Magnetic Resonance Imaging Phantom Cardiac Pump and Control Unit

Principles of Electrical and Computer Engineering Design ECE:4890

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Introduction

With millions of scans completed annually, Magnetic Resonance Imaging (MRI) is a very common technique for medical imaging ("Benefits and Risks", 2021). However, it is limited in some aspects by its ability to image the cardiovascular system (Saeed et al., 2015). Current MRI technology and research is hindered in how well cardiac abnormalities are imaged. There is a real need for proper MRI technology that correctly renders images with arrhythmias or hearts with physical defects too. Most research in the field of MRI imaging uses the assumption of a heart operating under proper conditions. A limitation of research today is that only few devices are offered for emulating the heart in an MRI ("Heart Pump for R&D - True Phantom Solutions Inc.", 2021). The focus of this project is designing a system which can replicate the normal behaviors of a cardiac system and can also emulate abnormal cardiac symptoms. Behind this is the intention that better imaging research can emerge via use of this phantom system in lieu of needing to find suitable research subjects which can be both time-consuming (for both researchers and subject) and costly. From this project a better system is to be designed with the aforementioned features, independent operation of each of the heart's chambers, and electronic control of the pumps allowing for specific signal generation. Because many cardiovascular problems are common, for instance atrial fibrillation (affecting an expected 12.1 million people in the US by 2030, >3%) the need for better medical imaging devices is very high to account for, detect, and monitor such issues ("Atrial Fibrillation", 2021). A device used for medical imaging should be able to detect such a common issue. Our project will be a new pump and control system that has the potential to simulate an irregular heartbeat and regular heartbeat. It will be MRI compatible and work with a phantom heart device. Magnetic Resonance Imaging (MRI) scans are one of the best techniques for medical imaging. Not only do they produce much clearer images than Computed Tomography (CT) scans they are also much safer, utilizing magnetic fields in lieu of x-rays which can cause harm over long periods of exposure ("Benefits and Risks", 2021). Despite this, MRI is more costly and time consuming to use. A single MRI scan may take hours, requiring patients to stay still for the duration of the scan. This proves quite difficult for certain patient demographics as they need to stay enclosed in the machine. With these issues in mind, research into MRI scanning is done to improve speed and lower costs through the integration of machine learning. Researchers such as Dr. Mathews Jacob at The University of Iowa, College of Engineering are developing algorithms and different methods of scanning to produce clear images in a shorter timespan. Currently, there are limited options; either subject patients and research participants to lengthy scans or purchase a phantom cardiac unit, with minimal abnormal cardiac state capabilities for tens of thousands of dollars , thus the need for a controllable phantom system arises.

Project Outcome

The focus of this project was to design and develop a pumping system, complete with a control unit, which provides the flow of a blood-like liquid and simulates the pumping of the cardiac phantom device. While this only addresses part of the phantom cardiac system (lacking the cardiac device itself), as a group composed of electrical and computer science engineers, we were not familiar with the biological stipulations required in making an accurate cardiac phantom for the purposes of this research. Thus we collaborated with a similar team of senior biomedical engineers at The University of Iowa to complete other aspects of this system. Our attention was focused on making a pump system which is MRI compatible and has the ability to simulate different heart signals with a close resemblance to those of real human hearts. The main derivations from our original plan came early on in the design process. By request of our sponsor a new design was implemented that was more cost effective and was easier for users to operate. The pump and controller we created has a significant amount of hardware required. Our team has found that the agile approach to design is the best option to be successful. We found it advantageous to follow a cyclic model. This allowed for fewer errors and inaccuracies to occur. The agile and iterative model is adaptive, meaning we could fine-tune and modify our progress when needed. This was the most beneficial method and allowed for maximum efficiency. The agile iterative approach allowed flexibility for modification, early problem identification/adjustment, and simplification in testing. In the end we have produced a working heart pump that can be used for research and testing. We have created a user-friendly system that simulates a pumping heart that can be controlled and scanned in an MRI. The program we have produced allows users to control the offset, heart rate, and amount of fluid flowing through the heart. At 10% of the cost of our competitors, we have improved upon the functionality and performance of an existing heart pump. With our pump, the user has the function of controlling the heart with the click of a button. Adjusting values, such as heart rate and blood pressure can be modified instantly, a major improvement from other pumps currently on the market. We have met all requirements detailed in our proposal, and believe our stretch goals will make a great project for future senior design students. Each chamber is independent of the others, and the user will have the ability to control functions as they wish.

Design Documentation

Design Concept

Our team has done extensive research on the existing device we want to reinvent. We have gained resources from Professor Jacob, the sponsor of our project, to gain a better understanding of how we can improve the device. The device that is currently being used cannot detect arrhythmias, or irregular heartbeat. Our goal was to create a heart pump and control system that can be used to generate irregular heartbeats and regular heartbeats.

We wanted to create a device that is also cost-effective. We have researched different styles of pumps that will be most beneficial for our use and have found one that will out-work the current pump being used. We have created a device that is compatible with an MRI machine. Our pumping system is similar to a normal human heart with the capabilities to operate in irregular states. The pressure that our system operates at is lower than 15 psi and only with a small, fixed volume of liquid. We decided to use a piston pump design utilizing syringes and stepper motors to act as a linear actuator. These allow us to control the position of the piston for volume of liquid as well as speed. Another reason we chose this design is the cost. Prices for these components are significantly cheaper than other alternatives. With such a small volume of liquid, this design is more than enough for our purposes. From the start of our design process we wanted to create a unit that was easy to use and efficient. Figure 1 shows our original design concept. Shortly after submitting our plan, we were contacted by our sponsors to redesign our unit. We had not yet started constructing our pump, so redesigning was not a major hurdle. Our new design, shown in Figure 2, comprises three major components. Figure 3 details our logic flow chart we planned for fluid flow. We began by constructing one stand alone unit. Our thought process was if we could get one pump working properly, then we would just need to make three more copies. The initial stages consisted of constructing this unit, our prototype for this unit is shown in figure 5. Once construction was complete we began testing with a simplified arduino stepper motor program. After the success of our first unit, three more were built. The units were set on an aluminum base to keep the unit sturdy, shown in figure 6a and 6b. Once all four units were built on the base, we moved onto the software portion of this project. Our initial program started with only one chamber pumping, but after some modifications all four units were pumping. The pumps were moving in sync, and could get a maximum 160 bpm. After getting all four units to pump, we had to accommodate for the fact that chambers of a real heart beat out of phase. This was the most burdensome hurdle we had to overcome. The first attempts of creating an offset were somewhat successful. The issue was that after a period of time the pumps would sync up and then go out of sync again. We needed to keep the pumps out of sync for the entire duration of the MRI scan. After testing and reevaluating the code, we determined that after the syringes are initially offset, the ones that will be out of sync were not moving their full distance back. They were moving only half the distance back, so when pumping started they would all eventually become synchronized. Doubling the initial distance the pumps moved back was the adjustment made to keep the pumps out of phase running synchronously. Throughout this process a GUI was being constructed. This allows the user to input the heart rate, volume of fluid, offset, and allows for a quick start/stop. After completing the software portion and coupling the two together through an arduino, we tested our unit on the biomedical engineering team's phantom heart. After some initial testing we saw that moving 35 mL through the heart was a sufficient amount of fluid to pump. This provided enough pressure that visible contractions and relaxations were observed on the phantom heart. Another issue we came upon was priming. In order to get air bubbles out of the system, we set up a priming cycle that will fill the tubing and syringes with fluid, before they actually begin pumping. Air bubbles pumping through the heart of a real human can be deadly, to ensure our heart functions similar to a real heart we developed a system that would expel this issue. The priming cycle was difficult to get just right, as we wanted it to take a short period of time but not move too fast so that it would overfill a heart chamber causing it to burst. Priming consists of each chamber finishing one complete cycle, and finding its starting position. Once all pumps were primed, the pumping process could begin. Figure 6 shows the electrical schematic for the phantom heart. We utilized four DM556 - 2-phase digital stepper drives to interface the motor to the control unit. This driver is designated to power the Nema 23 stepper motor.

