Robot Phantom User Manual

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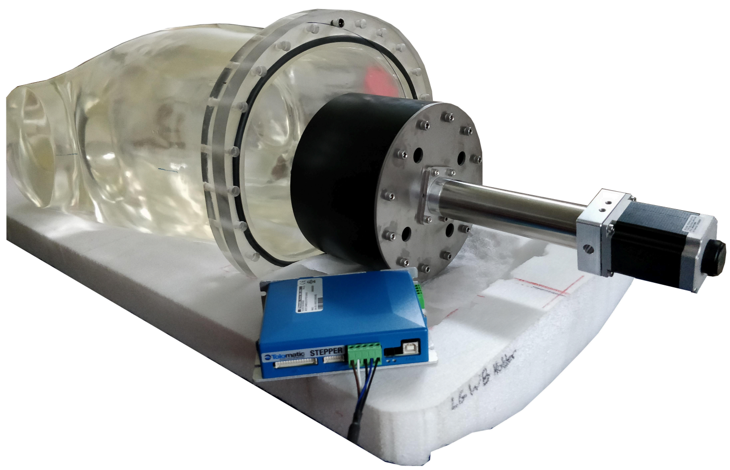

Contents

1 Components

This section identifies and explains all major components.

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Table 1: Summary of components, labeled as in Fig. 1, 2, 3

