labeled cable 1 (CC) to the FB. The cable extends from the cart and has two connectors, one for the motors and the other for the encoders. The connectors are different size and should be inserted into the matching receptacle on the FB. The connectors can only be inserted in a particular orientation – it may take slight rotation to find the point where the connectors can be inserted into the receptacle, which will be when the red dots on both cables face upward.

PLEASE ENSURE THE COLOUR OF TAPE ON THE CONNECTORS MATCHES WITH THE COLOR OF TAPE ON THE FB. IF NOT, THE FB IS ATTACHED BACKWARDS AND MUST BE FLIPPED. THE SYSTEM WILL NOT RUN IF THE FB IS NOT INSERTED IN THE CORRECT ORIENTATION.

Pictured above: Connectors from the cart plugged into the filter box.
Note the matching colors of the cables and box.

3. Plug in the cart power cable, located at the top left side of the cart and labeled with orange at the end, into any standard three-prong power outlet. This will give power to the PC, monitor, and controller box in order to move the platform. No other cables need to be plugged into a power outlet.

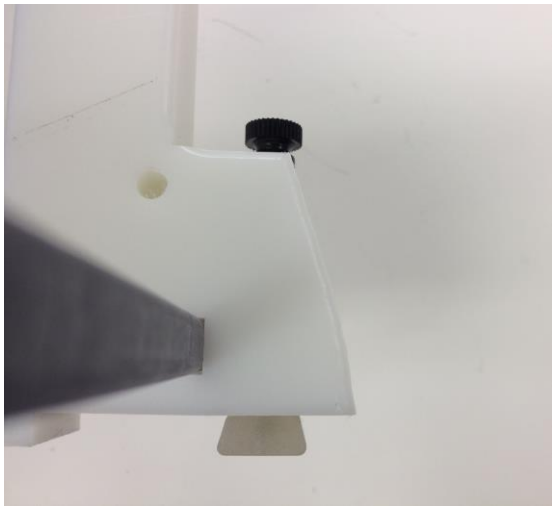
At this point all the necessary connections on the control room side are complete.

Magnet Room Connections:

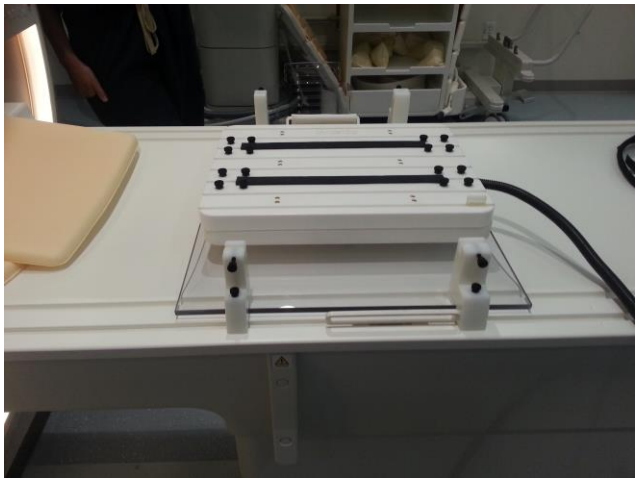
1. On the MRI table, slide in two of the four slide-in table inserts, one on each side of the table, then each followed by a slide-in soft strap holder and then another slide-in table insert. Refer to the photo below for the correct arrangement. The slide-in inserts are the mounting point for the plate that holds the motion pack. The strap holder is used to hold the pelvic coils once everything is in place.

Pictured above: One side of the MRI table with the soft-strap holder in-between the two slide-in table inserts.

2. Balance the motion pack vertically on a flat surface, making sure that the end with the cable connected is facing upwards. This position will make it the easiest to attach the base plate to the bottom of the motion pack. While the motion pack is vertical, align the holes on its bottom half with the holes on the base plate. **THE TOP SIDE OF THE MOTION PACK SHOULD ORIENT THE SAME DIRECTION AS THE SIDE OF THE BASE PLATE WITH PLASTIC PIECES EXTENDING A FEW INCHES FROM IT.**
3. Once the base plate and the motion pack holes are aligned, screw in the four 1” plastic thumb screws through the holes of the base plate and into the motion pack. This will ensure that the motion pack and base plate and tightly attached to one another.
4. Place the now-combined base plate and motion platform on top of the table, and line up each of the four slide-in table inserts with the holes in the plastic pieces extending outwards from the base plate. **THE END OF THE MOTION PACK WITH THE CABLE EXTENDING FROM IT SHOULD BE FACING AWAY FROM THE MRI, TOWARDS THE FILTER BOX ON THE PENETRATION PANEL.**
5. Screw in the four 2” plastic thumb screws through the plastic pieces extending outwards from the base plate and into the slide-in table inserts. Do not tighten them yet, so that the motion pack and combined base plate can slide along the table.



Pictured above: Side view of one of the plastic pieces of the base plate attached to one of the slide-in table inserts with a 2” plastic thumb screw.

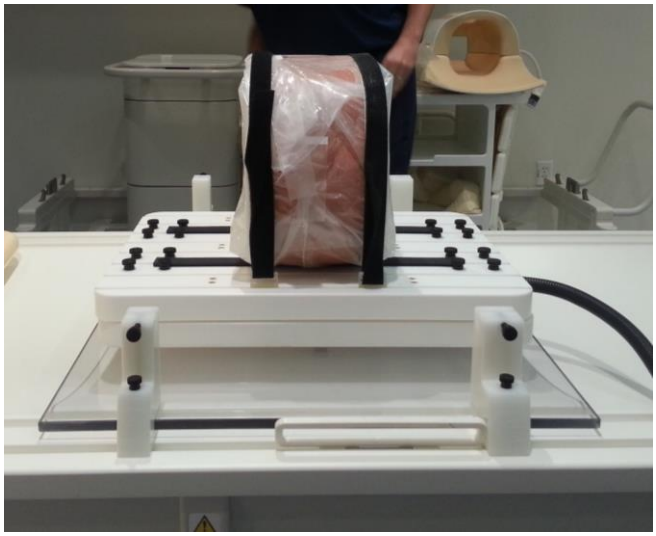


Pictured above: Motion platform attached to the base plate, which is then screwed into the four slide-in table inserts. Each of the soft-strap holders rests in-between the slide-in table inserts. Note the orientation of the motion pack, with its cable facing away from the MRI and towards the control room.

6. Place the two rubber straps on the motion pack parallel to its length, with each end of the straps laying in-between the four plastic screws coming out from the top of the pack at each corner. These are used to avoid slipping of the phantom on the stage during motion. They may not be necessary for all studies involving the motion pack.
7. Place the phantom on the motion platform with the end labeled “head” facing the MRI. The phantom should mainly be resting upon the rubber straps going end to end in order to reduce the amount of sliding that may occur.