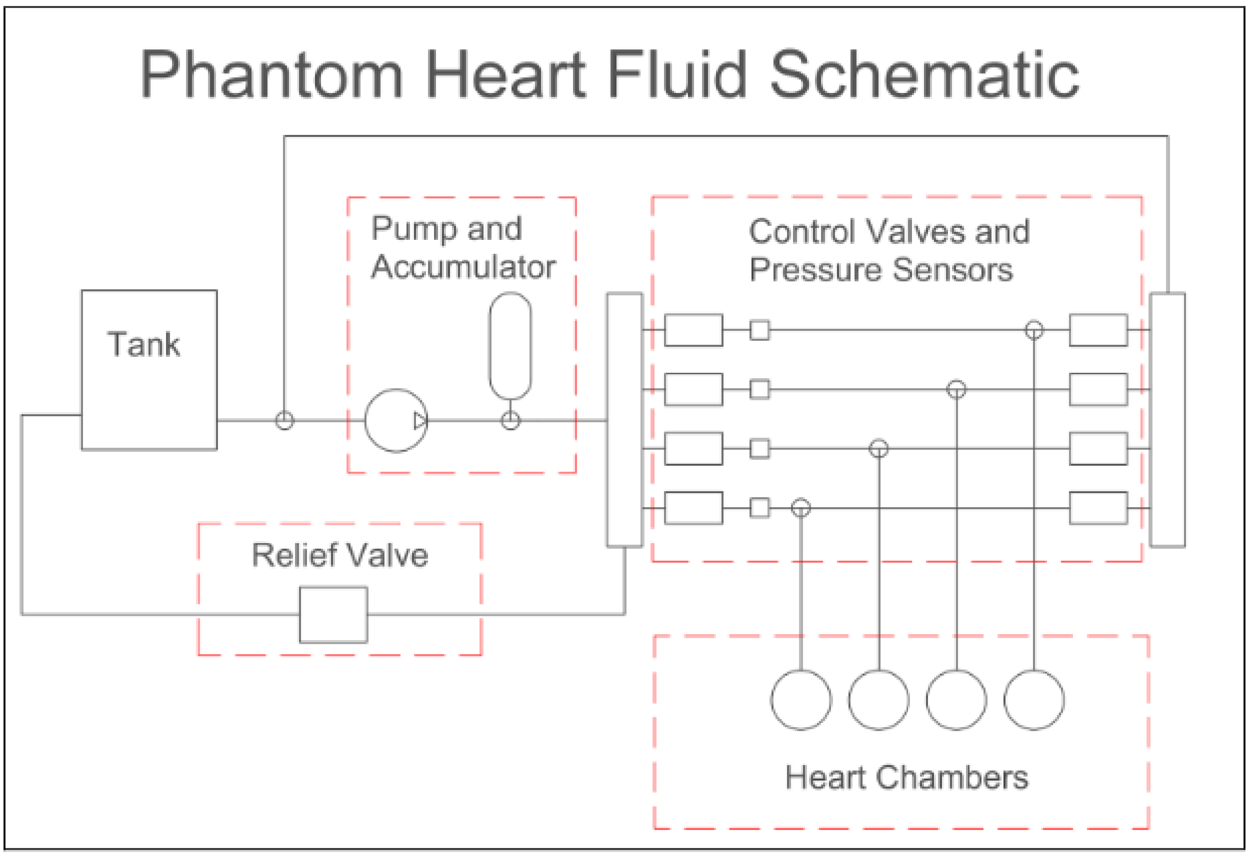

Figure 1: Initial Design Schematic

Deliverables

Designing a system that can meet all needs and goals for its intended purpose and those as desired by the end user is important. Having this consideration in mind the principle design objectives for the project are as follows:

- Emulate cardiac features like those observed in real subjects (heart rate, blood pressure, signals).
- An intuitive system to both use and adapt to various cardiac models
- Modular device for ease of maintenance and transportability (utilizing minimal magnetic components)

The finished product given is comprised of:

- Working pump and controller that is MRI compliant and can be used with a phantom heart
- Complete API, application programming interface, and documentation of software
- Documentation of all components and how they operate
- User Manual (Appendix)

Constraints

The main issues with heart pumps currently on the market is that most are not MRI compatible, and they are costly. With this in mind, we had to develop a pump unit that would not interfere with the MRI scan. The unit should also be easy for the user to transport from room to room, as researchers get one to two hours reserved for the MRI room. Maximizing the time given for testing and research is an important characteristic we wanted to keep in mind when designing our pump.The software portion had some limitations as well. We wanted our pump to be as close to a real heart as we could get it. That includes, chambers beating out of sync, having a heart rate range from 60-160 bpm, and being able to pump blood like fluid. A concise description of all major constraints will be detailed below. In summary, our project was designed for the betterment of research surrounding cardiac MRI imaging. All constraints were met by the end of the design.