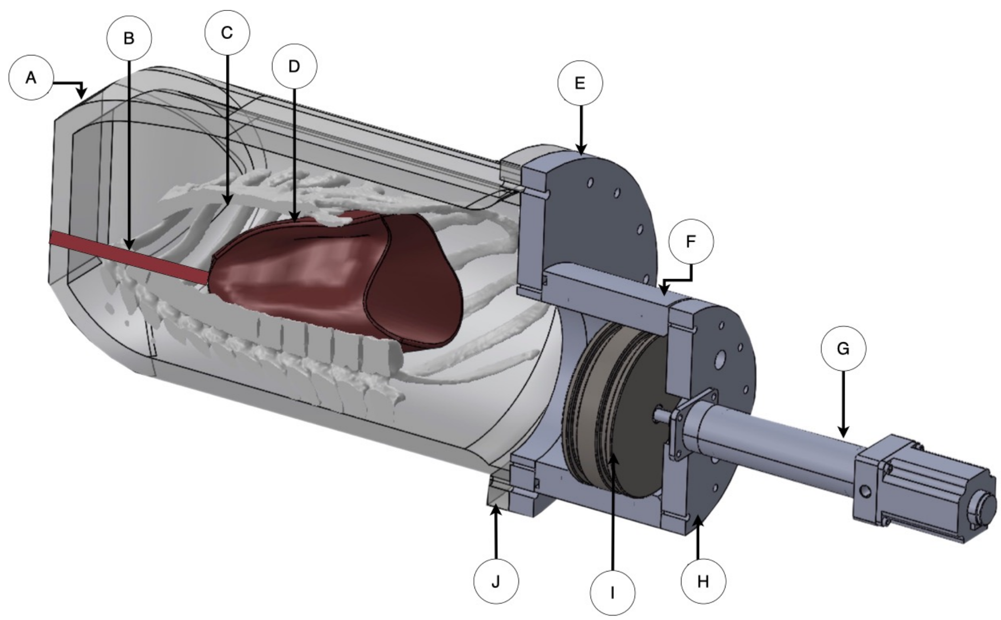

Figure 1: Phantom Components

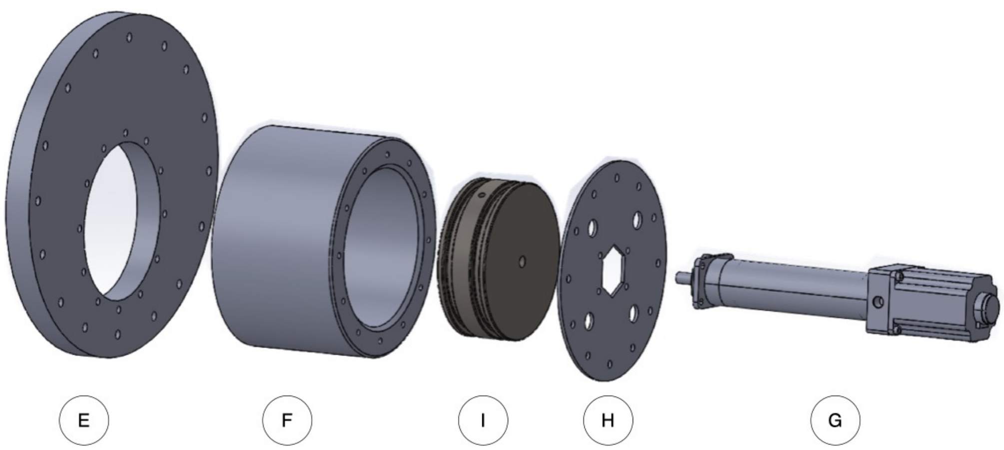

Figure 2: Exploded View of Actuation System

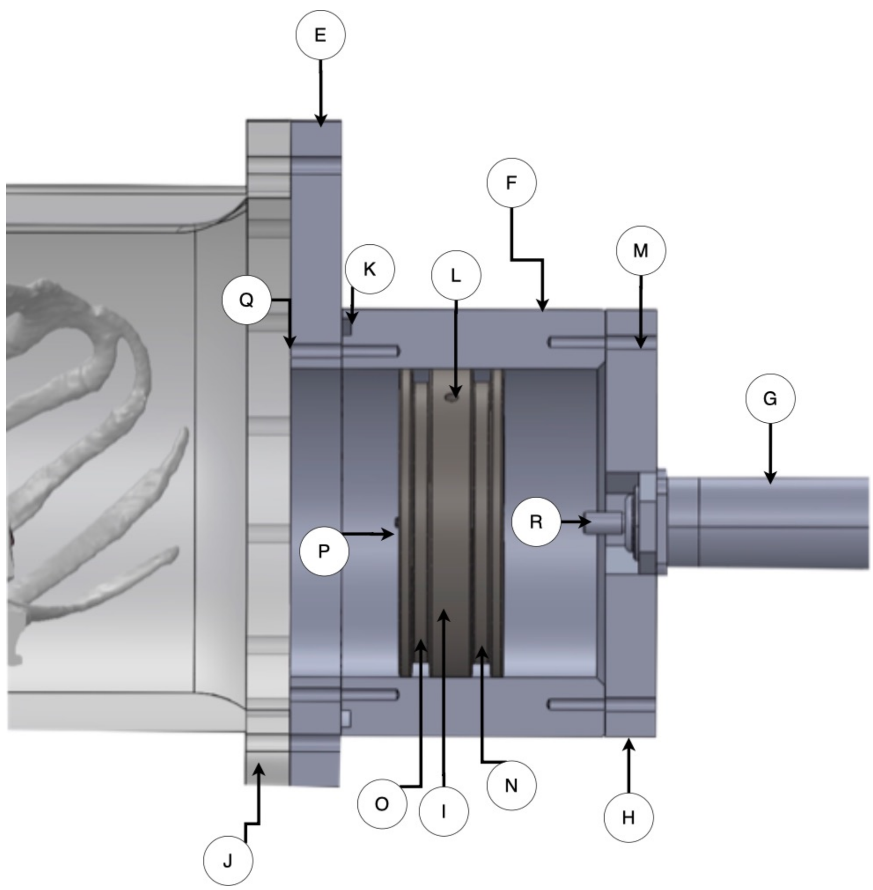

Figure 3: Piston Components

1.1 Plates

The phantom has three main plates. The base flange of the phantom itself is used to connect the base plate. The base plate [1.1.1] seals the phantom's base and connects the cylinder of the breathing mechanism to the phantom. Finally, the actuator mounting plate [1.1.2] connects the linear actuator to the cylinder.

1.1.1 Base Plate

Label E in Figs. 1, 2, 3
To ensure compatibility with DANN, the base dimensions were extracted to SolidWorks from a CT scan of the phantom, then waterjet cut from 1" thick polycarbonate. At this thickness, polycarbonate shatters locally upon piercing by the waterjet cutter. Thus, only the main outline and the large, central hole for the cylinder were waterjet cut so the piercing point could be sufficiently far from the actual material of the base plate. The remaining mounting screw holes were milled, using the old base plate as a template. For the cylinder mounting holes, a template was waterjet cut out of a 3mm aluminum sheet and used for milling. Finally, the holes were countersunk so the screws for the cylinder and phantom base flange are flush with the surface of the base plate.

1.1.2 Actuator Mounting Plate

Label H in Figs. 1, 2, 3
This mounting plate is fabricated from aluminum using a waterjet cutter and has mounting points for the cylinder and actuator. There are also 4 additional holes to provide venting for the piston and avoid pressure build-up. Though no O-ring is present on this end of the cylinder, the mounting plate does serve to lock in any minor drops of liquid that potentially make it through the piston O-rings.

1.2 Piston and Cylinder

Labels I (piston) and F (cylinder) in Figs. 1, 2, 3
The piston and cylinder were machined from Delrin by the UBC PHAS (UBC Physics and Astronomy) machine shop. They are explained in detail in the paper (Section IV.1), and their design is discussed more mathematically in the calculations section (Section 6.2).

1.3 O-Rings

Labels K (Cylinder Face O-ring Groove), N (Backup O-ring Groove), and O (Primary O-ring Groove) in Fig. 3
Up to 4 O-rings are installed on the phantom at one time to ensure effective sealing. Two are static face seals, the first being the large O-ring between the base flange and the base plate, and the second being the -364 size ring between the base plate and cylinder (K in Fig. 3). The sizing of these is straightforward and is described in Section 6.2.3.

Two additional O-ring grooves are found on the piston, which ensure alignment inside the cylinder and provide a watertight dynamic seal. The primary O-ring is positioned on the phantom side of the piston (O in Fig. 3), and provides most of the sealing. In testing, this O-ring alone was sufficient to waterproof the drive mechanism. In addition, the secondary O-ring is not strictly needed for alignment since the piston is coupled directly to the actuator, which is mounted on the cylinder, so misalignment is not a concern.

The secondary, or backup O-ring is positioned on the linear actuator side of the piston (N in Fig. 3), in a slightly deeper groove. This allows for lower friction due to a smaller % compression of the ring, which is acceptable since it is only a backup. A vent hole in the space between the O-rings eliminates the risk of pressure traps.

The O-rings are 70A durometer Buna-N rubber. Buna-N rubber is strong, resilient, and radiation resistant, making it a good choice for this application. Though the material is tough, the drive system was designed so the dynamic O-rings are the first component to fail. This is because they are cheap and easy to replace, unlike the piston and cylinder. While proper lubrication will greatly extend the life of both the O-rings and the piston and cylinder, the rings will eventually wear out. The dynamic O-rings should therefore be checked periodically for obvious signs of wear, re-lubricated, and potentially replaced if need be.

1.4 Linear Actuator

Label G in Figs. 1, 2, 3
The selected actuator is a Tolomatic ERD15 ball-screw linear actuator. The specifics of the actuator itself are discussed in detail in Section IV.3 of the paper. The actuation system can be seen in Fig. 10 and consists of the actuator itself, connected to a stepper motor. The stepper motor is powered and controlled by the stepper driver, which also receives encoder feedback from the motor. The driver, in turn, is controlled and configured by a Windows PC, and powered by a 48V power supply which plugs into a wall outlet.

1.5 Lungs

Label D in Fig. 1
The lungs are derived from a CT scan and simplified using mesh editing software, reducing the cardiac notch and making the left and right lungs symmetrical for ease of manufacture. Fabricated from Chlorosil-35 using special molding techniques which are discussed in detail in Section III.A of the paper, they are highly flexible, durable and thermostable, making them able to withstand thousands of breathing cycles.

1.6 Motion Coupling

Label P (motion coupling connector) in Fig. 3
To guarantee realistic respiratory motion, the lungs can be coupled to a removable mounting adapter on the piston using thin (<1mm thick) cables which do not cause image artefacts. This ensures that the lungs extend axially by 3.3cm for every 500ml of volume change, which is anatomically realistic (See Section 6.2.1).

1.7 Hardware

Type	Quantity	Usage
Steel Socket-Cap Screws		
$\frac{1}{4}$-20 × 9/16" (fully-threaded) [1]	12	Cylinder - Mounting Plate [1.1]
$\frac{1}{4}$-20 × 1-1/2" (fully-threaded)[2]	12	Cylinder - Base Plate [1.1]
$\frac{1}{4}$-20 × 2-1/4" (partially-threaded)	24	Base Plate - Base Flange [1.1]
10-24×9/16" (fully threaded)	4	Actuator Mounting [1.1.2]
70A Durometer Buna-N O-rings		
Size -429	1-2	Piston O-ring 1.3
Size -429 X-Profile	1-2	Piston O-ring 1.3 (To be tested)
Size -353	1-2	Piston O-ring 1.3 (To be tested)
Size -364	1	Cylinder O-ring 1.3

Table 2: List of hardware

2 Assembly

This section outlines how to assemble the respiration mechanism, which consists of actuator, piston, cylinder, base plate, and mounting plate. Reverse these instructions to disassemble the mechanism, for example to replace or check an O-ring. For helpful images see Fig. 4.

1) Lay the cylinder groove-side-up on a clean, smooth surface. Place the -364 size O-ring into the base groove of the cylinder. If removing an O-ring, use a soft, thin plastic tool to get under the ring and roll it out. Be careful to avoid scratching the O-ring groove.