8. Insert the four slide-in velcro strap holders into the outer slits of the motion pack, creating a rectangular boundary that encloses the phantom.
9. Place the two velcro straps across the phantom and insert the ends into the velcro strap-holders, first going through the bottom slot and looping back through and attaching to itself. Pull tightly to ensure the phantom does not move from its position on the motion pack. **MAKE SURE THE STRAPS ARE TRAVELLING OVER THE HARD PLASTIC CASE OF THE**

PHANTOM RATHER THAN THE SOFT PINK MATERIAL TO AVOID DAMAGING OR DISTORTING THE PHANTOM.



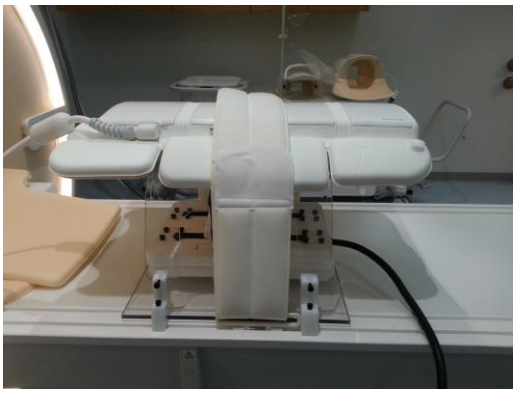
Pictured above: Phantom placed on top of the rubber straps of the platform, and held in place by the two velcro straps attached to the platform with the slide-in holders. Note that the velcro straps are not travelling over the soft tissue of the phantom, only the hard outer plastic.

10. Insert each extending corner of the plastic cover into the four slots of the plastic pieces of the base plate – there are no holes in the cover to align with those going through the plastic slots. The corners simply need to rest inside the slots so that the pelvic coil receiver can be safely positioned above the phantom for imaging.

11. Screw in the four 3/4” plastic thumb screws into the holes right next to the slots for the plastic cover. These will hold the plastic cover in place. **THE PLASTIC COVER SHOULD NOT BE ABLE TO BE MOVED OR LIFTED WHILE THE 3/4” SCREWS ARE IN PLACE.**

12. Place the Pelvic Coil Receiver centered on top of the plastic cover and plug it into its appropriate slot on the MRI table. The end of the receiver with the cable extending from it should be facing the MRI. The Pelvic Coil Receiver is necessary for being able to image the phantom. **MAKE SURE THAT THE RECEIVER COVERS THE WHOLE LENGTH OF THE BASE PLATE. THE RECEIVER MAY NOT COVER THE ENTIRE RANGE OF MOTION OF THE MOTION PACK IF IT IS NOT PLACED IN THE MIDDLE OF THE PLASTIC COVER.**

13. Place the soft strap on top of the Pelvic Coil Receiver and loop both ends through the slide-in soft-strap holders that are resting in between their two slide-in table inserts. Pull tightly to ensure the Receiver will not fall or slide off of the plastic cover.



Pictured above: Table attachment with the plastic cover on top and held in place.
The RF Receiver is then held in place with a soft strap, looped through the soft-strap holder.

14. Connect the cable labeled cable 2 (CM) to the FB. The cable extends from the motion pack and has two connectors, one for the motors and the other for the encoders. The connectors are different size and should be inserted into the matching receptacle on the FB. The connectors can only be inserted in a particular orientation – it may take slight rotation to find the point where the connectors can be inserted into the receptacle, which will be when the red dots on both cables face upward.
15. In the control room, turn the key lock on the front of the computer case to the right in order to open up the front panel where the power switch is located. This switch is designated by a circle with a vertical line through it and will turn on the PC when pressed. In addition, flip the switch located on the front of the motion pack control box to the "on" position, as designated by | for on and O for off.
16. The motion pack should now be controllable by the "Motion Pack Controller" application found on the desktop of the PC.

At this point all the necessary connections on the magnet room side are complete and the motion

Motion Pack Controller User Guide

Setup:

Please refer to the Motion Pack Assembly Guide on how to setup up the motion pack for testing within an MRI machine. This guide assumes that the system has been set up correctly and is ready for testing.

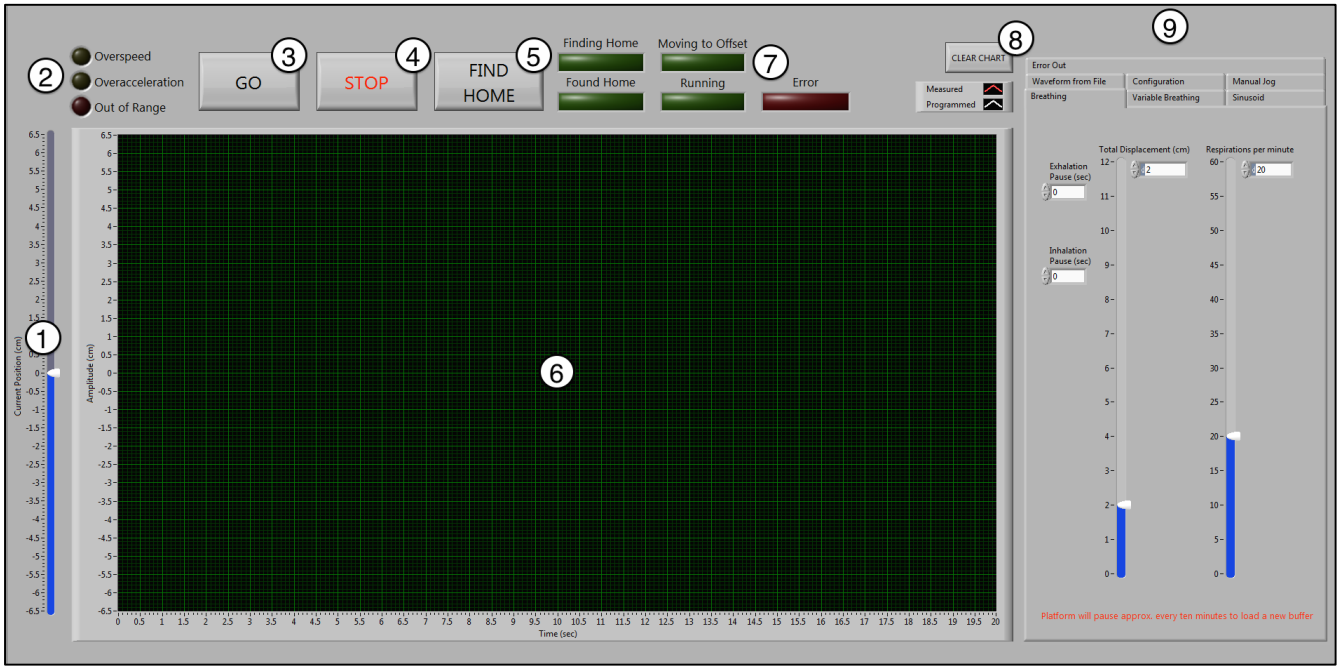
Startup:

Upon startup of the PC, a blue **POWER** light should turn on in the front and the Windows starting screen will appear on the monitor. If it does not appear, check that the monitor is plugged into the power strip at the back of the cart and that it is on - the power button for the monitor is located at the bottom right of the screen.