As design implementations are factored in the main system requirements consist of:

SC1) The system should be able to fit in a 4ft x 4ft x 4ft space.

SC2) The system should have a computer based input.

SC3) The system should simulate heart rates from 60-160 BPM.

SC4) The system should have mechanical components with less than 300ms response time.

SC5) The system should operate with a fluid similar to the consistency of human blood.

SC6) The system should have a flow rate near 5L per minute at 100 BPM operation.

Trade Offs

Creating a pump unit that was both cost effective and user friendly was the most predominant aspect contemplated throughout the duration of this design. After establishing our initial plan for a pumping unit and sending our plans to our sponsors, we had to make some major adjustments. Our original design was far too costly, while it did stay within the budget, it still was overcomplicated by unnecessary components. By request of our sponsor, we needed to propose a new design. This new design cost a third of the original design, and also simplified down to a device that was easy to operate, maintain, and transport. Utilizing stepper motors was another feature we had to deliberate on. Figure 4 shows an in depth schematic of the specific motor we decided to use. The Nema 23 Stepper Motor was our first decision we made. The motor had a matching driver we used to interface the motor with an arduino. Stepper motors are composed of inner permanent magnets that rotate which makes up the rotor. The coils on the outside stay static, making up the stator. The magnets will be a major interference with the MRI scan. The reasoning for using stepper motors comes from their ability for precise control, meaning the user can make them move from a defined angle. Stepper motors are low cost and high reliability. Utilizing stepper motors was the most efficient use of our budget, our only concern was how it interacted with the MRI. To resolve this issue we will use 30 feet of tubing for each motor that will transport fluid from the pump to the MRI machine. This eliminates the issue of the stepper motors obstructing and damaging the MRI scan. The stepper motors have enough power to accommodate for the distance the fluid must flow.

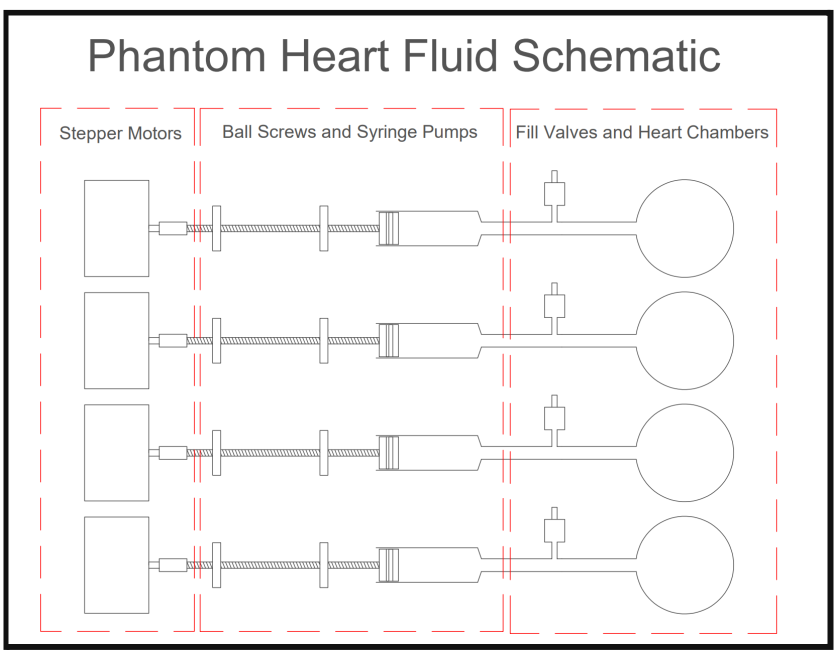

Figure 2: Final Phantom Heart Fluid Schematic

Standards

Applicable standards for this device include:

- Medical device compliance
- Magnetic Resonance Imaging safety standards
- American College of Radiology Manual on MRI safety
- Human cardiovascular conditions

Architecture

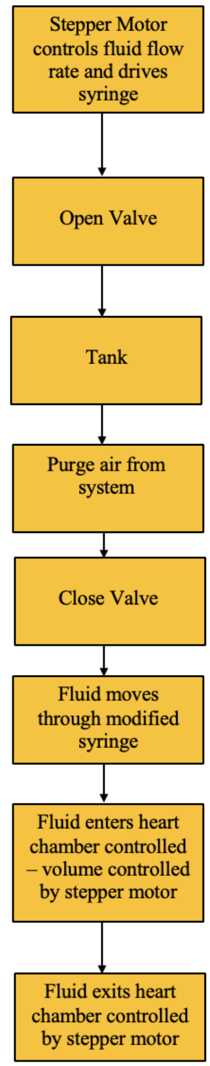

Figure 3: Logic flow chart of fluid flow

Application Control Program:

This system is controlled with a computer program via a graphical user interface (GUI). The framework used to create the GUI is a suite called Processing which handles the compilation of native applications for Linux/Windows/Mac. The source code for this GUI application will be included. The communication between the GUI/Computer and the Arduino on the pump is serial communications. Over this serial connection, strings of data are sent which the Arduino interprets to control the components of the pump. Upon launching the GUI application, the user selects the port on the computer which the pump's Arduino is connected to. After selecting the port the computer and Arduino will establish a connection. This connection will be used to send the command strings. There are commands to start all pumps, to stop all pumps, to purge pumps, to set volumes, to set offsets, to set the heart rate, and to get all pumps status. Most of the controls are handled with button interfaces in the GUI. The exception to this being the volume, offset, and heart rate inputs; these are text fields.

Parts used:

Parts:	**Purpose:**
DROK 48 V Power Supply	Power to run pump
Nema 23 Stepper Motor (x4)	Driving Syringe
CNC Digital Stepper Driver DM556 (x4)	Provide power to motor
Arduino Mega 2560	microcontroller
500 ml Large Syringe (x4)	Move Fluid
Lead Screw (x4)	Converts Rotational Motion to Linear Motion
Aluminum base	Base for pump to stand on
Limit switch (x4)	Homing
Thru-Hull Connections	Allow passage of fluid
Irrigation Fittings	Change direction of fluid flow.
Vinyl Tubing Flexible PVC Tubing	Passage for fluid to go from pump to heart
Switch Valve Gate Valves	All fluid to run through