2) Screw the base plate onto the cylinder, making sure the face of the base plate with the countersunk holes (the wider diameter side of the holes) is the one that contacts the base of the cylinder. The O-ring should be visibly compressed and flattened under the base plate.

3) Mount the primary (and potentially secondary) O-ring onto the piston. Ensure there are no kinks or twists.

4) Apply the lubricant (Super Lube Multi-purpose Synthetic Grease with Syncolon (PTFE)) to the O-ring so it is fully covered by a thin layer of lubricant. Also smear some onto the inner surface of the cylinder. It is probably advisable to be somewhat sparing with the lubricant as it is not cheap, but actually the more the better. Lubricant is essential to minimize the piston-cylinder friction, thus making the motion as smooth as possible, reducing wear on the O-rings, piston, and cylinder, and keeping actuator forces low, which will increase the actuator's life as well.

[1] Can be replaced by 1" length after COVID-19 for maximum thread engagement
[2] Similarly, can be replaced by 2" length

5) Check to make sure the piston's outer surface and O-ring, as well as the inner surface of the cylinder are well lubricated and free of any dust, dirt, or other particles. These will affect water-proofing and increase friction and wear.

6) Insert the piston into the cylinder, careful to avoid scratching the outer surface of the piston against the inner surface of the cylinder, which should remain as smooth as possible. Ensure the vent hole is facing away from the base plate, and the back of the piston is approximately flush with the back of the cylinder.

7) Attach the aluminum mounting plate to the linear actuator using the bolts specified in Table 2. These should be cranked pretty tight.

8) Thread the piston carefully onto the end of the linear actuator.

At this point, the breathing mechanism is fully assembled. It should generally be kept in this state, ideally attached to the phantom as well. This way, no dirt or particles will get into the inside of the cylinder. When filling the phantom, the whole assembly can be removed and reattached to the base of the phantom:

9) Place the phantom's base O-ring into the groove on the mounting flange.

10) Holding the base plate in one hand and the actuator close to the mounting plate in the other, carefully lift the mechanism and screw it onto the base of the phantom (with the O-ring in between).

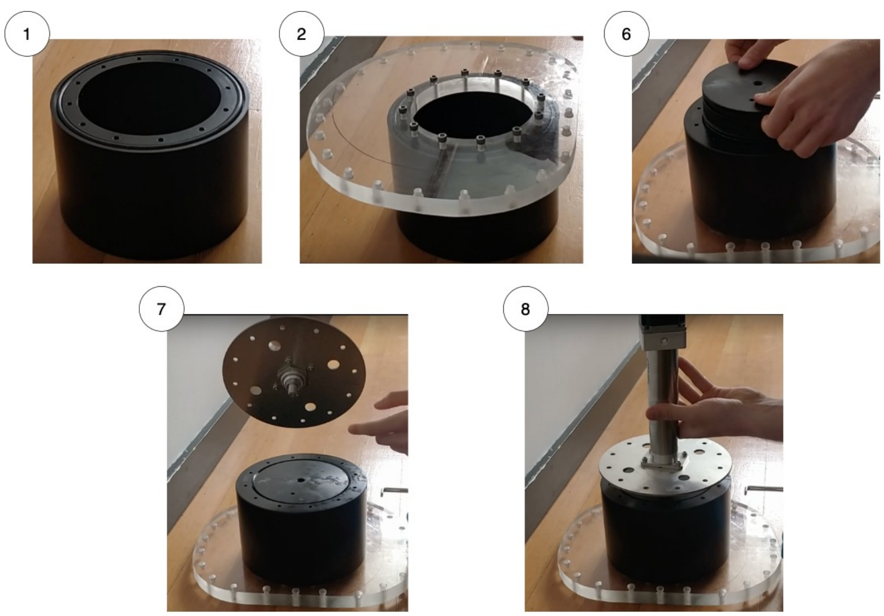

Figure 4: Assembling the Respiration mechanism

3 Filling the Phantom

To set up the phantom, the following steps are taken (as outlined in Fig. 5):

1. Position the lungs, organs, and bones inside the thorax.
2. Inflate the lungs to their maximum capacity and seal them.
3. Attach the base plate
4. Ensure the piston is set to its most retracted position (i.e. the phantom is at maximum volume).
5. Turn the torso upright without the linear actuator taking any load.
6. Completely fill the torso with radioactive water solution using the ports in the neck.
7. Seal the torso.
8. Open the lungs to the atmosphere.
9. The lung volume can be fine-tuned by opening the water-filling port while pumping air into the lungs through the breathing tube valve using a manual pump, or releasing air through the same valve.
10. Select the desired respiratory pattern, rates, and volumes using the provided software programs.

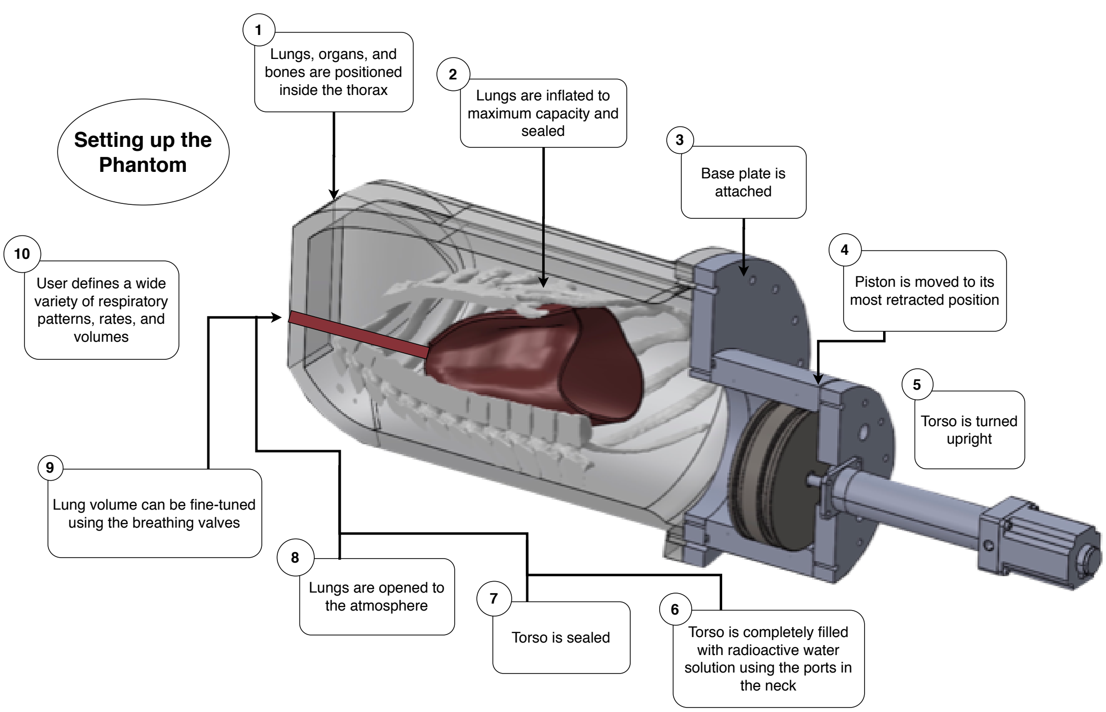

Figure 5: Setting up the Phantom

4 Software

4.1 Tolomatic Motion Control

The Tolomatic Motion Interface (TMI) is described here.