To be able to access to Motion Pack Controller application, make sure that the computer logs into to **Motion,** which should happen automatically. Once logged in, the Motion Pack Controller application will be available from your desktop screen.

Once the application starts up, the motion pack will quickly move back and then forward about half a centimeter - this is to make ensure that the motor is operating properly and is able to move. If this doesn't happen, the error light will turn on with the error **Motor is Off**, displayed under the **Error Out** tab. If this occurs, check that the power switch for the Motion Pack Control Box, located under the computer, is in the **ON** position (represented by a |). Close out of the application and open it again once the control box is on.

Operation:



(1): **Current Position Slider:** Outputs the position of the motion pack relative to the last acquired home position (set as 0 cm) at all times, even when the pack is not moving or finding home.

(2): **Motion Warning Lights: Overspeed** and **overacceleration** yellow lights turn on to serve as a warning that the motion pack may malfunction due to the speed that it will be or is operating at. The **Out of Range** red light turns on to indicate that the currently selected contouring motion is out of the range of movement for the motion pack (6 cm both directions from home). The motion pack will not follow this motion (**GO** will not function) until the problem is resolved.

(3): **GO Control:** Starts the currently selected contouring motion for the motion pack. Once it is pressed, it does not need to be pressed again. The motion pack will continue to move until **STOP** is pressed. To start motion again, simply press **GO**. Will not operate when the **Out of Range** warning light is on or the currently selected tab is not for contouring motion (**Manual Jog** or **Error Out**).

(4): **STOP Control:** Immediately halts all motion pack movement. If the pack does not stop moving at its offset, the motion pack will move back to the currently selected offset. Only needs to be pressed once to stop all motion. Will not stop **FIND HOME** motion or prevent the pack from moving to its offset when pressed.

(5): **FIND HOME Control:** Has the motion pack find its center position (home) and then move to its designated offset. Ensures that the motion pack can correctly calculate out of range and other motion errors. It is recommended to find home upon application startup. Will not operate while the pack is following contour motion.

(6): **Waveform Graph:** Outputs the programmed motion and measured motion in real time, side by side, whenever the platform is running. Does not graph finding home motion or moving to offset motion. Will store up to twenty seconds of movement and will begin to scroll once that limit is exceeded.

(7): **Operation Lights:**

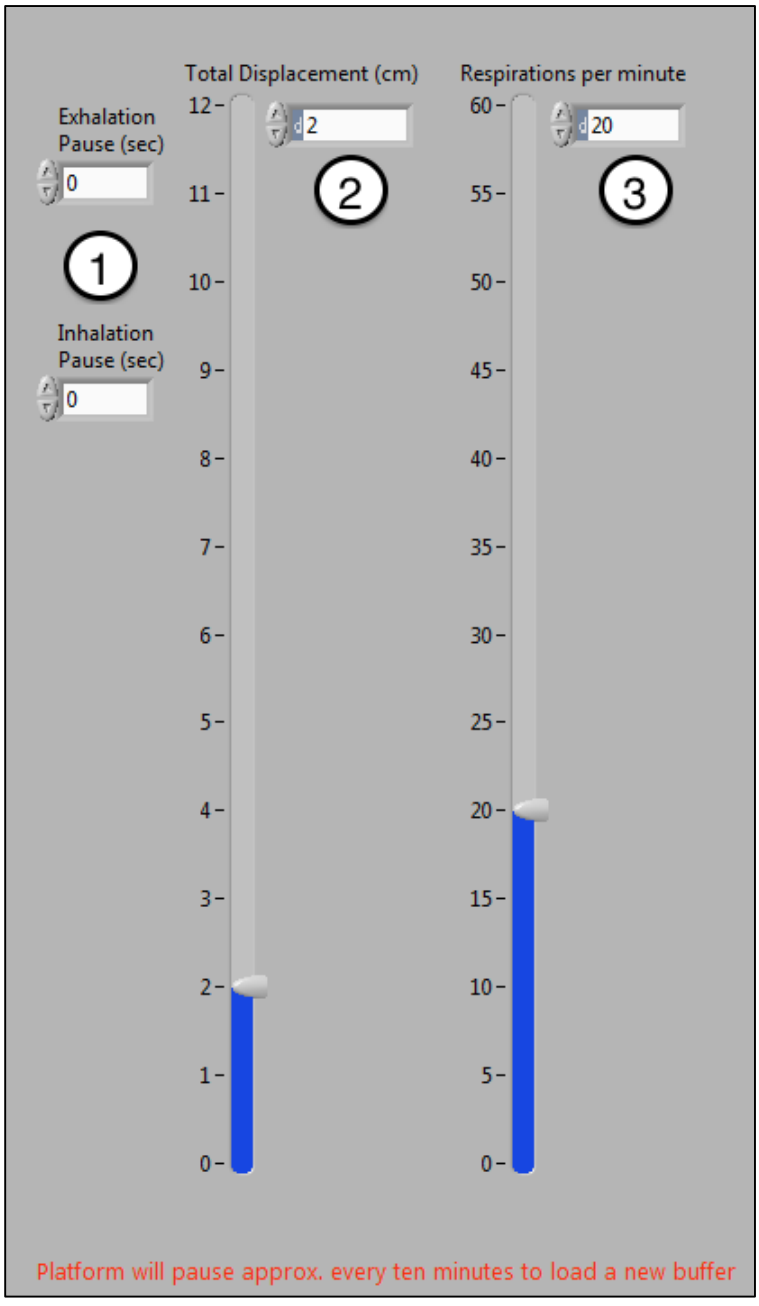
- **Finding Home** indicates that the motion pack is in the process of finding home, and will turn off once it is found.
- **Found Home** indicates that the last time **FIND HOME** was pressed, home was successfully found. Will turn off whenever **FIND HOME** is pressed and will not turn back on until home is found. Is by default off when the application starts.
- **Moving to Offset** indicates that the motion pack is currently moving to its designated offset. Will turn off whenever the motion pack reaches its offset position.
- **Running** indicates that the motion pack is currently following contouring motion. Will turn on when **GO** is pressed and the pack starts moving and will turn off when **STOP** is pressed and the pack stops moving.

