Pulsatile Flow System for Surgical Robotics

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Abstract

Surgical robotics is an evolving field where robotic medical devices are utilized to perform surgery either on or within the body. In order to mitigate errors that may occur during surgery due to the medical devices being used, testing environments are created for better development of the device and for clinical training. A Pulsatile Flow System (PFS) is a machine that recreates the physiological conditions of flow rate and pressure as the heart pumps blood, and can be created using materials such as pipes and motors. The research at hand developed a PFS and specifically focused on the electrical components of the system, using a motor, a motor controller, a flow sensor, and a circuit board. By creating code that is able to control the system and the speed at which the PFS functions, the system was able to pump water at 40 beats per minute through the circuit. Moving forward, the PFS can be improved to become an even more accurate model by including changes such as substituting the water in the system with a liquid of a similar viscosity to blood. The development of a machine like this is crucial in order to provide a cost effective system capable of imitating the human body in order to properly test surgical robots that travel through arteries in the body. Using an external testing environment will ensure that the devices created in the laboratory are properly developed before they are used in surgery, ensuring that the patient's life is kept out of harm's way.

Introduction

Surgical robotics is an evolving field where robotic medical devices are utilized to perform surgery either on or within the body (1). Surgical robots can come in a variety of sizes to provide assistance with minimally invasive surgeries and may be needed to travel within the body or to function in specific areas (1). When testing these robots within the body, different methods have been tried to allow for the observation of the function of the robots in their intended environments (which can include blood vessels, tissues, muscles, and organs). The use of human and animal cadavers in order to model the mobility of certain robots through the body is simply one of the many ways to test the quality of medical devices (2). In order to help mitigate "medical errors," an occurrence that can lead to deaths in over 250,000 patients per year (3), preoperative planning and clinical training is implemented. In order to continue to decrease this number of deaths, research is necessary to develop robust clinical scenarios that can provide a thorough testing of medical devices before use on patients (3).

As a result, the method of using 3D printers in order to create replicas of arteries, organs, and tissues in order to use in these planning and training settings has become increasingly prevalent (3). Researchers have tried to recreate the walls and textures of the arteries themselves, rather than just the general shape (4), which allows for the observation of the robot medical device in an artificial environment that is more similar to a natural artery. An example of human body functions in an external environment is a pulsatile flow system, a machine that can replicate the flow of blood (5). A Pulsatile Flow System (PFS) can be used to recreate the physiological conditions of flow rate and pressure as the heart pumps blood, providing a setting in which devices can be tested (5). Components of the overall system may include a pump, valves to mimic the heart's valves and create pressure, a reservoir for the solution being pumped, tanks, and a prosthesis through which the solution will run (5). The system may also contain openings for air intakes and outtakes, pressure regulators, and machinery to control the speed and amplitude of the solution being pumped (5).

In general, systems that recreate the way blood is pumped, 3D printed technology, and materials such as soft silicones to create blood vessels for surgical robots not only allow for the testing of the robotic medical devices to occur at a relatively less monetary expense, but also allow for accurate productions of artificial body parts to occur quickly and save time (6), allowing the testing process to pass rapidly as well.

After reading the methods that several different scientists have used to approach replication of human vessels, the research at hand replicates the way that blood is pumped through human arteries by using simple motors and programming boards. Nikhil Chittaluru assembled the mechanical aspect of the machine, including components such as the reservoir, the tubes, and the pump. Ankita Verma built the electrical portion of the machine using Arduino programming and a motor for power. With these aspects combined, the machine will allow for the eventual production of artificial human vessels. This can be facilitated by the 3D printing process and the manner in which blood flows through them. Thus, in the end, there is an environment external to the human body in which robots or other medical devices can be easily tested as they travel through or perform their functions (e.g., cauterization, cutting, transport of other material) within replicas. The PFS at hand is different from those already created because it will be a cheaper alternative. Many existing PFSs are expensive and which can make their acquisition difficult. However, by creating the PFS within the laboratory, an alternative solution can be found that is much more accessible and cost effective.

It is important that inexpensive testing environments be available so the critical step of testing is not skipped if cost effectiveness is an issue. If robotic medical devices are not tested within replicas or clinical testing environments before they are taken to the patient, there will be no way of knowing how well the device works before it is used on a human. This can prove to be fatal to the patient since flaws in the design will not have been improved prior to actual use. Thus, an artificial testing environment will allow for clinical assessment of medical devices before they are introduced to patients, ensuring that by the time a device has been introduced to a human patient that it will have been fully tested through the use of the external environments to protect the health of the patient.