1) When the actuator is plugged in to power and the USB is connected to the computer, open the TMI executable. The first time this is opened you may have to install a USB driver (it should do this automatically). With the TMI open, the screen shown in Fig. 6 should appear. If the actuator is on and connected, make sure Port says 'Auto', and click 'Connect'.

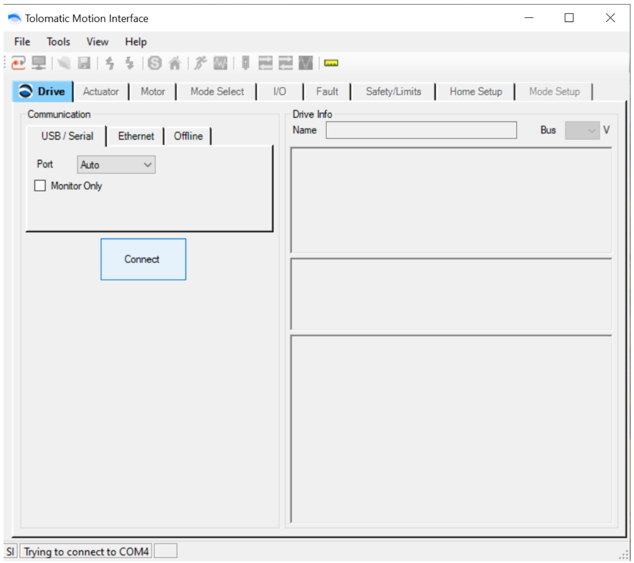

Figure 6: Screenshot of TMI application window.

2) Once a connection is established, there will be a picture of the actuator in the right panel, along with some information. A stop button will also appear as a separate window. This button can be used to stop the actuator immediately in case something is wrong. There are a number of tabs along the top. The first one, 'Drive', is only used to initially connect to the drive. 'Actuator' and 'Motor' give essential information about the actuator, motor, and driver, and should not be changed. It is best not to open these tabs. Mode Select allows you to choose how to control the device. You should select Index Move to control it using the TMI. To control using analog input, select Analog Position.

3) When selecting Index Move, there are two options. For simple motions, such as sinusoids where the breathing rate and amplitude are fairly constant, or have only 1 inconsistent breath every now and then, use the '4 Move Commands' option. To specify some complicated motion in which multiple (> 4) positions have to be specified, select the 'Basic Indexer' option.

4) The next tab is I/O. This can be used to configure the digital inputs. Input 1 is always the enable bit, but 2,3,4 can be changed. They can also be unconfigured so they are simply unused and do nothing.

5) The Fault tab can mostly be ignored. Its function is fairly obvious and is not necessary in the phantom application.

6) The Safety/Limits tab should look like Fig. 7, except with Positive Software Limit of 89mm and Maximum Velocity of 166.667mm/s. It is important to have the correct position limits to avoid damaging the actuator by trying to drive too far.

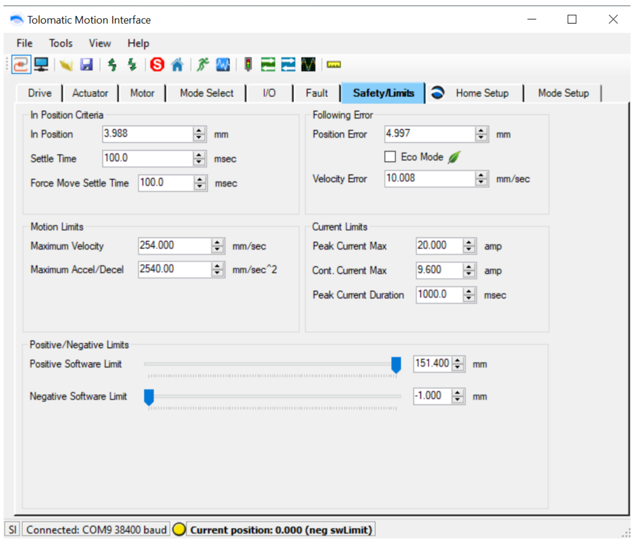

Figure 7: Screenshot of TMI Safety/Limits window.

7) The Home Setup tab can be used to configure how quickly the actuator moves when homing. You can test it by pressing 'Home'. The negative direction of motion means it homes to the most retracted position. The positive direction of motion homes it to the most extended position. Be aware that the signs of the position limits from step 6 change when switching between these options.

8) The final, most important tab is the 'Mode Setup' tab. This is where you can control the actual movement of the actuator. When in '4 Move Commands' mode, the screen will look as shown in Fig. 8.

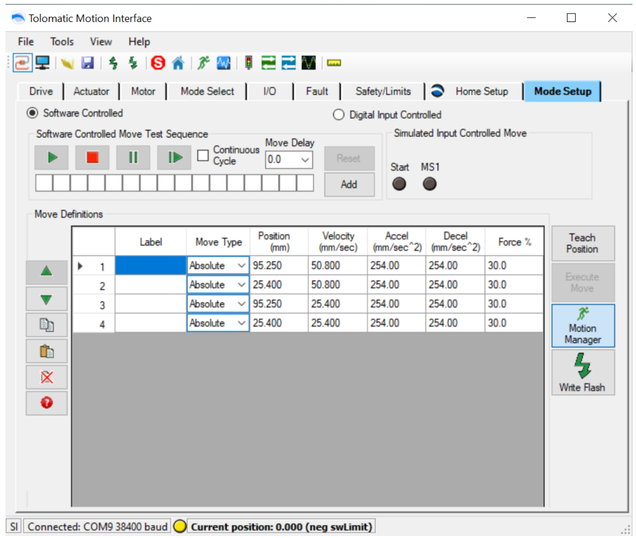

Figure 8: Screenshot of TMI application window.

9) Here we can input a number of positions, along with the velocity, acceleration, and deceleration of the actuator when moving to this position. A series of up to 16 of these 'moves' can be placed in any order in the white boxes just below the start, stop, and pause icons. Checking the 'Continuous Cycle' box makes the actuator repeat this series of moves indefinitely. In this way one can easily program a respiratory cycle. The motion can also be changed from absolute to be relative, incremental, etc., or to a pause in the Move Type drop-down menus.