- **Error** indicates that the application or motion pack has encountered an error. This error will be output in the **Error Out** tab with its error code and description. An error will not cause the application to close.

(8): **CLEAR CHART Control and Waveform Legend: CLEAR CHART** will wipe the history of the waveform graph, but does not affect the save file that is storing the contouring points of the pack. The waveform legend indicates which wave on the graph corresponds to the programmed motion and measured motion.

(9): **The Seven Modes of Operation:** Breathing, Variable Breathing, Sinusoid, Waveform from File, Configuration, Manual Jog, and Error Out. Each mode will be covered in detail.

Breathing:

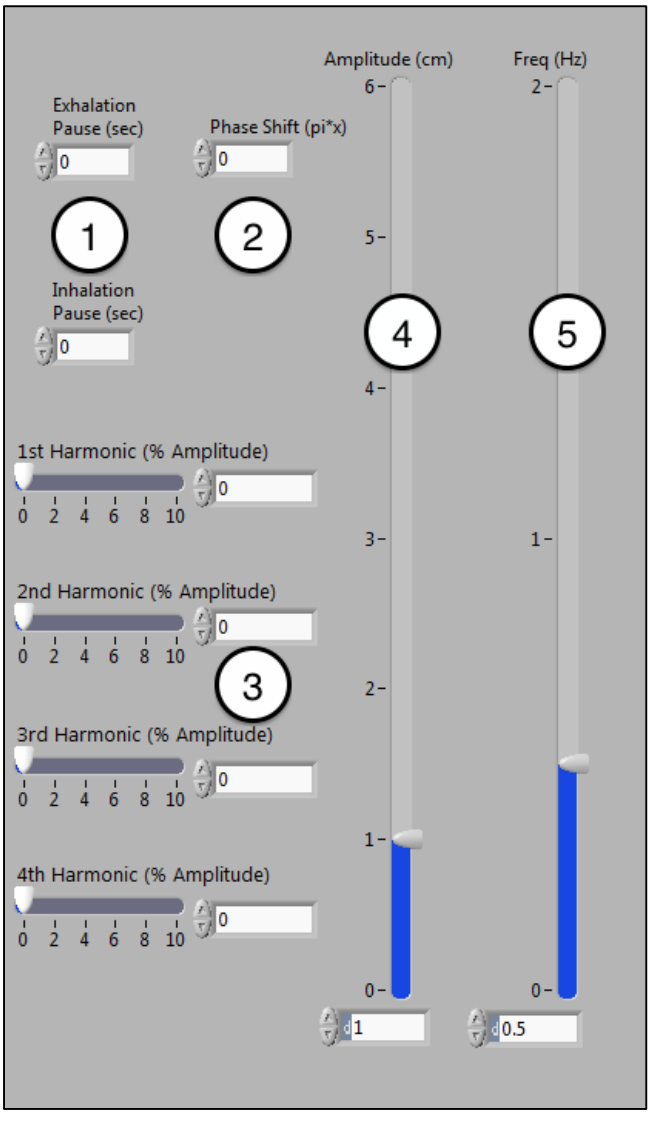


(1): **Exhalation and Inhalation Pauses:** Will have the motion pack stop moving at the maximum and minimum distance from the center of the waveform for a set amount of seconds each breath. Exhalation pauses will stop the pack at its maximum and inhalation pauses will stop the pack at its minimum. Exhalation pauses will occur at the first maximum of each waveform. Can be any real number equal to or greater than 0.

(2): **Total Displacement:** The total distance covered by the motion of the pack (2x the amplitude of the waveform). Will not exceed 12 cm (the maximum range of motion of the motion pack) and does not need to be an integer number. The motion pack will automatically move to a calculated offset so that the zero of the waveform is at its home position. This can be altered in the **Configuration** tab. Can be any real number inclusively between 0 and 12.

(3): **Respirations per Minute:** The number of cycles, or breaths, that the motion pack will go through every minute. Determines the speed of the motion pack. Must be an integer inclusively between 1 and 60.

Sinusoid:



(1): **Exhalation and Inhalation Pauses:** Will have the motion pack stop moving at the maximum and minimum distance from the center of the waveform for a set amount of seconds each breath. Exhalation pauses will stop the pack at its maximum and inhalation pauses will stop the pack at its minimum. Exhalation pauses will occur at the first maximum of each waveform. Can be any real number greater than or equal to 0.

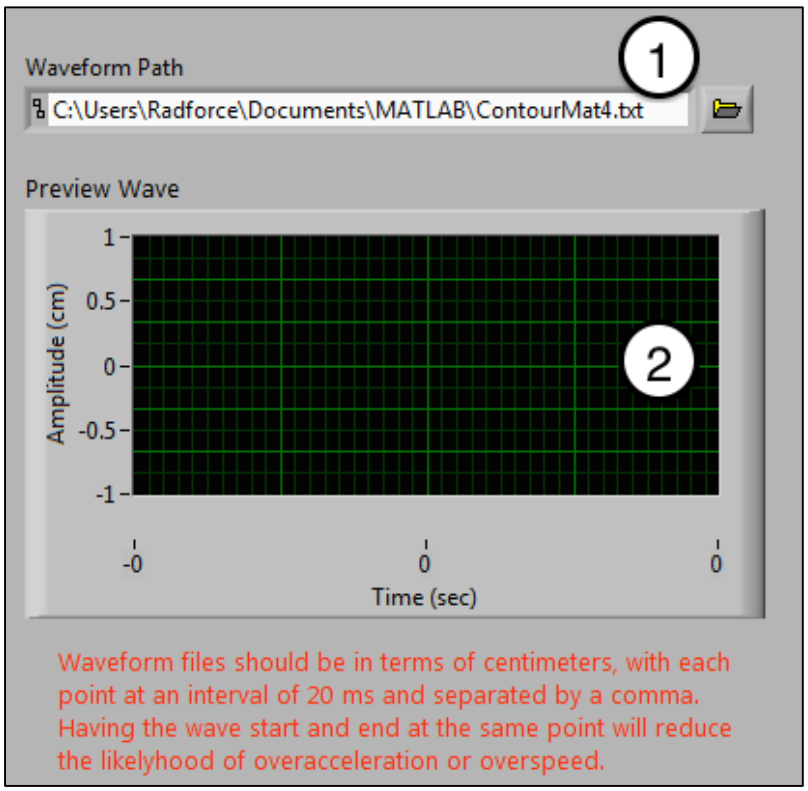
(2): **Phase Shift:** Shifts the starting point of the waveform by pi*x, where x is the numerical value entered. Phase shifts that are not integer values will often cause overspeed and overacceleration warnings, but are still viable for use. Can be any real number.

