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Design and implementation of a cost-effective, open-source, and programmable pulsatile flow system

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ABSTRACT

The primary objective of this research was to design, implement, and validate a programmable open-source pulsatile flow system to cost-effectively simulate vascular flows. We employed an Arduino-compatible microcontroller combined with a motor driver to control a centrifugal direct current (DC) motor pump. The system was programmed to produce pulsatile flows with an arterial pulse waveform. Validation with Doppler ultrasound and flow measurements confirmed that our Arduino-based system successfully replicated arterial vascular flow. The materials are easily accessible, with a total bill of materials as low as $99. This open-source programmable pulsatile pump platform offers superior cost-effectiveness and adaptability relative to commercial offerings.

Specifications table

Hardware name	Programmable Pulsatile Centrifugal Pump for Vascular Flow Simulation
Subject area	• Medical (cardiovascular simulation) • Educational tools and open source alternatives to existing infrastructure
Hardware type	• Other: software and hardware to control a pump to generate arterial/vascular flow
Closest commercial analog	United Biologics Flowtek 125. https://unitedbiologics.com/product/flowtek125/
Open source license	CC BY-NC-SA 4.0
Cost of hardware	*$99–$167*
Source file repository	*Vezeridis, Alexander; Herwald, Sanna (2024), "Programmable Pulsatile Centrifugal Pump for Vascular Flow Simulation", Mendeley Data, V1, https://doi.org/10.17632/6dscgdg2b5.1* *https://doi.org/10.17632/6dscgdg2b5.1*

1. Hardware in context

The accurate in vitro replication of cardiac and peripheral vascular flow physiology has long been an area of interest in medicine and biomedical engineering. Researchers have utilized commercial systems to recreate pulsatile flow conditions for various purposes such as drug testing, medical device validation, and training of medical professionals [1,2].

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While these systems offer reliable performance and are programmable, they require significant financial overhead and are constrained by proprietary designs that inhibit adaptability for specialized research needs. Previously described high-performance pumps that allow customization come at the cost of bespoke engineering [3,4]. Simpler and cheaper commercial offerings are available but still cost thousands of dollars, limit customization to only pulse rate and flow rate, and are not intended to accurately replicate pulse waveforms [5,6].

The open-source microcontroller platform Arduino [7] has been used to create pulsatile flow pumps for cardiovascular studies, but these studies required expensive specialized hardware [8,9]. One such prior effort used a specialized pump from a hemodialysis machine that would be very challenging to source for most researchers and educators [8]. In addition, this system required proprietary software (MATLAB) for real-time feed-forward control, resulting in further complexity and cost [8]. Another group used Arduino to provide PID (proportional–integral–derivative) control for a specialized expensive gear pump [9].

The goal of the current work was to make an open-source pulsatile flow pump at absolute minimum cost and complexity with readily available materials that could be replicated easily by others for use in research or education.

2. Hardware description

This work presents an open-source, customizable, small, inexpensive, and accurate pulsatile pump for mimicking physiologic vascular flow. All utilized printed circuit boards (PCBs) are inexpensive, commercially-available, and open source. Hence, construction

Table 1
Components of the pulsatile pump with material sources and prices.