Table 1: Parts and their use

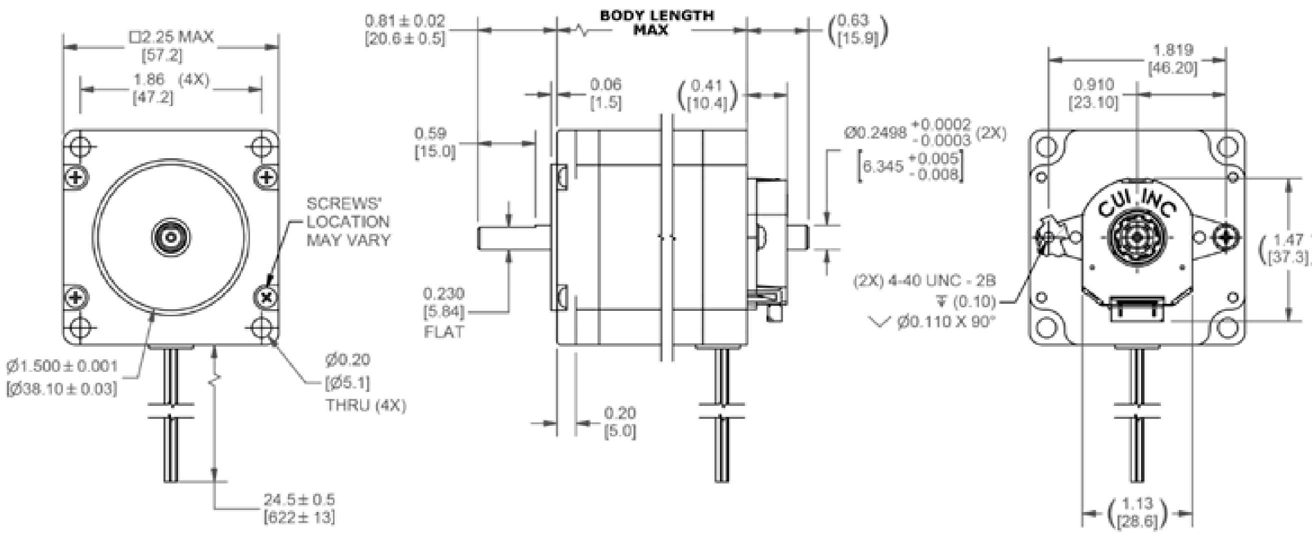

Figure 4: Nema 23 Stepper Motor Schematic

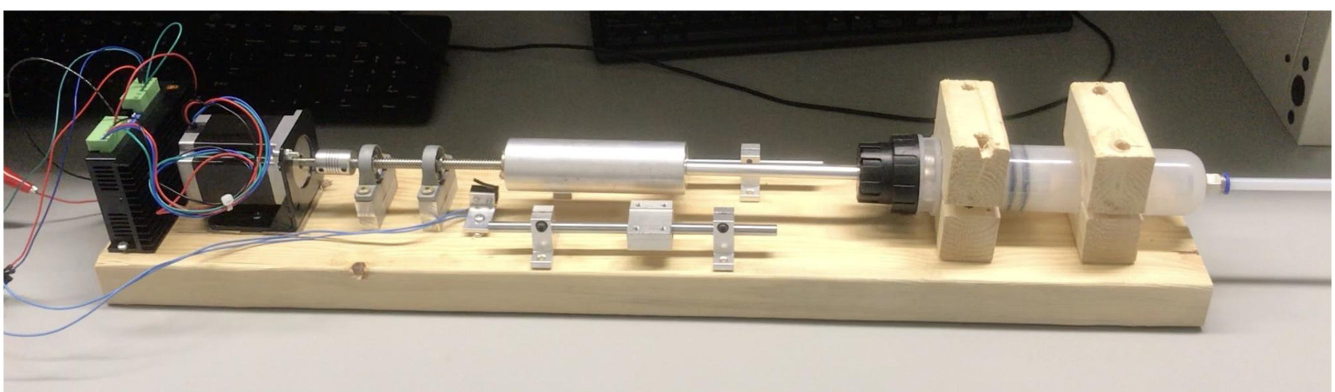

Figure 5: One Complete working pump

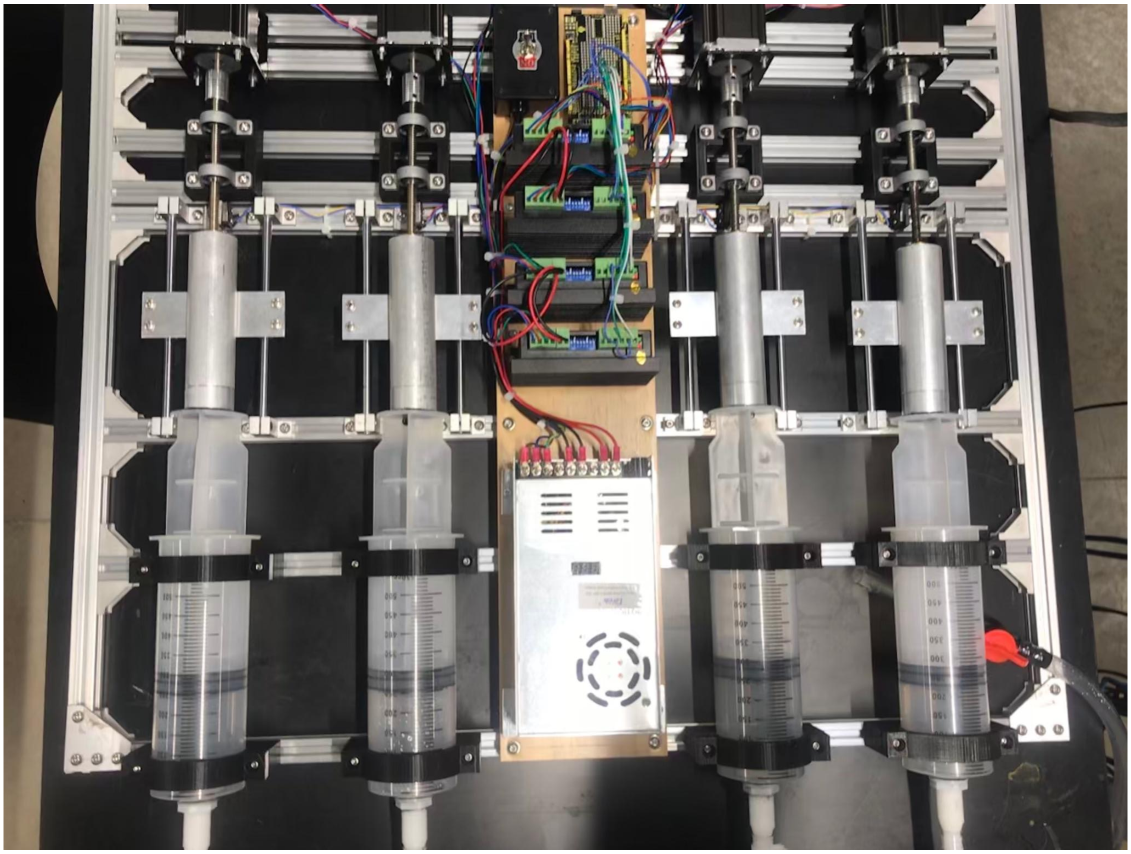

Figure 6a: Four complete heart pumps (overhead view)