10) Once the motion has been set satisfactorily, click 'Enable' in the 'Motion Manager' panel. If this is not already open, open it by clicking 'Motion Manager' on the right, or in the top toolbar.

11) Once enabled, click 'Home'. Now the motion can be started by pressing the play button. To pause the motion, hit the pause button. To stop the motion completely, press any of the three available stop buttons.

12) It is also possible to move the actuator gradually using the controls on the 'Motion Manager' panel, until it is in exactly the position you want, then selecting one of the moves and clicking 'Teach Profile'. This sets the selected move to the exact current position.

Some Notes:
- If the acceleration and deceleration are sufficiently slow, the actuator may never reach the desired velocity.
- Try to avoid reaching or exceeding 100mm/s velocity as the movement becomes slightly unpredictable at this speed.

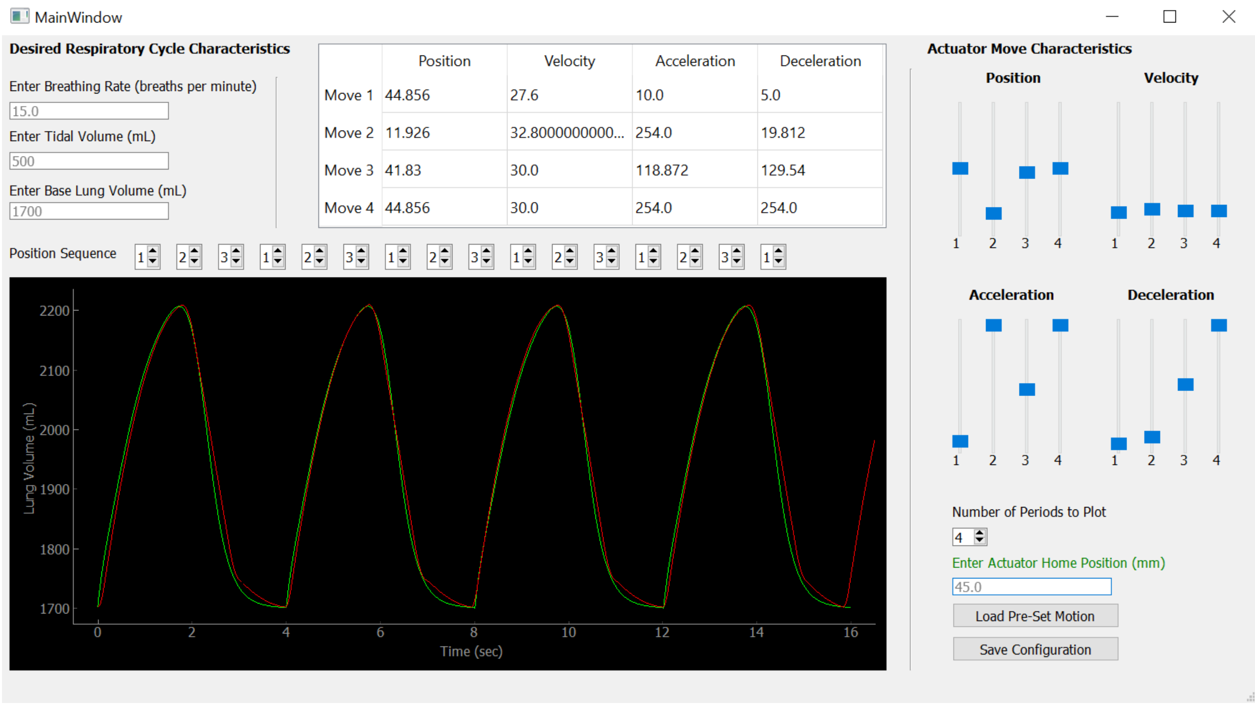

Figure 9: Screenshot of motion planning application.

4.2 Motion Planning

While it is easy to program a move pattern for the actuator, the connection between this and the respiratory cycle is a bit abstract. To help plan and visualize the respiratory motion, open the Motion Planning application, as shown in Fig. 9. Enter your desired breathing characteristics in the top left corner. You should now see a respiratory signal plotted in green. The red curve represents the lungs' actual volume, as controlled by the actuator.

The GUI allows the user to specify up to 4 TMI-style Moves and their order by changing the Position Sequence, as well as the position, velocity, acceleration, and deceleration of each Move. The red waveform is generated in real time by kinematic simulation of the actuator given the selected move parameters. The sliders on the right side allow for easy parameter adjustment, while the numbers in the table are used for fine-tuning. Once the red and green curves are sufficiently well-matched, the move parameters and sequence can be read off the GUI and entered into the TMI.

Note that this may take some time, and there is no one-size-fits-all solution. To help get started, it is possible to load pre-made respiratory cycles into the GUI from specially formatted JSON files. The current configuration can also be saved to an automatically-formatted JSON file for later reuse.

5 Electrical Connections

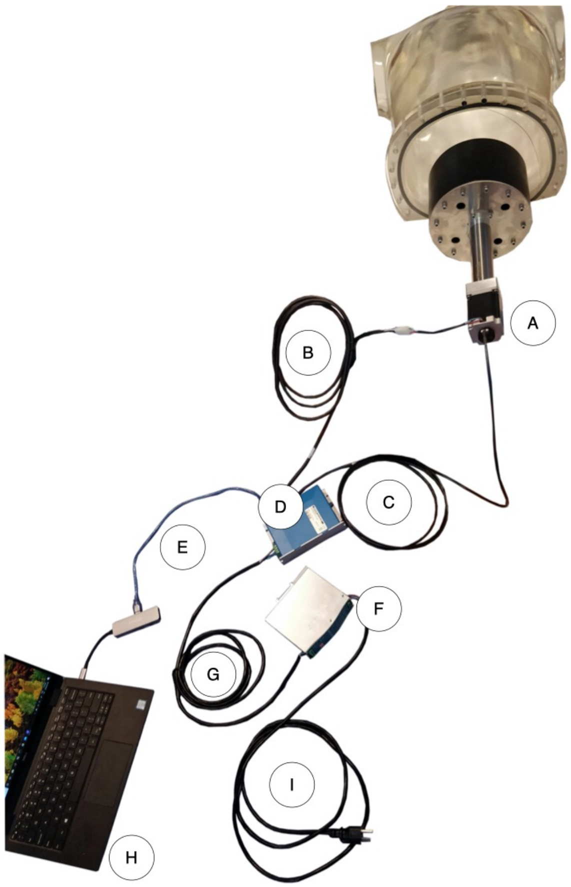

Figure 10: Cabling of Actuator System

Diagram Label	Term
A	Stepper Motor and Linear Actuator
B	Stepper Controller Cable
C	Encoder Cable
D	Stepper Driver
E	USB Cable for Laptop Interface
F	Power Supply
G	Stepper Driver Power Cable
H	Controller Windows PC
I	Power Cable (To Wall)

Table 3: Cabling System Diagram Labels

6 Design Specifics

Mechanical drawings, electrical schematics and code are open-source and can be found here.