Designator	Component	Number	Cost per unit —USD	Total cost – USD	Source of materials	Material type
Microcontroller board	Feather ESP32 V2 Microcontroller	1	$19.95	$19.95	Adafruit https://www.adafruit.com/product/5400	Other: PCB
Stacking header	Stacking header	2	$1.25	$2.50	Adafruit https://www.adafruit.com/product/2830	Other: Electronic connectors
OLED display & interface board	FeatherWing OLED – 128x32	1	$14.95–15.95	$14.95–15.95	Adafruit https://www.adafruit.com/product/3045	Other: PCB
Motor driver board	DC Motor + Stepper FeatherWing	1	$19.95	$19.95	Adafruit https://www.adafruit.com/product/2927	Other: PCB
Barrel jack leads	Barrel jack leads (one pair: one male and one female)	1 pair	$0.92	$0.92^{+}	Amazon https://www.amazon.com/dp/B09XQZLM1Q/	Other: Electronic connectors
Centrifugal pump	Bayite BYT-7A015 12 V DC Pump	1	$27.50	$27.50	Amazon https://www.amazon.com/gp/product/B01G305PK0	Other: Pump
Silicone tubing	3/16″ silicone tubing	10 feet	$1.33	$13.30	McMaster-Carr 51135 K23	Polymer
Nylon tubing clamps (optional)	Tubing clamps	4	$0.60	$2.40^{+}	McMaster-Carr 9579 K111	Polymer
Inflow barbed fitting (optional)	¼” barbed hose to ½” NPT female connector	1	$3.99	$3.99^{+}	Amazon https://www.amazon.com/gp/product/B08S79KKJC/	Metal
Outflow T-fitting (optional)	½” NPT female 3-way tee connector	1	$18.99	$18.99	Amazon https://www.amazon.com/dp/B07DT6M532	Metal
Outflow barbed fitting (optional)	¼” barbed hose to ½” NPT male connector	1	$6.99	$6.99^{+}	Amazon https://www.amazon.com/gp/product/B07P2WGVYS	Metal
Pressure transducer (optional)	1/8″ NPT male pressure transducer	1	$14.33	$14.33	Amazon https://www.amazon.com/gp/product/B07N8SX347	Other
Threaded reducer (optional)	½” NPT male x 1/8″ NPT female	1	$8.99	$8.99	Amazon https://www.amazon.com/gp/product/B07KX3X8S2	Metal
Acrylic pump base (optional)	Acrylic slab ¼” thick	80x120 mm	$9.98	$9.98	Amazon https://www.amazon.com/dp/B0BLLK17W2	Polymer
Pump base feet (optional)	Square rubber bumper pads	4	$0.48	$1.92^{+}	Amazon https://www.amazon.com/gp/product/B008UFKE26	Polymer
Pump base screws (optional)	M3-0.5x16mm socket head machine screws	4	$0.10	$0.40^{+}	Amazon https://www.amazon.com/gp/product/B07CK1LFL8	Non-specific

would be within reach of most facilities even if the specific PCBs were no longer to be sold. The cost of our system hardware is one quarter that of previously reported efforts and does not need the additional cost or complexity of proprietary software such as MATLAB [8].

- The described hardware and software solution realizes a pulsatile pump for vascular flow simulation or other tasks that require customizable pulsatile flow.
- An ideal use case could be simulation for training, including training physicians on diagnostic vascular ultrasonography, arterial access, or arterial embolization under realistic flow conditions. The low cost of this pumping system is attractive to educational budgets, even in low-resource settings.
- Other use cases could include providing pulsatile flow to test medical devices under vascular flow conditions, or to evaluate diagnostic vascular imaging systems (such as Doppler ultrasound).

3. Design files summary

Design file name	File type	Open source license	Location of the file
pulsatile_pump.ino	Arduino Firmware	*CC BY-NC-SA 4.0*	https://doi.org/10.17632/6dscgdg2b5.1Folder: Arduino Program
Centrifugal Pump Base.svg	SVG design for laser cutter	*CC BY-NC-SA 4.0*	https://doi.org/10.17632/6dscgdg2b5.1Folder: Laser Cutting File

The Pump Control Program (pulsatile_pump.ino) is the Arduino source code that is loaded onto the microcontroller board to run the interface finite state machine and the waveform loop for motor control.

The optional pump base (Centrifugal Pump Base.svg) is a scalable vector graphics (SVG) file that can be used to laser cut a piece of acrylic that serves as a larger base for the pump. This optional base prevents the pump from leaning towards the inflow due to the weight of the barbed coupling and tubing. Alternatively, the pump can be secured to another platform/enclosure as desired.

4. Bill of materials summary

All components in Table 1 are listed with current prices as of December 2023 and do not include tax or shipping/handling. Some parts, labeled with a superscript cross ($^{+}$), are bought as part of a larger pack and therefore could incur higher cost than listed. The silicone tubing minimum order is 10 feet, which is longer than needed. Acrylic can be bought in a 4x6 inch size that is slightly larger than the 8x12cm dimensions used in the laser-cut pump base without additional cost. If bought locally at a plastics store, scrap acrylic can be acquired for much less.