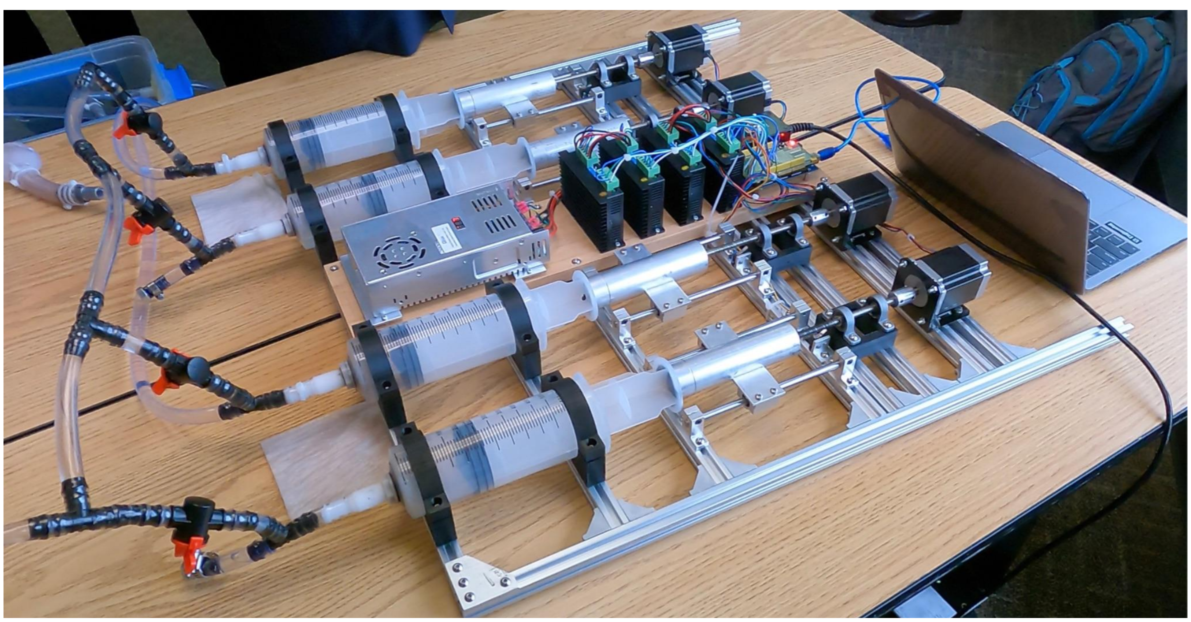

Figure 6b: Four complete heart units (side view)