6.1 Bill of Materials

The Bill of Materials (BOM) can be found here.

6.2 Design Calculations

6.2.1 Breathing Calculations

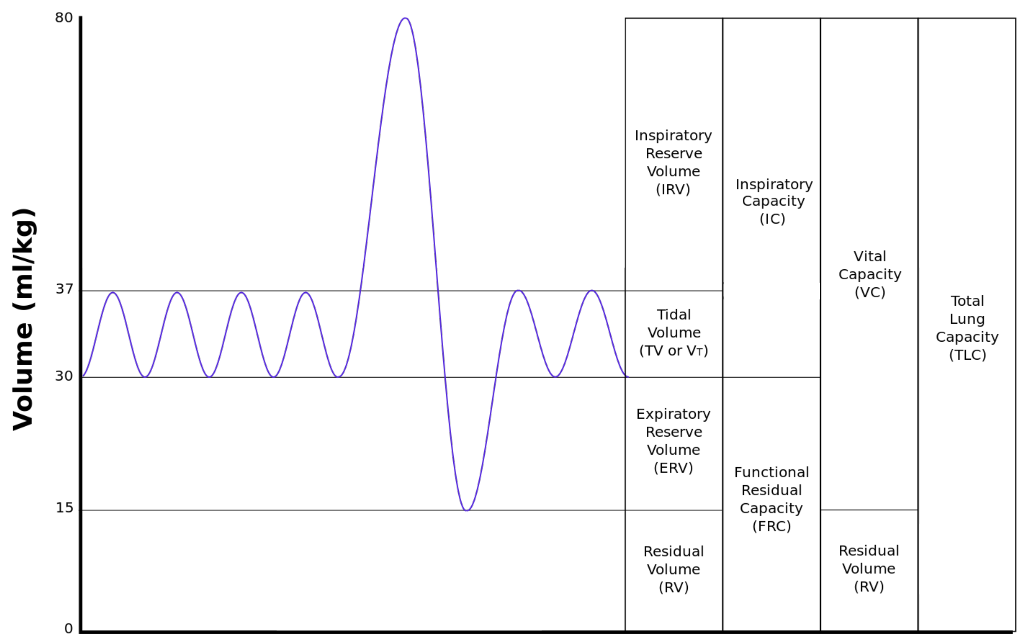

Figure 11: Typical adult lung volumes (this includes the air in both lungs) [5].

Volumes and Dimensions
The tidal volume is the volume of air that flows into and out of the lungs during every breath. A typical, relaxed, adult tidal volume is 500ml. In Fig. 11, this is given as 7ml/kg, which corresponds to 500ml in a 72kg person, which is standard for an average, healthy male. To have some flexibility in the breathing pattern, we required the respiratory mechanism to provide up to at least 1000ml tidal volume.

To achieve this volume we face a trade-off between stroke and diameter of the piston. The larger the diameter, the shorter the stroke for a given volume change, and the slower the actuator has to move. However, larger diameters are more expensive, harder to machine accurately within tolerance, more cumbersome to fit onto the base plate of the phantom, and more likely to leak. To make a decision, we considered the flex pattern of the lungs.

Given a small, spherical balloon in a pressure chamber like DANN, upon pressure changes, the balloon will expand approximately uniformly, ignoring the pressure gradient as a function of depth in the liquid (hence the assertion that the balloon is small). On the other hand, human lungs extend axially more than they expand laterally. The extension is about 3cm per 500ml of volume change [3]. While the lungs are not spherical, and are constrained laterally by the ribs, which will lead to more realistic and less balloon-like expansion, the exact flex pattern is unknown. To try fine-tuning it, we can roll the silicone on thicker in parts of the lungs that we want to expand less. This will require some trial and error. Alternatively, we can design the piston and cylinder to have the same relation between volume change and axial displacement as human lungs. In this way, the piston can be coupled directly to the base of the lungs using thin cables (approx $\leq$ 1mm) that are not visible in PET and do not cause significant scattering or absorption of gamma photons. This guides the lungs, making them expand in an anatomically realistic manner.

The piston diameter (D), extension (Δx), and tidal volume (ΔV) are related by the simple cylindrical geometry:

$$\Delta V = \frac{\pi}{4} D^2 \Delta x \tag{1}$$

The piston diameter as a function of tidal volume and extension is also plotted in Fig. 12. Recall, at 500ml, the extension should be around 3cm. In addition, due to size constraints it was determined that the diameter should not exceed 15cm, and should be smaller if possible. Finally, standard O-ring sizes provide another constraint, as they do not cover every possible diameter. Therefore, we chose a piston diameter of 14cm, which gives 3.3cm extension per 500ml volume change. The length of the cylinder was chosen accordingly, so we can achieve up to 1232ml tidal volume.

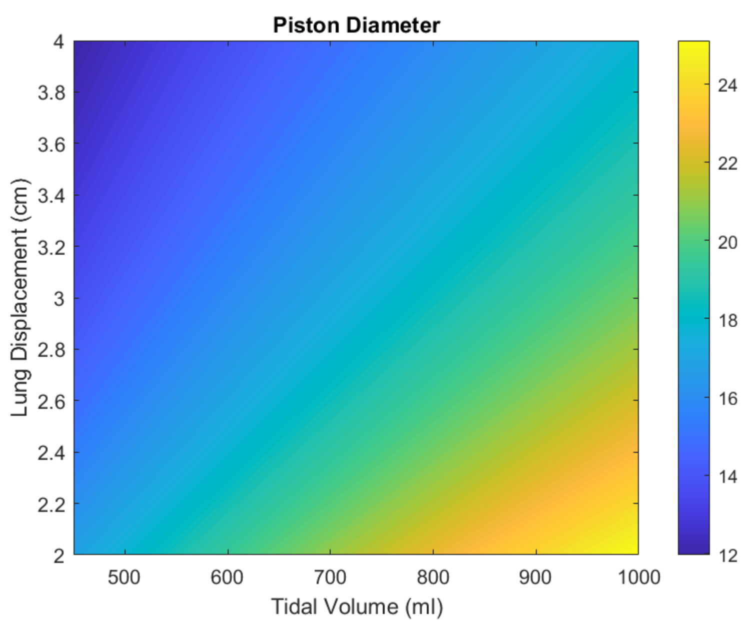

Figure 12: Relation between piston diameter, extension, and tidal volume

With the piston diameter set, the lung dimensions remain to be determined. The functional residual capacity (FRC), or volume of air remaining after a normal exhale, is generally taken to be 2200ml (According to [4] and Fig. 11). However, in reality the lungs consist of tissue containing many tiny, air-filled alveolar sacs. Thus, the lungs' air volume does not necessarily describe their actual dimensions. Since the phantom lungs consist entirely of air, their FRC will be much higher than in real lungs in order to maintain the proper dimensions. One way to estimate the actual volume is to consider that the human lungs' 511keV mass attenuation coefficient is about 40% that of soft tissue. We can therefore estimate that 60% of the lungs is made up of air. Hence, the total relaxed volume is approximately $V \approx \frac{10}{6} \cdot FRC \approx 3667$ml. In addition, according to Kramer et al. [1], the lungs are typically about 20cm high. We used both of these facts to design the lungs.