Literature Review

Various methods can be used in order to test medical devices created for the function in the human body. When testing small medical devices meant to interact with the body, it is not possible to test the device within an actual human being until the device has been fully developed. An environment must be introduced that allows for testing without the use of a live subject. This is to ensure that no patients are harmed with an underdeveloped medical device used on them. Using a PFS to recreate blood flow in the body is a viable option that allows for the testing robotic and non-robotic medical devices in an environment that mimics a blood vessel. Previous research has explored this method of experimentation and has tried to construct pulsatile flow systems for different purposes.

Researchers have created PFSs in order to allow for in vitro evaluations of devices (5). In order to recreate the blood flow in the body they have designed an independent pulsation unit, which allows for different flow rates to be implemented (5). Doing so allows for the testing of different pressures, flow rates, and temperatures and observations of how changes in each variable effects the other, allowing variations and fluctuations to be tracked (5). The experimental system is able to reproduce normal physiological blood flow conditions as well as extreme conditions, allowing a wide range of devices to be tested without harming any patients (5).

PFSs can also be designed to use for the study of blood transfer through capillaries and venules (7). The system set up in these cases is similar to pulsatile flow systems designed to test devices, with peristaltic pumps and gas permeable silicon tubing involved in order to recreate the flow and the diffusion of gases (7). Because this type of system aims to study capillaries and venules, the system has different settings than a regular PFS, which usually focuses on arteries and veins (7). Because capillaries and venules are smaller and hold different characteristics, such as pressure, these differences are taken into account in the circuit (7).

Finally, some prior research has found that implementing PFSs in medical settings actually helps improve vital organ recovery and prevent multiorgan failure (8). In this environment, PFSs are used to provide an external source of oxygenation to human organs in order to relieve respiratory distress or address lung disease (8). In the test set-ups, the PFS is created using machinery such as rotary pumps and a dSpace systems to measure pressure (8). PFSs used for extracorporeal membrane oxygenation include heat exchangers and oxygenators to ensure that when the contents running through this particular type of system are connected to a patient, the blood will flow directly into their organs without any issues (8). Thus, the blood is also kept at the proper temperature in order to take into account the effect on the settings of the organs in the human body (8). Other setups utilize phantom ECG simulators in order to trigger pulsatile flow instead of using simple motors or rotary pumps which allows a capture of optimal pulsatility rate when creating the circuit for the PFS (9).

Methods

In order to complete the design of the electrical components of the PFS, first the type of circuit board, which would be used to program the system, was determined. It was decided that a DC motor, which would be used to drive the pump of the system, would be the best to use for the system. In order to achieve this, it was necessary to ensure that the motor used was compatible with the circuit board. After deciding on a motor that would provide the proper amount of specifications needed (taking into account the power, amps, and voltage output), the specifications of the motor were matched with the specifications that the circuit board would be able to withstand. After researching which circuit board would be the best fit by comparing which ones were programmable, the Arduino was chosen since it is intuitive to program and is compatible with the motor that was selected.

Next, the DC motor, shown in Figure 1, was connected to the Arduino, and a code that would allow to control a DC motor was searched for.

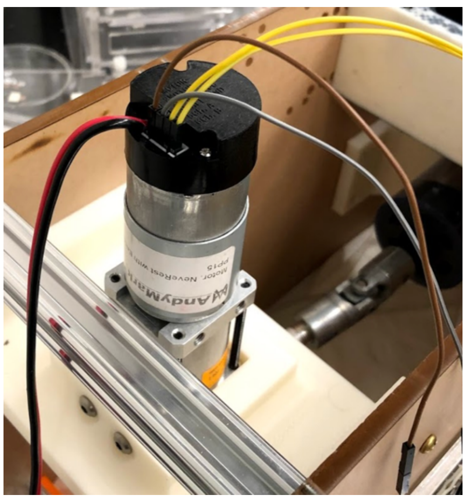

Figure 1. DC Motor implemented in the Pulsatile Flow System

Once the proper code was found that activated and deactivated the DC motor, experimentation with controlling how fast the motor could function began. This was necessary in order to allow the machine to mimic the speed of a blood flowing through the body. After searching through research articles, it was decided that the resting blood flow rate of a patient laying down is 40 beats per minute (bpm), a metric that can be modeled in order to mimic the blood flow of a patient who is lying on an operation room table while a surgical robot (a product that is to be tested in the system) is inserted into them. The next steps included working to ensure the motor achieved that speed.