(3): **Harmonic Sliders:** Controls the amplitudes of the first four harmonic waveforms based on the original. The frequencies of the harmonics are set integer multiples of the original (first harmonic is 2x the original frequency, second is 3x, etc.). Amplitudes can be set as % values of the original amplitude, up to 10%. Large values for all four harmonics often gives overspeed and overacceleration warnings, but are still viable for us. Can be any real number inclusively between 0 and 10.

(4): **Amplitude:** The amplitude of the contour waveform that the motion pack will be following, in centimeters. Will not exceed 6 cm. A 4 cm amplitude equals an 8 cm displacement. The motion pack will automatically adjust its offset so that the center of the waveform is located at the pack's home position. Can be any real number inclusively between 0 and 6.

(5): **Frequency:** The number of cycles, or breaths, that occur every second. Cannot exceed 2 Hz. A 0.5 Hz frequency is equal to 30 respirations per minute, as 1 breath occurs every two seconds. Can be any real number inclusively between 0 and 2.

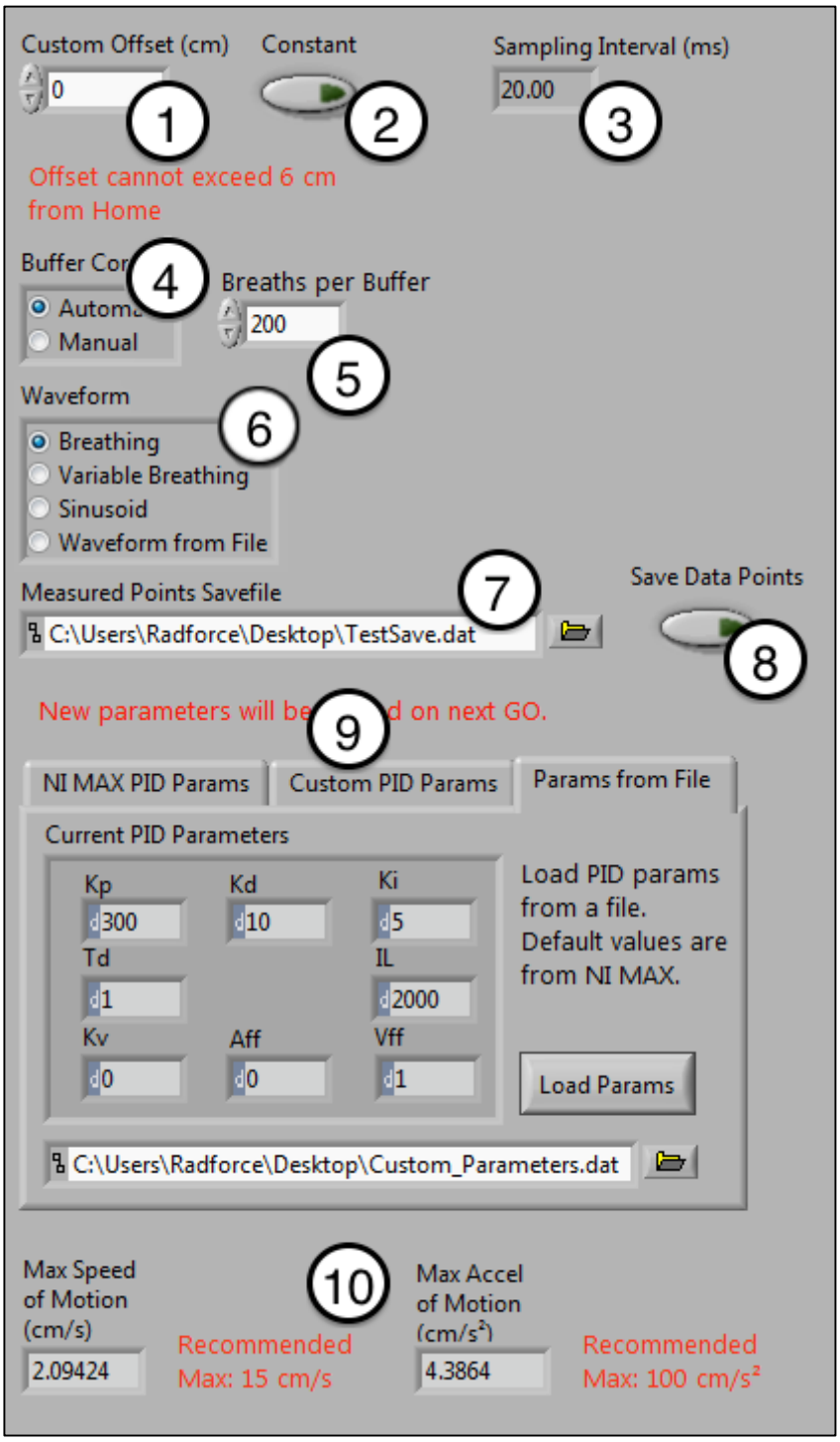
Waveform from File:



(1): **Waveform Path:** The file path to access the points corresponding to a custom waveform. File must be in the .txt format. Default path is a custom MATLAB file.

(2): **Preview Wave:** Automatically shows a small preview of the currently selected waveform. Will automatically scale to the length of time one cycle takes at an interval of 20 ms per point. Also automatically scales to the amplitude of the waveform.

Configuration:



(1): **Custom Offset:** Sets an offset that, as long as the **Configuration** tab is selected, will be applied. Can be used to have one offset across all three modes of contouring (**Breathing, Variable Breathing, Sinusoid, Waveform from File**) when selecting the mode through the radio buttons under **Waveform**.

(2): **Constant:** Makes the **Custom Offset** apply no matter what tab or radio button is selected. However, **Manual Jog** will override the **Custom Offset**. Will apply as long as the **Constant** button light is on.

(3): **Sampling Interval:** Indicates the interval at which the motion pack reads in contouring points and records its position to a save file. Is set at a constant 20 ms.

(4): **Buffer Control:** The motion pack contouring points are stored on a buffer that is read as it moves through the points. However, the buffer has a maximum amount of storage that limits one buffer read to approximately ten minutes. The **Automatic** setting on **Buffer Control** will load the maximum amount of cycles possible, while the **Manual** setting will allow a custom amount of cycles to be loaded. Will apply the last settings created even when outside of the **Configuration** tab.

(5): **Breaths per Buffer:** Input for controlling the amount of cycles per buffer load. Will be automatically changed when **Automatic** is selected and can be manually changed when **Manual** is selected. Must be a positive integer that cannot exceed the maximum amount possible. Will apply the last settings created even when outside of the **Configuration** tab.