In order to achieve consistent, predictable, and reproducible lung motion, the lungs should be fabricated at their minimum volume so they only stretch during breathing. If they were to compress, unpredictable folding and collapse could occur. The lungs should therefore be sized a bit smaller than the expected FRC to allow for the simulation of forced exhalation. We chose to design our lungs at 1700ml per lung (3400ml total), and 18cm height. Since the Chlorosil-35 material is highly flexible, expanding to larger volumes is not an issue.

Breathing rate

One of the design objectives was to achieve breathing rates of at least 25 breaths per minute at the goal tidal volume of 1000ml. The actuator speed, $\dot{x}$, in mm/s as a function of breathing rate, ν in breaths per minute, and amplitude, V in ml is:

$$\dot{x} = \frac{2\nu V}{\frac{\pi}{4}14^2 \cdot 60} \approx \frac{\nu V}{461.8} mm/s \tag{2}$$

The chosen actuator can move at a maximum of 167mm/s, but starts behaving unpredictably at 100mm/s. Thus, to stay well within the predictable range, we limit ourselves to 80mm/s. The maximum breathing rate as a function of tidal volume is plotted in Fig. 13. Clearly, the actuator can operate well below its maximum speed and still meet the rate objective.

6.2.2 Actuator Calculations

To choose the actuator, we first had to determine a set of requirements that the actuator had to fulfill. This included force, stroke, duty cycle, linear speed, and lifetime. These are described in detail in Section IV.3 of the paper.

6.2.3 O-ring Calculations

Once the general dimensions of the piston and cylinder were selected, the O-rings dictated much of the remaining design. The specific dimensions and tolerances were determined using the Parker O-ring Handbook, as well as a similar resource from Apple Rubber.

The primary known dimension was the inner diameter of the cylinder. Only two O-rings of this diameter are used in dynamic applications because rings of this size but with a smaller cross-section (CS) easily become unstable in reciprocating seals. We purchased both of the sizes (-429 and -353) in order to test. In general a smaller CS means lower friction, but a less

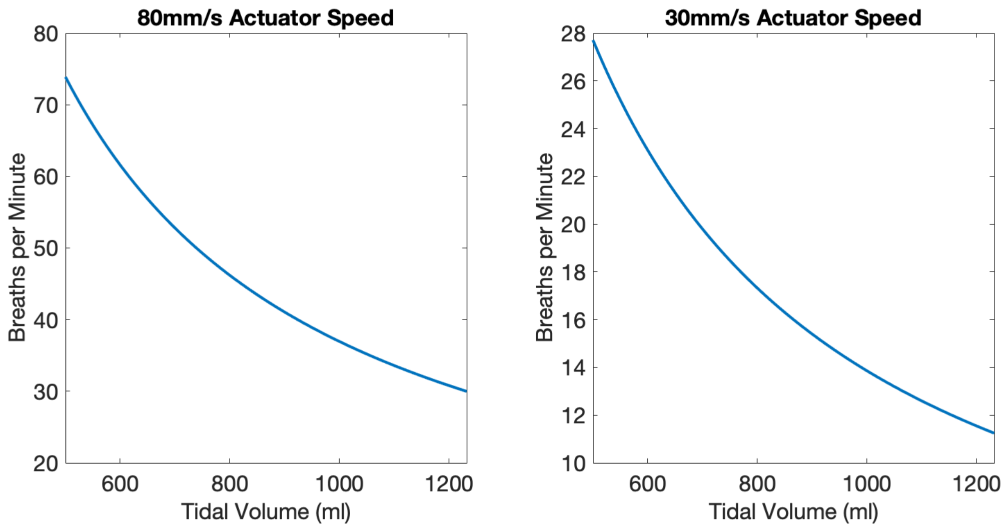

Figure 13: Breathing rate vs. tidal volume for the maximum actuator speed (left) and a more typical actuator speed (right)

robust and stable seal. As we have a powerful actuator, seal quality is our primary concern, so we designed for the larger CS O-ring (-429 size).

The remaining O-ring gland (the groove in which the ring sits) dimensions and diametral tolerances of the piston and cylinder were established by finding dimensions that meet certain parameter recommendations from Parker, as listed below:

- *%-ID stretch* is how much the inner diameter (ID) of the O-ring must increase to fit over the O-ring gland's outer diameter (OD): %ID-stretch= $\frac{OD - ID}{ID} \times 100\%$. Ideal values are between 1-5%. A table in Parker also gives the %-decrease in CS of the O-ring for a given ID stretch. This is important to note for the following three parameters.

- *%-gland fill* is defined as the percentage of the gland cross-section filled by the O-ring cross-section. Mathematically, %-gland fill= $\frac{CS}{W \cdot D} \times 100\%$ where W is the width of the gland and D is the depth. This value should be greater than 75% for an effective seal but must not exceed 85% to avoid breaking the O-ring or causing excessive friction.

- *%-contained* is related to the gland fill. Apple Rubber recommends at least 75% of the O-ring CS is contained within the groove, not extending into the piston-cylinder gap, to avoid extrusion. Extrusion is where the O-ring is pinched and folded into the piston-cylinder gap, which can cause stiction and damage to the ring.

- *%-squeeze* is the % decrease in cross-sectional diameter of the O-ring from being compressed between the piston and cylinder: %-squeeze= $\frac{CS - D - \delta}{CS} \times 100\%$ where δ is the piston-cylinder clearance. Higher squeeze affords a better seal but also more friction. For reciprocating applications, values between 10.5% and 14% are recommended.

Through careful balancing of these 4 main parameters, the dimensions and tolerances shown in Table 4 were determined. These dimensions lead to the parameter values shown in Tab. 5. The tolerances were designed so that even the worst case combination of dimensions within their respective tolerances, including water expansion of the Delrin and O-ring, still fulfill the recommendations.