5. Build instructions

Control Electronics Assembly:

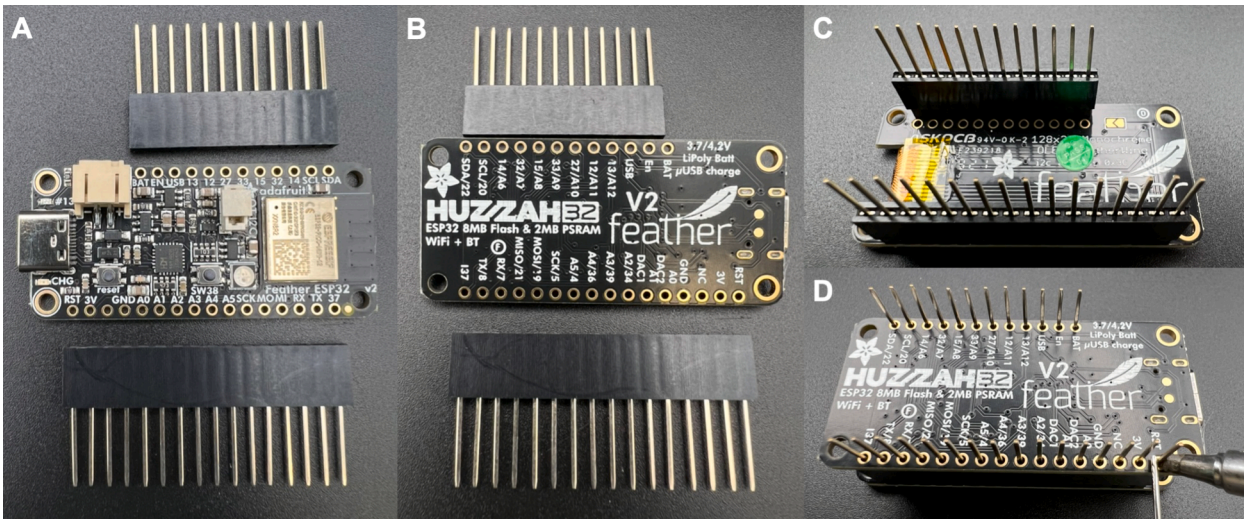


Fig. 1. Soldering of the microcontroller PCB. The motor driver PCB should be soldered in an identical fashion. (A) Top view of the microcontroller board with stacking headers. (B) Bottom view of microcontroller board with stacking headers. (C) Bottom view of display board with stacking headers attached to display board headers, making it easier to solder stacking headers to the microcontroller board. (D) Microcontroller board placed onto stacking headers connected to display board, with stacking headers being soldered to the microcontroller board.

1. Solder stacking headers to the microcontroller board and the motor controller board (Fig. 1). The OLED display and interface board is pre-assembled and does not require soldering of its header pins. CAUTION: high temperatures risk tissue burns and fire, and flux fumes risk inhalation injury. Use a solder fume extractor. Use lead-free solder. Use appropriate local/municipal/institutional protocols for soldering including personal protective equipment and attention to solder waste streams.
2. Connect the female DC barrel jack to the motor output "M4" screw terminals (Fig. 2). Note that the board does not have a specified polarity for outputs M1-M4 on the board silkscreen, but that to have the pump run in the "forwards" direction the red (positive) wire of the motor output barrel jack needs to be attached to the pin on the outer end of the board. Connect the male DC barrel jack leads to the DC in ("5-12VDC") screw terminals in the correct polarity (Fig. 2).
3. Stack boards in the following order from top to bottom (Fig. 3): (a) OLED display & interface board; (b) motor controller board; (c) microcontroller board. The bottom board (microcontroller board) header pins can either be plugged into a solderless breadboard (Fig. 3), or the board stack can be mounted into the user's application with custom mounts that leave the header pins free. Using a breadboard conveniently provides a mechanical base for the board, and the header pins can be accessed by using jumper wires.
4. Optional analog and digital outputs: If the user needs an analog output of the waveform, this is provided as an analog output (voltage 0–3.3 V) on pin A1/DAC1 (see Fig. 1B). For easier and more reliable synchronization and triggering, a digital/TTL output is provided on pin 13/A12 (see Fig. 1B). The waveform is also provided through serial communication, as described later, providing a convenient method of saving/syncing digital data sources.