(6): **Waveform**: Selection of one of the four modes of contouring from within the Configuration tab. Only applies from within the **Configuration** tab. This allows for the custom offset to apply to any waveform, and for the maximum velocities and accelerations of each waveform to be analyzed. Pressing **GO** will run the contouring mode currently selected by the radio buttons, along with the custom offset.

(7): **Measured Points Savefile:** Destination pathway for saving the measured points of the platform when it is in motion. Saves each run to a line with recordings at an interval of 20 ms, and each data point separated by a comma. File format is .dat. Will not save each run unless **Save Data Points** is pressed.

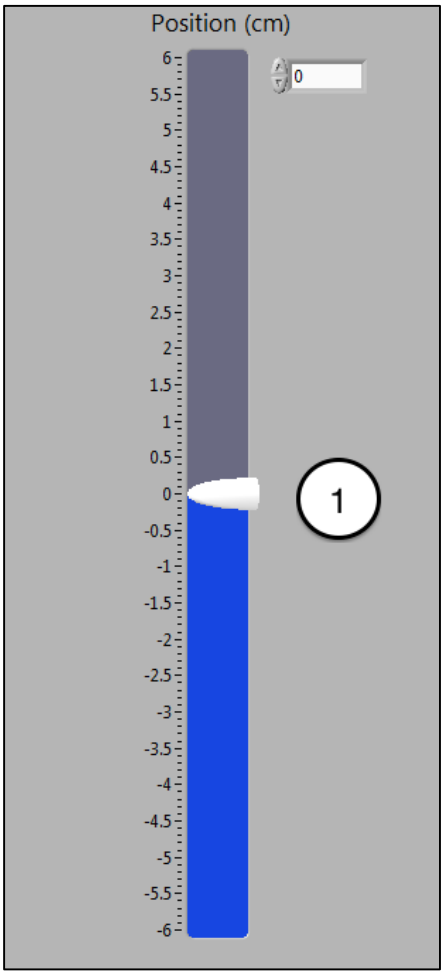
(8): **Save Data Points:** Controls whether or not each run is saved to a file. Default value is set to false. Will save points at every run if pressed once, and will turn off if pressed again.

(9): **PID Parameter Control:** PID values (which controls how the platform moves) can be set through three different options - Default, Custom, and Load. **NI MAX PID Params** will load the default PID Parameters set through NI MAX. This is also the default tab when the application is started. **Custom PID Params** will allow, from within the application, custom PID Parameters that will apply so long as the **Custom PID**

Params tab is not changed. **Params from File** will allow for loading of PID Parameters from a custom .dat file on the computer. Each value in the file should be on the same line, which each parameter separated by a space or tab over. The order of the parameters loaded from the file is: Kp, Ki, IL, Kd, Td, Kv, Aff, and Vff. Loaded PID parameters will not apply until "Load Params" is pressed. The default values for all three tabs are those from NI MAX.

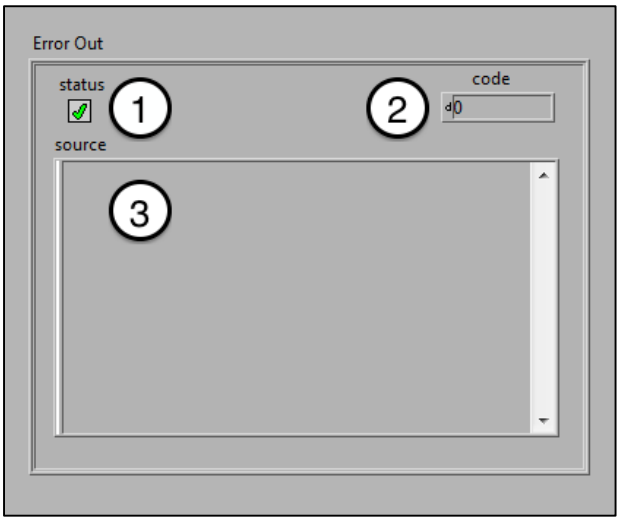
(10): **Max Speed of Motion and Max Accel of Motion:** The maximum acceleration and speed that the platform will undergo while running the currently selected tab from within configuration. To the side of the indicators are the recommended maximum values. Exceeding those two values will cause the overacceleration or overspeed lights to turn on.

Manual Jog:



(1): **Manual Jog Control:** Sets the current position of the motion platform. The platform will move to any value indicated by the slider, and this position will override the constant offset set by the configuration tab. **GO** will not function while on this tab because there is no specified motion.

Error Out:

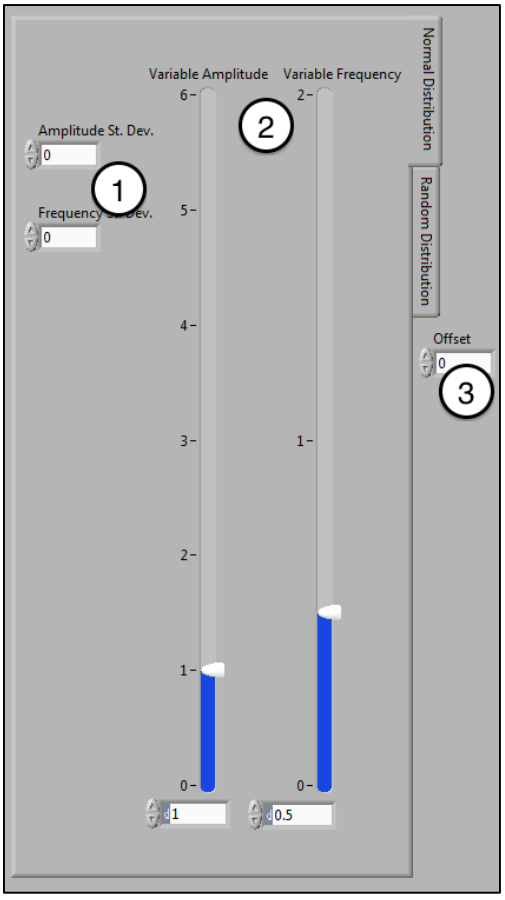


(1): **Error Status:** Details whether or not an error has occurred - a green check mark either means that there is no error or that there is only a warning.

(2): **Error Code:** Gives the error code for that specific error, some of which may be looked up online, if it is a common NI Motion error. 0 means no error.

(3): **Error Dialog Box:** Details what the error means and possibly where it arises from. Will be blank if there is no error.