In order to do this, it was necessary to ensure that the right amount of Pulse Width Modulation (PWM) was applied in order to allow the motor to run at the desired speed. PWM is a method of controlling the amount of average power delivered from the board by an electrical signal and can be adjusted with the help of the code in order to reach my end target speed of 40 bpm. The number of pulses within one rotation of the DC motor was determined by manually rotating the tip of the motor and counting the number of pulses present. Next, the Serial Monitor in the Arduino was used to monitor how many pulses were recorded by the Arduino in the frame of a second. PWM values were observed ranging from 50 to 200 at intervals of 25 and at 255, which was the PWM cap for an Arduino board. This was done in order to develop a mathematical formula, seen below in 1, that allowed for the input of the target bpm desired by the system to be calculated automatically to determine what PWM is required. When the formula was inputted with 40 bpm, the PWM found was 205.4. The formula allowed for the automatic input of the PWM value to the Arduino board.

$$\textbf{1.}\ \text{PWM} = 5.135 * (flowrate\ bpm)$$

The purpose of using a formula instead of simply inputting 40 bpm into the code was to allow one to run the system at any speed desired instead of locking the bpm of the system to 40 bpm. Thus, one could theoretically model the blood flow of a standing person, which would be higher than the blood flow of a person lying down, by inputting the heart rate they would like to see, allowing the code to perform conversions for the motor to output the correct result, and allowing for the automatic input of the value to the board.

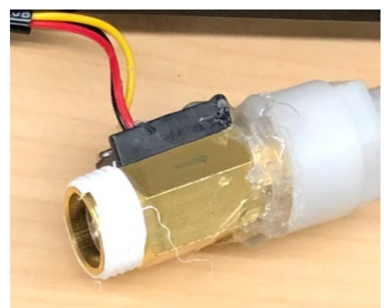

Figure 2. Flow Sensor

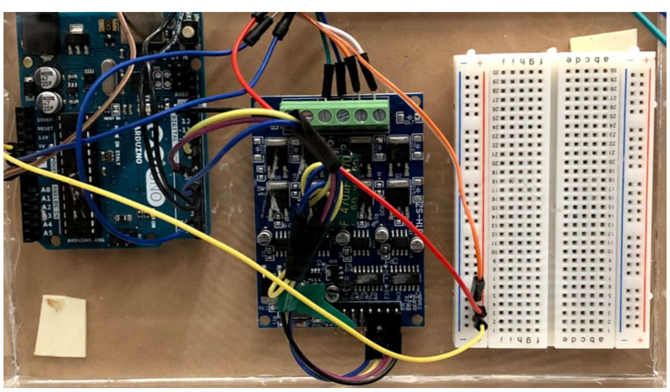

Figure 3. Arduino and Motor Controller in the Pulsatile Flow System

Once all of the settings were set for the board, the code for the motor was combined with a flow sensor (a device to monitor the speed of the liquid passing through the system), shown in Figure 2, to work on one Arduino board in order to consolidate spacing and ensure that the machine could be made as compact as possible without the need for extra boards, as seen in Figure 3.

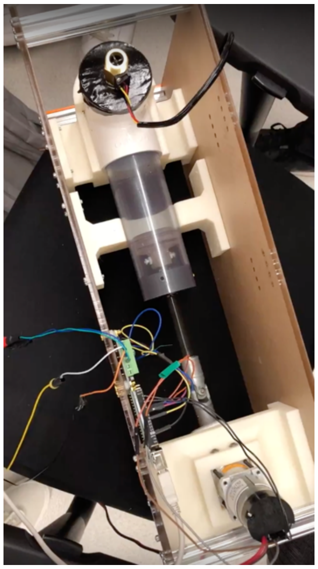

Figure 3. Mechanical Components

Nikhil Chittaluru designed and assembled the mechanical components of the system. He developed the circuit of pipes for the water to flow through and included a reservoir to store the water in the system, a pump, and one-way valves to ensure the water flow follows the design. A few of the mechanical components are depicted in Figure 3 with the water reservoir removed from the system for better visibility. The electronics and the mechanical components were combined, as shown in Figure 4, and the PFS was filled with water to be turned on for several runs. This allowed for the recording of data and ensuring that the results received were accurate with a consistent amount of volume outputted by the system.