Firmware Loading & Terminal Access:

1. Install the Arduino Integrated Development Environment (IDE) on a computer [10,11].
2. Install the necessary USB-to-serial driver for the Adafruit ESP32 Feather microcontroller [11].
3. Within the Arduino IDE, install the ESP32 Board Support Package [11].
4. Connect the microcontroller board to the computer using a USB cable (Fig. 3B-C).
5. Open pulsatile_pump.ino in the Arduino IDE.
6. Under the "Tools" menu, select "Board" > Adafruit Feather ESP32 V2 (Fig. 4). Under the "Tools" menu, select "Port" > cu.wchusbserialXXXXXXXX (Fig. 5).
7. Upload pulsatile_pump.ino to the microcontroller board by hitting "Upload" in the Arduino IDE.
8. To monitor the current pump rate from the pump, terminal access is available either through the Ardunio IDE or through a dedicated serial terminal program. The program outputs the current pump rate from 0 to 255.

Pump Hardware Assembly:

1. If optional pressure sensing is desired: (a) attach the inflow barbed fitting to the inflow of the pump using Teflon tape to ensure a good seal. (b) Assemble the outflow construct by attaching the pressure sensor to the middle part of the T-fitting through the threaded reducer, using Teflon tape between each component (Fig. 6). Attach the outflow barbed fitting to one of the side T-fitting connectors.
2. Attach the optional laser-cut pump base to the pump using four M3x16mm machine screws (Fig. 7A). Stick on four pump base feet (Fig. 7B). Attach the assembled outflow construct to the outflow of the pump and an inflow barbed connector to the inflow of the pump (Fig. 7C). Final assembled pump is shown in Fig. 7C.
3. If optional pressure sensing is not desired, attach the brass barbed fittings included with the pump using included Teflon tape (Fig. 8), but note that the brass barbed tubing connectors included with the pump are for 3/8″ tubing.

Fluid Circuit Assembly:

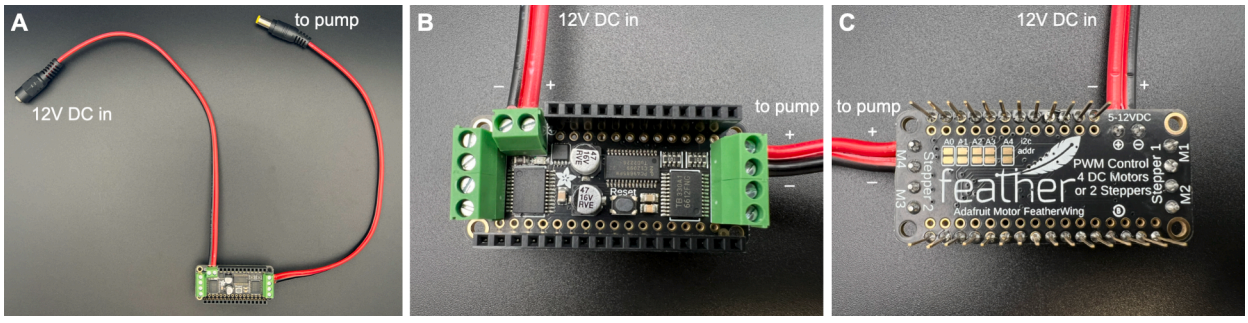


Fig. 2. Assembly of the motor driver PCB. (A) Top view overview of the assembled motor driver PCB showing attachment of the barrel jack leads. (B) Top and (C) bottom view closeup of the assembled motor driver PCB with stacking headers, showing correct polarity of the barrel jack leads.