Variable Breathing, Normal Distribution:

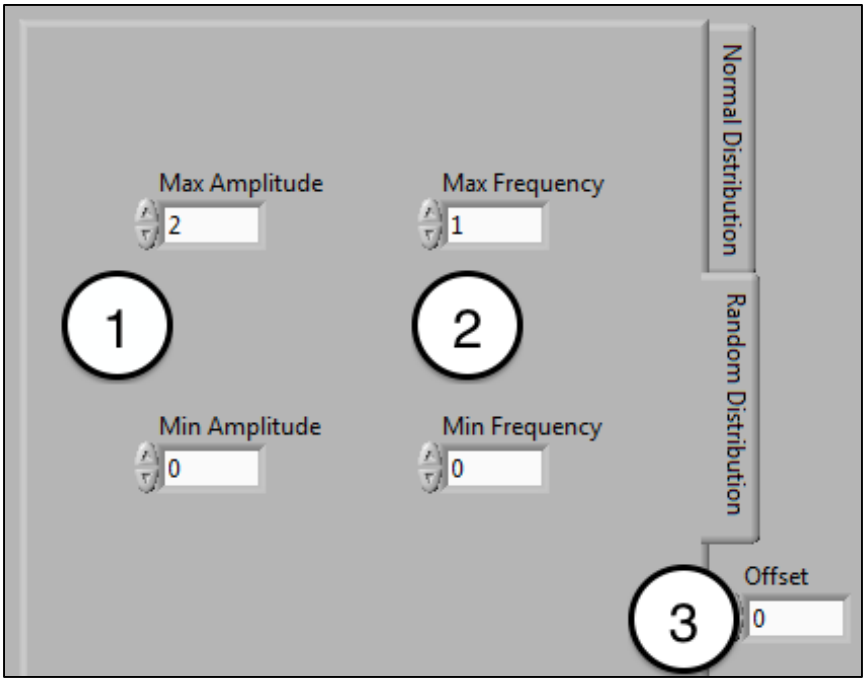


(1): **Amplitude and Frequency Standard Deviations:** Controls the standard deviation of the set amplitude and frequency of the waveform. Amplitude standard deviation cannot be any value that will cause an out range error within three standard deviations of the set amplitude. Frequency standard deviation cannot be any value that will cause a frequency greater than 2 Hz within three standard deviations of the set frequency. Waveform values will not exceed three standard deviations away from the set frequency or amplitude. Must be greater than or equal to 0.

(2): **Variable Amplitude and Frequency:** Controls the set mean amplitude and frequency. Every cycle, a new amplitude and frequency will be pulled from the normal distributions set by the mean amplitude and frequency and their respective standard deviations. Variable Amplitude can be any positive number inclusively between 0 and 6, while variable frequency can be any positive number inclusively between 0 and 2.

(3): **Offset:** Controls the current offset for the **Variable Breathing** tab for both **Normal Distribution** and **Random Distribution** motion. Can be any real number inclusively between 6 and -6.

Variable Breathing, Random Distribution:



(1): **Max and Min Amplitude:** Sets the boundaries for the range of values to be randomly pulled from when determining the amplitude of each cycle. **Max Amplitude** sets the maximum amplitude that can be randomly pulled from while **Min Amplitude** sets the minimum amplitude that can be randomly pulled from. All values randomly selected will lie within the range of **Min Amplitude** <= x <= **Max Amplitude**. **Min Amplitude** cannot be greater than **Max Amplitude**. If the two values are the same, the

only amplitude produced will be that of the value both **Min** and **Max** share. Both can be any real number inclusively between 0 and 6.

(2): **Max and Min Frequency:** Sets the boundaries for the range of values to be randomly pulled from when determining the frequency of each cycle. **Max Frequency** sets the maximum frequency that can be randomly pulled from while **Min Frequency** sets the minimum frequency that can be randomly pulled from. All values randomly selected will lie within the range of **Min Frequency** <= x <= **Max Frequency**. **Min Frequency** cannot be greater than **Max Frequency**. If the two values are the same, the only frequency produced will be that of the value both **Min** and **Max** share. Both can be any real number inclusively between 0 and 2.

(3): **Offset:** Controls the current offset for the **Variable Breathing** tab for both **Normal Distribution** and **Random Distribution** motion. Can be any real number inclusively between 6 and -6.

Description of trajectory files

The trajectories are written in a text file, in the form of points separated by commas (see trajectory examples below). Each value represents the position of the platform from the home position over time.

Unit: The data is in units of centimeters. At least 3 decimal points are recommended.

Stepping frequency: Data points are read every 20 milliseconds, i.e. 50 points are read over one second. A higher or lower simulated stepping frequency can be achieved by up sampling or down sampling the trajectory by linear interpolation, but this will result in a non-realistic motion.

Time buffer: A maximum of 10 minutes of trajectory length is currently supported, which is equivalent to 30,000 points in total. At the end of the file, the trajectory is repeated from the beginning.

Special considerations:

- When creating a trajectory file, it is necessary to match the first and last points, such that when all of the points are read, the transition to the beginning of the trajectory is smooth.
- If possible, it is preferable to start the trajectories at the 0 location to avoid a “jump” to the first value. To do this, an offset corresponding to the first value of the trajectory can be added.
- If the previous point is not achievable, the starting value of the trajectory must be between -0.35 cm and 0.35 cm.