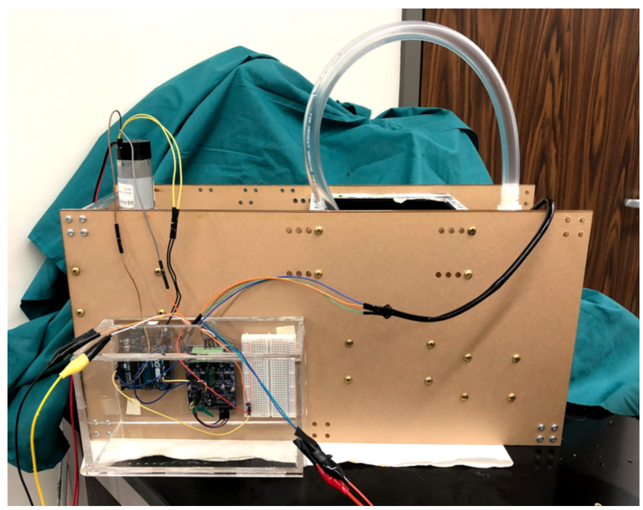

Figure 4. The completed Pulsatile Flow System

Materials

The materials used to construct the electrical component of the PFS included an Andymark NeveRest Motor with an Encoder, which is a 12 V DC motor. An Arduino board was also used, along with DC Brush Motor Controller from DROK that was 16A. The motor controller allowed for direction to be determined while all of the coding for the system was done through the Arduino. A generic breadboard was utilized to provide extra ports of connection, and alligator clips along with jumper cables were used for wiring purposes. Finally, a 12V battery source was used in order to provide power to the system by connecting to the motor controller since 12V was sufficient to power the circuit system.

Results and Discussion

Once an assembly was made of the PFS, water was used as a preliminary test of being pushed through the circuit. The system was able to use the motor and electrical signals to pump the water in a heartbeat motion. A timer was used to count the amount of times the PFS pumped water in one minute. For example, with 40 beats per minute set in the code, it was experimentally confirmed that the machine was outputting 40 beats per minute. As a result, it was verified that the beats per minute inputted in the code matched the same beats per minute that was outputted by the PFS system.

Moving forward, the water in the pump should be replaced with a liquid that matches the viscosity of blood. It is assumed that increasing the viscosity of the liquid within the PFS would cause the pump in the system to exert more effort since the amount of friction produced within the circuit will be increased. Thus, Formula 1 will have to be adjusted accordingly based on experimental results in order to account for the increased friction. As a result, when a certain variable of bpm for "blood" is inputted into the code, it provides the correct respective output.

Moving forward, in order to complete the development of the PFS, life size 3D printed organs should be inserted into the circuit. This will mimic the way the body pumps blood to an organ and back, providing a more realistic model of how blood is retained and expelled by different parts of the body. Tubing in the system should also be replaced with tubing that is similar to the diameters of arteries and veins in the body. This will help create the same pressure and diameter that is experienced within blood vessels. All of these aspects will cause the PFS to become more realistic and accurate, causing the PFS to match the environment of a human body even more closely. This is significant because it will ensure that any medical device tested in this environment will garner in more accurate results that can be applied to a human. Improvements can be made to the medical device accordingly, causing patients in the long run to receive treatment from safer devices and culminating in a decrease in mortality rates due to medical device errors.

Once these aspects are integrated within the PFS, the PFS should be ready to be a testing facility for different medical devices, whether they are robotic or not, that are to travel through the blood stream. The PFS can be used for circumstances other researchers have applied PFSs, such as in vitro evaluations of different robotic medical devices. One can test different settings with the PFS to ensure that the device can withstand several different conditions as it travels through the body. As mentioned before, some researchers have also utilized PFSs to study blood transfer between different sized capillaries (7). The PFS developed in my research can be used for this application by simply using tubes of different diameters to replicate the different sizes of capillaries. The PFS at hand provides a way to be able to study the human body and test medical devices while being relatively inexpensive. It provides a cost effective solution in efforts to create safer surgeries for patients.

Conclusion

In the surgical robotics field, it is crucial that surgical medical devices are tested before they are implemented in surgery. In order to ensure that no patient's life is ever put in harm's way with an underdeveloped device, a testing environment such as a Pulsatile Flow System is necessary. A PFS is able to mimic the physiological function of a heart pumping blood through the body (5). The approach of building a PFS in the laboratory setting at hand is not only relatively inexpensive, but also allows for the testing of several different robotic medical devices relatively easily. The electronics of the Pulsatile Flow System in the current research were completed with a DC motor, a circuit board, a motor controller, a flow sensor, and coding. The system was programmed to mimic how the heart pumps blood through the body at 40 beats per minute, and it was successful in consistently pumping water through the circuit. With patient safety in mind, the research will continue to work toward the goal of establishing a cost effective testing environment for surgical robotics in order to ensure that all devices are fully developed and tested before they are used in surgery.

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