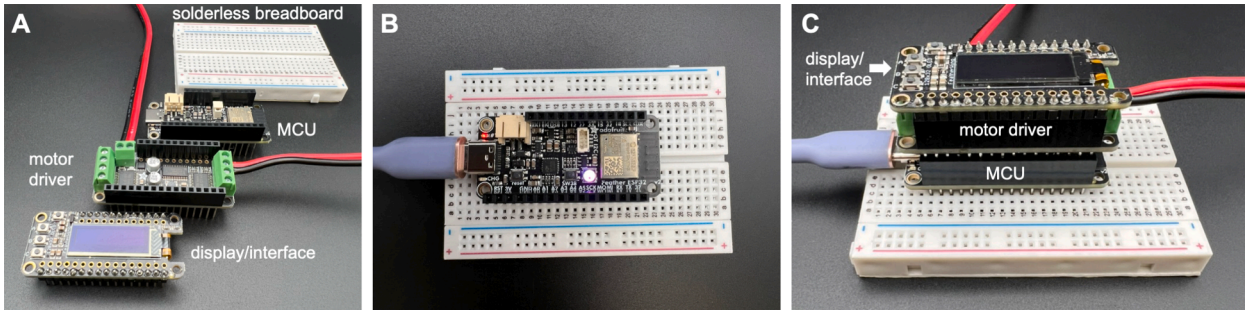


Fig. 3. Assembly on breadboard. (A) Assembled components including OLED display/interface board, motor driver board, and microcontroller (MCU) with breadboard prior to stacking assembly. (B) Microcontroller inserted into the breadboard. USB-C cable is shown connected. (C) Final assembled stack of boards on the breadboard.