Left Kidney trajectory

0.31436,0.29396,0.27445,0.25586,0.23801,0.22112,0.20522,0.19031,0.17643,0.16356,0.15172,0.14091,0.13111,0.12214,0.11418,0.10723,0.10128,0.096335,0.09237,0.089367,0.087302,0.086144,0.085696,0.086107,0.087358,0.089423,0.092275,0.09588,0.1002,0.1052,0.11083,0.11691,0.12355,0.13071,0.13836,0.14646,0.15498,0.16386,0.17306,0.18255,0.19214,0.20193,0.21188,0.22195,0.23212,0.24234,0.25258,0.26279,0.27294,0.28289,0.29272,0.30241,0.31191,0.32123,0.33032,0.33918,0.34777,0.35607,0.36398,0.37158,0.37886,0.38582,0.39245,0.39875,0.40473,0.41037,0.41568,0.42056,0.42512,0.42939,0.43337,0.43709,0.44056,0.4438,0.44684,0.44968,0.45224,0.45466,0.45697,0.45922,0.46144,0.46366,0.46592,0.46825,0.47067,0.47306,0.47563,0.47842,0.48146,0.48481,0.4885,0.49257,0.49705,0.50197,0.50716,0.51288,0.51914,0.526,0.53349,0.54165,0.55049,0.56005,0.57033,0.58114,0.59271,0.60509,0.61828,0.63232,0.64722,0.66297,0.67959,0.69705,0.71513,0.73405,0.75382,0.77445,0.79593,0.81824,0.84136,0.86526,0.88992,0.91505,0.94087,0.96736,0.99449,1.0222,1.0505,1.0794,1.1087,1.1384,1.1682,1.1984,1.2288,1.2594,1.2901,1.321,1.3519,1.3827,1.4135,1.4438,1.4739,1.5037,1.5332,1.5622,1.5908,1.6187,1.6461,1.6727,1.6985,1.7233,1.7473,1.7704,1.7924,1.8134,1.8333,1.852,1.8695,1.8855,1.9003,1.9137,1.9257,1.9362,1.9453,1.9529,1.959,1.9635,1.9663,1.9676,1.9672,1.9652,1.9617,1.9565,1.9497,1.9413,1.9313,1.9197,1.9064,1.8916,1.8753,1.8575,1.8383,1.8177,1.7957,1.7724,1.7477,1.7217,1.6946,1.6663,1.637,1.6066,1.5754,1.5433,1.5103,1.4764,1.4419,1.4068,1.3711,1.335,1.2985,1.2618,1.2248,1.1876,1.1502,1.1127,1.0753,1.0381,1.0011,0.96435,0.928,0.89206,0.85661,0.82147,0.78693,0.75308,0.71996,0.68765,0.65618,0.62561,0.59597,0.56729,0.53937,0.5125,0.48671,0.46204,0.43853,0.41618,0.39503,0.37507,0.3563,0.33849,0.32189,0.30651,0.29235,0.27941,0.26768,0.25714,0.24777,0.23953,0.23218,0.22592,0.22072,0.21658,0.21344,0.21128,0.21005,0.2097,0.21019,0.21127,0.2131,0.21563,0.21882,0.22262,0.22698,0.23185,0.23717,0.24288,0.24878,0.25496,0.26139,0.26801,0.27478,0.28165,0.28856,0.29548,0.30234,0.30899,0.3155,0.32184,0.32798,0.33387,0.33948,0.34479,0.34977,0.35438,0.3585,0.36222,0.36551,0.36837,0.37078,0.37275,0.37425,0.3753,0.37588,0.37591,0.37549,0.37462,0.37334,0.37164,0.36955,0.36709,0.36427,0.36113,0.3576,0.3538,0.34976,0.34552,0.34113,0.33661,0.33201,0.32736,0.3227,0.31796,0.31329,0.30875,0.30438,0.30023,0.29634,0.29275,0.28951,0.28665,0.28407,0.28196,0.28037,0.27932,0.27888,0.27906,0.27992,0.28146,0.28372,0.28656,0.29017,0.29458,0.29982,0.3059,0.31285,0.32067,0.32937,0.33894,0.34922,0.36037,0.37241,0.38534,0.39914,0.41381,0.42933,0.44567,0.46281,0.48055,0.49903,0.51822,0.53811,0.55867,0.57984,0.6016,0.62388,0.64665,0.66968,0.69309,0.71684,0.74088,0.76515,0.7896,0.81418,0.83882,0.86346,0.88788,0.91219,0.93631,0.96021,0.98381,1.0071,1.0299,1.0523,1.0741,1.0953,1.1158,1.1356,1.1546,1.1729,1.1904,1.207,1.2226,1.2373,1.2509,1.2634,1.2749,1.2852,1.2945,1.3026,1.3095,1.3152,1.3198,1.323,1.325,1.3258,1.3254,1.3238,1.3209,1.3169,1.3117,1.3052,1.2976,1.2888,1.2789,1.2679,1.2559,1.2428,1.2288,1.2138,1.198,1.1812,1.1635,1.1451,1.126,1.1062,1.0858,1.0648,1.0433,1.0214,0.99892,0.9761,0.95299,0.92965,0.90614,0.8825,0.8588,0.83508,0.8114,0.78765,0.76404,0.74063,0.71746,0.69459,0.67205,0.6499,0.62817,0.60688,0.58592,0.56549,0.54562,0.52636,0.50771,0.48973,0.47241,0.45579,0.43986,0.42447,0.40981,0.39589,0.38272,0.3703,0.35865,0.34774,0.33758,0.32815,0.31927,0.3111,0.30363,0.29685,0.29075,0.28529,0.28046,0.27623,0.27256,0.26929,0.26652,0.26425,0.26243,0.26105,0.26006,0.25944,0.25914,0.25912,0.25924,0.25957,0.2601,0.26078,0.2616,0.26251,0.26349,0.2645,0.2655,0.26637,0.26718,0.26791,0.26855,0.26906,0.26944,0.26965,0.26969,0.26952,0.26906,0.26837,0.26746,0.26632,0.26495,0.26335,0.26152,0.25945,0.25716,0.25455,0.25173,0.24872,0.24552,0.24217,0.23867,0.23505,0.23132,0.22751,0.22354,0.21953,0.21553,0.21156,0.20766,0.20386,0.20019,0.19669,0.19338,0.19017,0.18723,0.18459,0.1823,0.18039,0.1789,0.17787,0.17732,0.17729,0.17766,0.1786,0.18017,0.18238,0.18529,0.1889,0.19326,0.19837,0.20425,0.21076,0.21807,0.22622,0.23522,0.24509,0.25585,0.26748,0.28,0.2934,0.30748,0.32243,0.33826,0.35496,0.37253,0.39095,0.4102,0.43026,0.4511,0.47249,0.49462,0.51745,0.54096,0.56513,0.58992,0.61528,0.64118,0.66757,0.6942,0.72124,0.74863,0.77634,0.80433,0.83254,0.86092,0.88942,0.91798,0.94637,0.9747,1.003,1.0311,1.059,1.0867,1.114,1.1411,1.1677,1.1937,1.2193,1.2442,1.2686,1.2924,1.3155,1.3379,1.3595,1.3804,1.4003,1.4193,1.4374,1.4546,1.4709,1.4862,1.5005,1.5139,1.5262,1.5373,1.5473,1.5564,1.5643,1.5712,1.577,1.5818,1.5855,1.5882,1.5897,1.5901,1.5895,1.5879,1.5854,1.5818,1.5774,1.572,1.5657,1.5584,1.5503,1.5413,1.5316,1.5211,1.5099,1.4981,1.4856,1.4725,1.4587,1.4443,1.4295,1.4142,1.3984,1.3823,1.3659,1.3492,1.3322,1.3147,1.2971,1.2793,1.2614,1.2434,1.2253,1.2072,1.1891,1.171,1.1527,1.1345,1.1165,1.0985,1.0807,1.063,1.0456,1.0283,1.0112,0.9941,0.97723,0.9606,0.94421,0.92807,0.91218,0.89655,0.88117,0.86602,0.85092,0.83606,0.82143,0.80703,0.79286,0.7789,0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Right Kidney trajectory

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Spleen trajectory

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