O-ring Size	Cylinder ID	Piston OD	Gland OD	Gland Width
-429	$140.06_{+0.08,-0.00}$	$139.8_{+0.00,-0.16}$	$128.00_{+0.00,-0.16}$	$8.13_{+0.25,-0.00}$

Table 4: O-ring, gland, piston, and cylinder dimensions and clearances

Parameter	Recommended value	Actual Value	Worst Case Value
%-Squeeze	10.5-14%	12.9%	11.2%
%-Gland Fill	75-85%	78.4%	max=79.5%, min=76.2%
%-ID stretch	1-5%	1.06%	0.99%
%-Contained	>75%	84%	80%
Piston-Cylinder Clearance	0.25-0.5mm	0.256mm	0.496mm

Table 5: O-ring design parameter values with chosen system dimensions

Selection of an O-ring for the static face seal on the cylinder base was much more straightforward and could essentially be read off the tables in the Parker Handbook.

One factor that is more difficult to quantify is the effect of O-ring cross-section shape. All of the above calculations were based on the assumption of a circular cross-section but other shapes also exist. From conversations with a seal engineer at Apple Rubber, it seemed that circular cross-sections were best for the application. However, given the low pressure application, X-cross-sections could potentially give more leeway in the tolerances, and have lower friction. We therefore purchased a set of -429 size X-cross-section O-rings to test.

This testing, as well as some other work remains to be done, partly due to the COVID-19 pandemic. This is outlined in the conclusion and last paragraph of the testing section of the paper.

7 Appendix

7.1 Sponsor

This project was proposed and is funded by a recently-created lab group in the BC Cancer Research Centre (BCCRC). Led by Dr. Arman Rahmim, this group is looking to make UBC and the BCCRC a centre for PET expertise and technical proficiency. We work most directly with one of the scientists who was recently recruited by the group, Dr. Ivan Klyuzhin, whose PhD thesis and area of expertise are motion correction and image reconstruction of PET data [2].

The goal of the sponsor is to use the phantom to carry out research on various PET and/or

PET/CT scanners. Hence, their priorities lie in producing high quality data, meaning they need consistency and exact reproducibility of the respiratory motion, anatomic and physiological accuracy, and ease of use for the nuclear medicine technologists who are ultimately the ones operating the device.

7.2 Deliverables

The sponsor will receive a working prototype of the phantom to be used for conducting research on the PET scanner, including:

- Lungs (To be fabricated when possible, after COVID-19)
- Linear Actuator
- Actuation Mechanism
- Control Software with User Interface
- User Manual including Bill of Materials

8 System Level Diagram

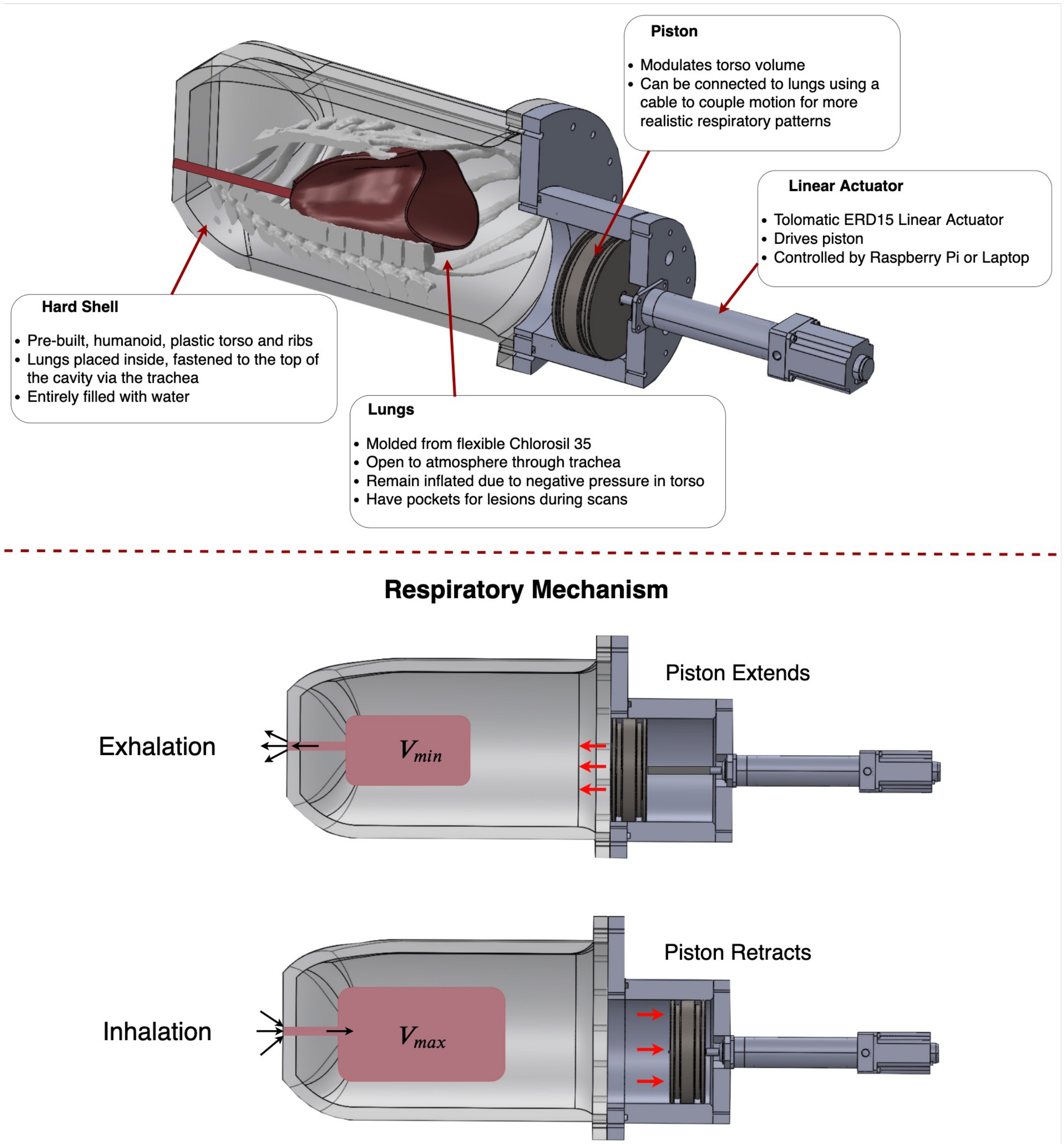

Figure 14: System Level Diagram of Phantom

References

[1] G. Kramer et al. "Linear dimensions and volumes of human lungs obtained from CT images". *Health Physics*. 2012, vol. 102, no. 4, pp. 378-83.

[2] Klyuzhin, I.S.. "Deformable motion correction and spatial image analysis in positron emission tomography." Thesis, University of British Columbia. 2016.

[3] O.L. Wade. 'Movements of the thoracic cage and diaphragm in respiration'. *Journal of Physiology*. 1954, vol. 124, pp. 193–212.

[4] Physiopedia. "Lung Volumes". https://www.physio-pedia.com/Lung-volumes

[5] Wikipedia. "Lung Volumes". https://en.wikipedia.org/wiki/Lung-volumes

See the paper for a full list of references.