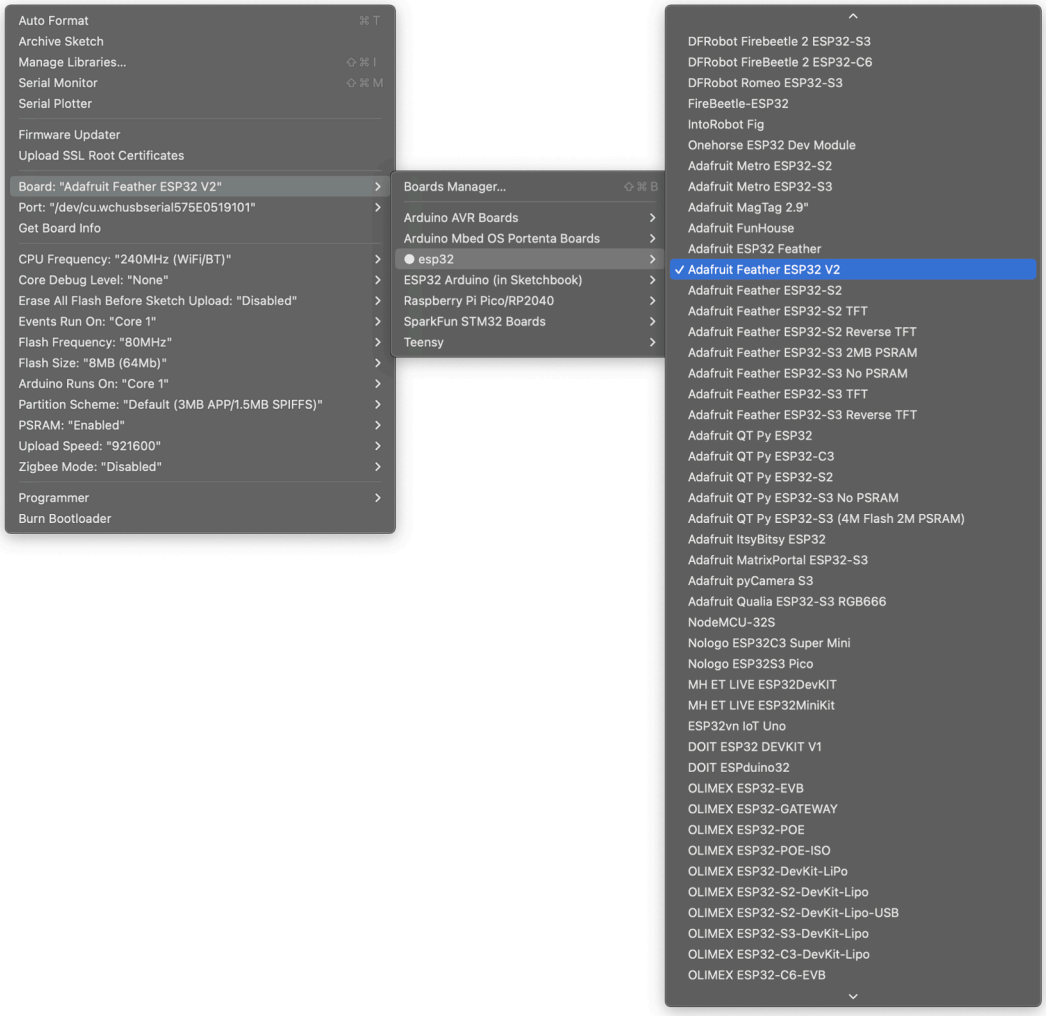


Fig. 4. Selecting the microcontroller board from the Tools menu for uploading the firmware.

1. Connect a silicone tubing of desired length between the inflow of the pump and a reservoir (Fig. 9). A cup, beaker, or bottle is a suitable reservoir.
2. Connect a silicone tubing of desired length between the outflow of the pump and a desired test chamber/circuit (Fig. 9).

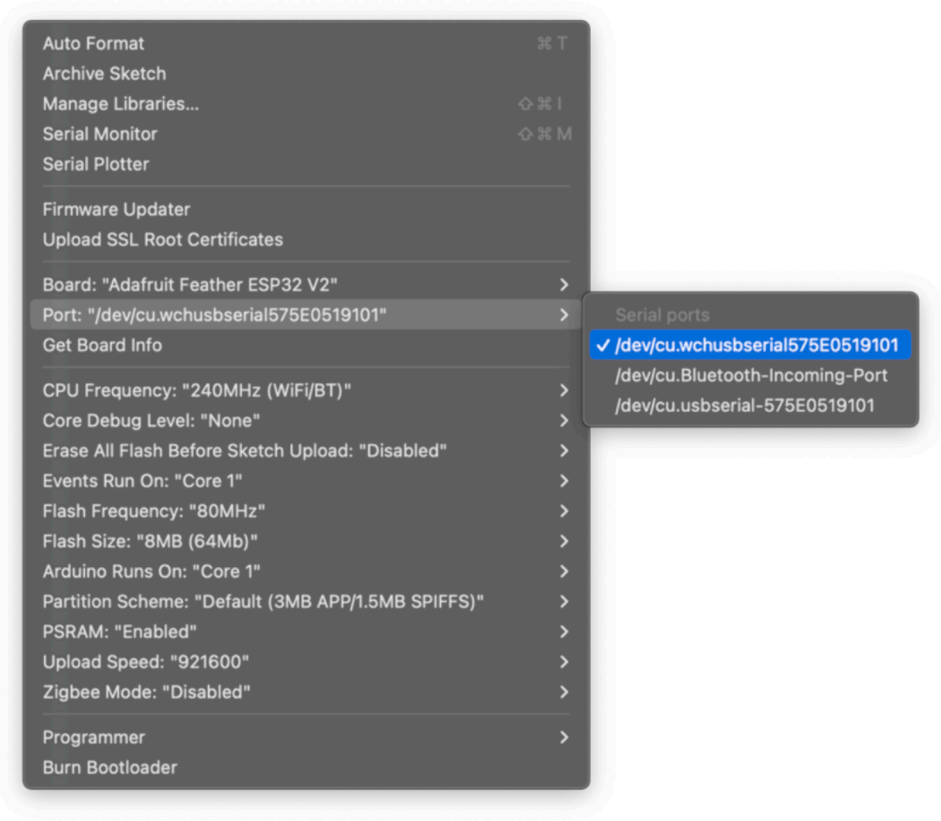


Fig. 5. Selecting the serial port from the Tools menu for connecting to and uploading firmware to the microcontroller board.