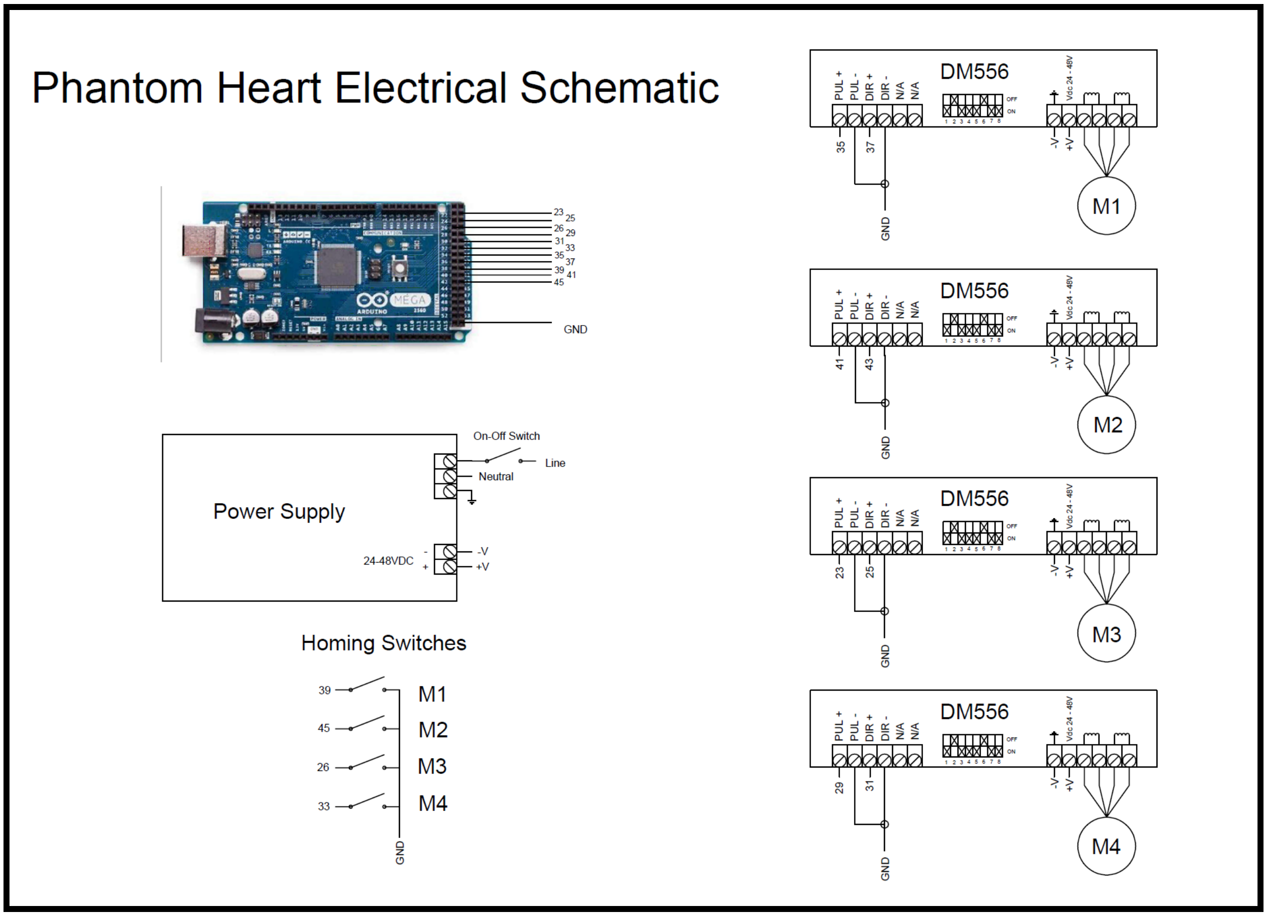

Figure 7: Phantom Heart Electrical Schematic

UI/UX

The user will be prompted with figure 8 when they need to operate the unit. The following steps are then taken to operate the device. Starting with plugging in the unit to an outlet and turning on the power supply. This program is a stand-alone executable that can operate on Mac or Linux and is used to send real time commands to the pump's control unit which will change how the pump operates. First the user must select the port of the control unit and then connect to the device. These two steps are shown in figure 8 and 9. Once connected the user can set the volume in ml, at that time the pumps will move and then the user can set the offset. Changing the volume can be seen in figure 10. When inputting the volumes, the user will input the volumes by order of the motors. The first value corresponds to the first pump, the second value corresponds to the second pump, and so on. Offset will be input the same way. The offset can be input as percentages, so inputting 50 corresponds to 50% offset or a 180 degree phase shift. The pumps will then move to the desired position. This is shown in figure 11. The user then can change the heart rate, shown in figure 12. To start pumping the user would activate the start pumping button, by clicking on it. Once the user is finished, they can click the stop pumping button, shown in figure 12. Any alerts, messages, and a summary of the current parameters pump is using will be shown in the bottom right side of the screen.