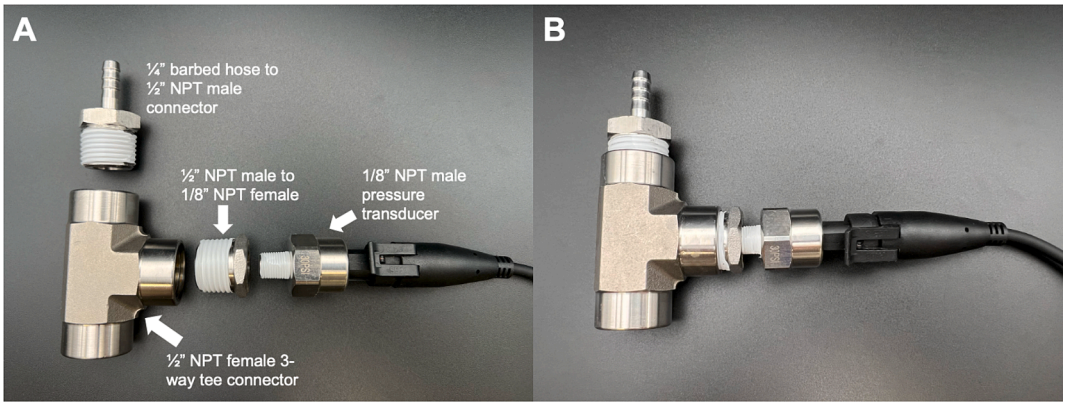


Fig. 6. Components and assembly of pump outflow and pressure transducer. (A) Components with Teflon tape added in between connectors and fittings. (B) Outflow assembled.

3. Complete the circuit by connecting a silicone tubing of desired length between the outflow of the test chamber/circuit and the reservoir (Fig. 9).
4. Prime the pump circuit as described below.

6. Operation instructions

Pump fluid circuit setup: Most centrifugal pumps should not be run dry, and eliminating large bubbles from the pump and tubing is easier before the pump is turned on. The pump and tubing can be easily primed by placing the pump inflow tubing into the fluid reservoir and then drawing liquid from the pump outflow tubing using a luer-lock syringe (which conveniently press-fits into 3/16″

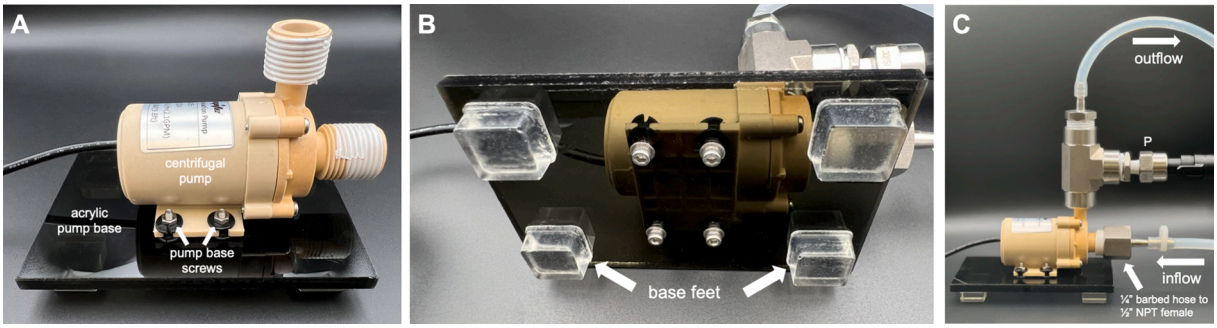


Fig. 7. Assembly of pump and pump base. (A-B) The pump is attached to an optional laser cut acrylic base, and elastomeric feet are added with double-sided adhesive. (C) Assembled pump, with optional pressure transducer, P, and white arrows showing direction of fluid flow.