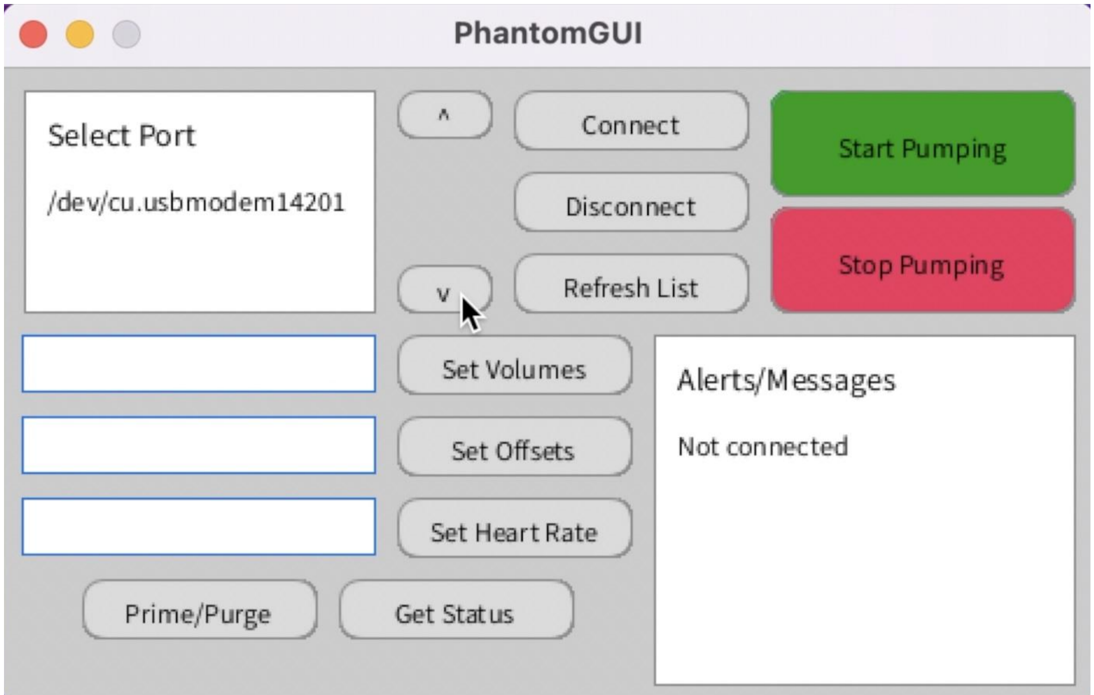

Figure 8: GUI Application opening window, and port selection

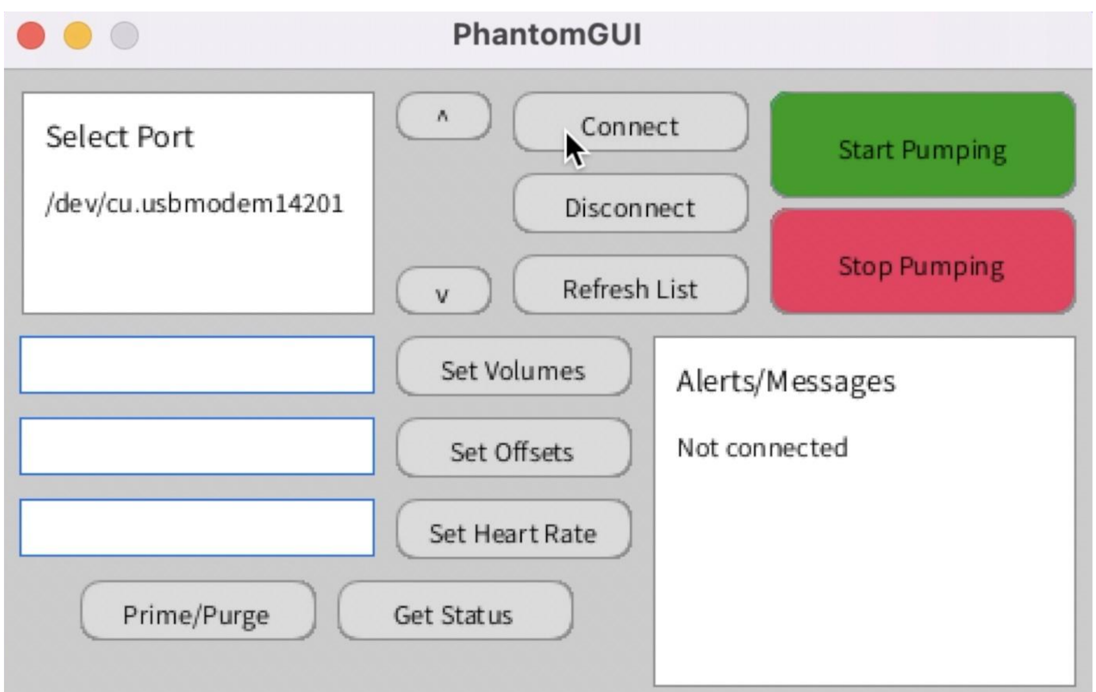

Figure 9: Connection Step

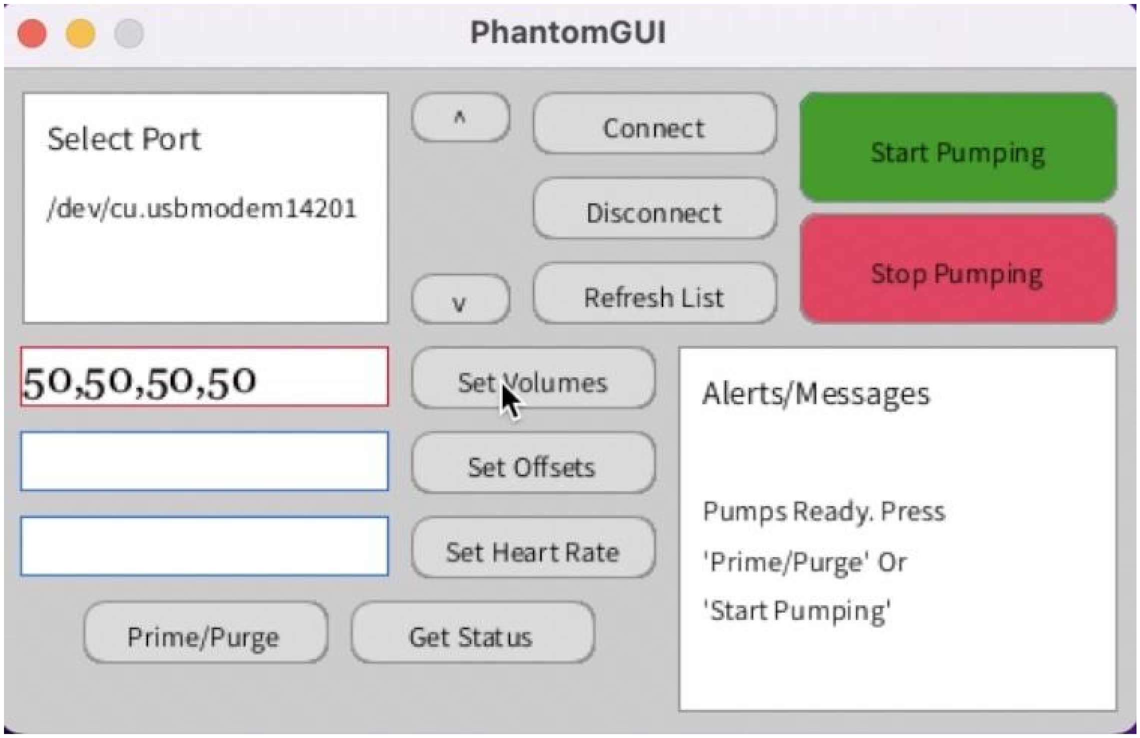

Figure 10: Setting volumes

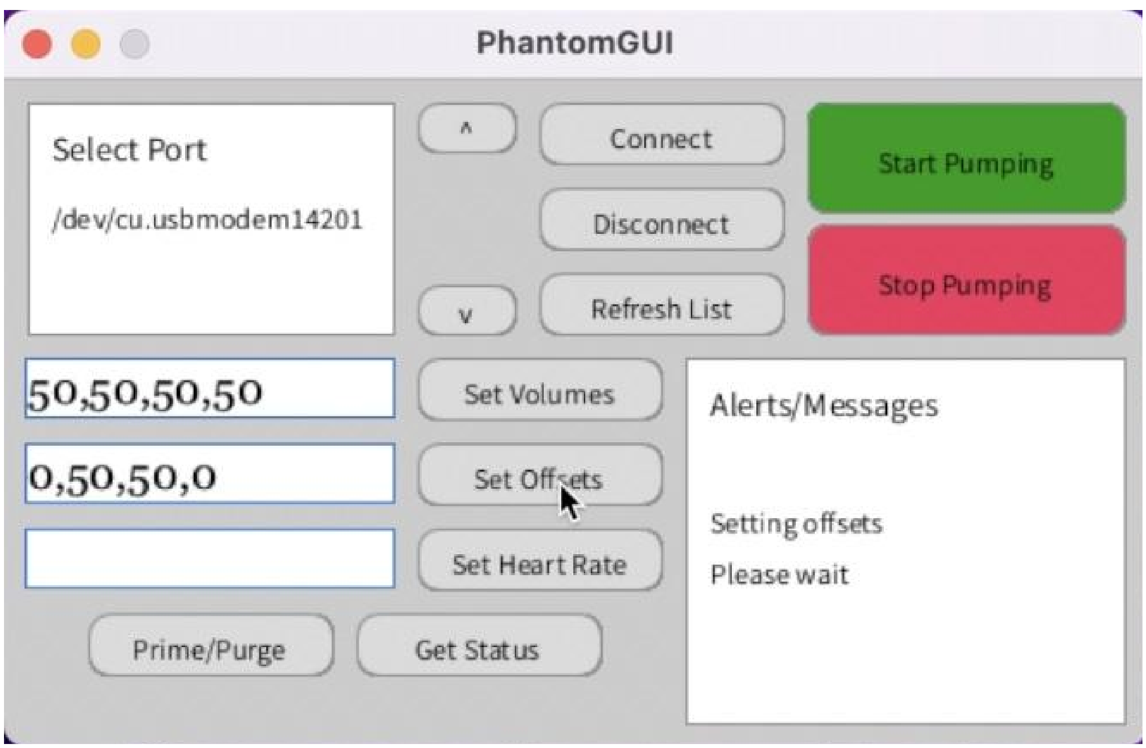

Figure 11: Setting offset

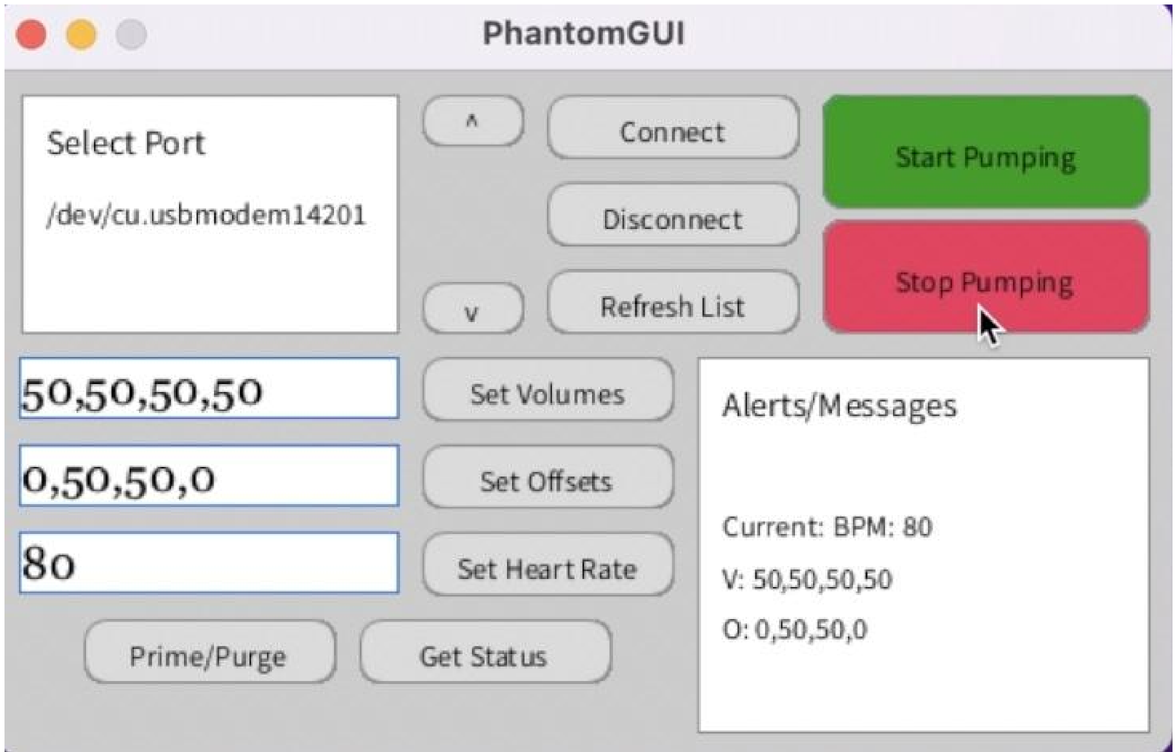

Figure 12: Setting heart rate

Other Design Factors

Design of our project came from previous heart pumps created. We wanted to emulate the effectiveness of their designs, but create a more cost effective, user-friendly, efficient design. The pump is laid on an aluminum base for strength, with all four units placed parallel to each other. Our team wanted to establish a simple and clean design to ensure maintenance would be easy for the user. Figure 7 shows our initial planning, but our new design is durable and will run for longer periods of time, without possible malfunctions. We replaced the wood with an aluminum base, and the syringe holders were 3D printed. All four pumps are connected to the same base, so it is easier to transfer from each room. One of our main goals was to make a more efficient heart pump that can withstand the long periods of time an MRI takes. Users of the heart pump will need to run it for one to two hours at a time. With this concern in mind, we created a sturdy and long-lasting machine.

Maintenance

Fluid is a major component to our design, so creating a water-proof machine was one of the most crucial issues we had to resolve. Expelling all fluid out of the tubing and syringes when the MRI test is complete is the first step in maintaining the integrity of the machine. The machine should be wiped down regularly to ensure no clogs or build up of grease and dirt which hinders the effectiveness of the pump. The system we created has a large hardware aspect, therefore regularly lubricating equipment to reduce friction around moving parts will help decrease wear and tear. Equipment should be checked thoroughly for wear and tear, and aging will eventually affect components. These components will then need to be replaced. Since our design is simplified for most users, replacement is very easy. Moving forward, we would expect some enhancements to our design. Currently the machine has metal components so the pump system can not be in the same room as the MRI machine. Having this metal means we have to run approximately 30 feet of tubing from the pump to the heart. Ideally we could create a system that could be in the same room as the MRI machine, so simplify transportation of the pump.

Test Report

Test	Expected Results	Pass/Fail	Observed Results
Emulate cardiac features	Heart beats at minimum of 60 bpm, max 100 bpm	Pass	Heart can beat from a range of 50-120 bpm
Emulate normal heart pressure	Heart pumps 10-20 ml of fluid	Pass	Heart pumps 10-40 ml of fluid
EKG mimicking capabilities	System can process and mimic an EKG reading	Fail	System does not have EKG processing capabilities
User can control functions of the heart independently	Each pump can be controlled on its own, or all pumping not in sync	Pass	User can control the pump independently and out of sync
System controls four chambers independent of each other	Each pump can move at its own rate, and own pressure	Pass	Each pump can move out of sync at, with its own heart rate and fluid pressure
Pump phase offset	The pumps can be offset from each other	Pass	Individual pumps can be set with an offset from the first pump
System allows heart to sit in steady state	Pump can pause at a certain pressure and retain its pressure for a period of time	Pass	System pauses at a moment and holds its pressure
The system can be operated continuously	The system can run for at least two hours	Pass	System has run for at least two hours and a half

Computer or software based input	The system has a GUI for user input	Pass	System has a GUI for user to input volume, bpm, and phase offset
Physical input	The system has a physical input method	Fail	System does not have a physical input, only communicates with a computer through serial
MRI safe	The system either has no metal or be able to operate with an MRI	Pass	System includes metal but operates with 30 ft hoses to stay outside of the MRI range
Transportable	The system can be easily transportable	Pass	System is mounted onto a grid of rails as one singular unit
The whole unit can fit through doorways	The whole system fits in a 4 ft x 4 ft x 4ft space	Pass	The system has dimensions of 33 in x 38 in x 11 in (2ft 9 in x 3ft 2 in x 11 in)
The unit operates with a blood-like fluid	The system can run with fluid with blood-like properties	Fail	The system has not been tested with a fluid of blood-like properties

Appendices

"Difference between 4-Wire, 6-Wire and 8-Wire Stepper Motors." *NI*, 10 Jan. 2019, https://knowledge.ni.com/KnowledgeArticleDetails?id=kA00Z000000PAkPSAW.

"NEMA 23 Stepper Motor." *Components101*, Components101, 23 Aug. 2019, https://components101.com/motors/nema-23-stepper-motor-datasheet-specs.

"Phantom User Manual", *Team sparkBug*, 03 May 2022, https://docs.google.com/document/d/1KS-DLbETjNkE4v9W4pfjd6P2IMRpXN9SFDzmsPjAywQ/edit?usp=sharing.