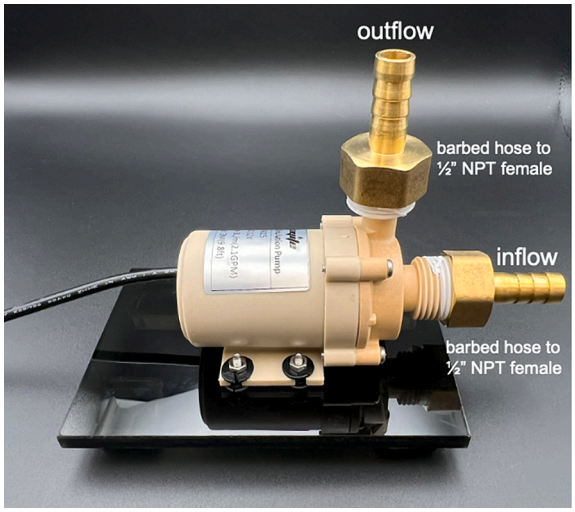


Fig. 8. Simplified setup of pump without optional pressure sensor. Note that the included barbed tubing connectors are for 3/8″ tubing.

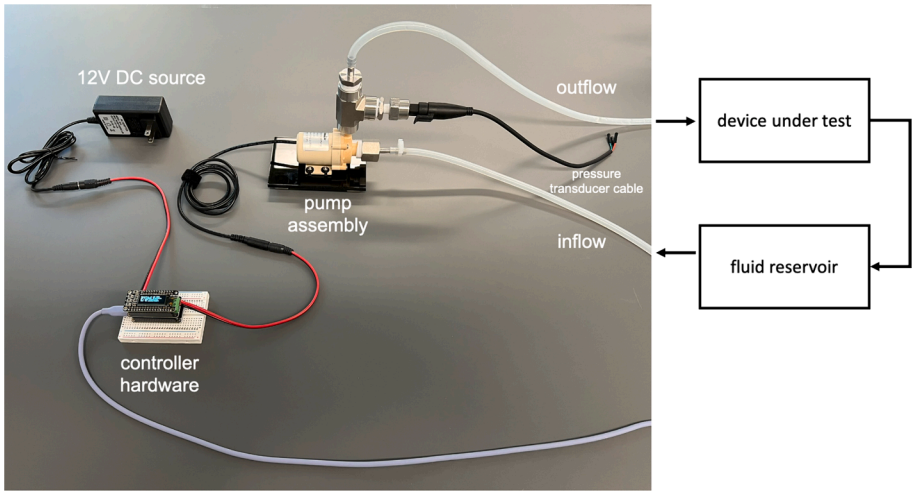


Fig. 9. Overview of control hardware, pump, and fluid circuit assembly.

silicone tubing).

Pump control: Power the microcontroller using USB (either from a host computer or through a USB charger). The finite state machine of the control program is depicted in Fig. 10. Upon powering the microcontroller, the program enters setup mode. The pulse rate is first selected by using the A button to increment, the B button to decrement, and the C button to advance to the next setting, pulse fraction selection (Fig. 11A). The default pulse rate is 60 beats per minute (BPM). Next, the desired pulse fraction (default 25 %) is selected in similar fashion (Fig. 11B), followed by the baseline flow parameter (default 5/255). Once baseline flow is selected and the C button is pressed (Fig. 11C), the program starts driving the pump in the pumping loop according to these parameters. While within the pumping loop, the pump can be paused and all three parameters reselected by either pressing the C button or the reset button (Fig. 11D). Conveniently, the pulse rate can be changed while in the pumping loop by pressing the A and B buttons, which increases or decreases the pulse rate, respectively, in units of 10 BPM.

Pump monitoring: In addition to general state of pump as displayed on the OLED, pump status can be monitored through analog output of the pulse waveform on pin A1, pulse start through digital pin 13, or USB-to-serial output to terminal (pins labeled on PCB in Fig. 1B). These analog and digital outputs offer multiple convenient ways of syncing to external sensors or data capture platforms.

Programming a custom waveform: The pulse wave data is stored in the Arduino program as a 100 element vector named flowVector. The main loop of the program steps through each element of the flowVector at a delay time defined by the selected pulse rate. Because this will shorten the overall pulse duration as BPM is increased (and delay time decreases) we have an option to increase the pulse fraction to make the absolute pulse duration longer. Data for the pulse waveform must be fit within a 100 element vector of 0–255 dynamic range. Example waveforms were obtained from a published dataset [12] and resampled from a 1013 element vector into the 100 element flowVector. Flow reversal in the waveform was eliminated for simplification and the baseline amplitude was set at 5/255 rather than 0 to maintain some minimal baseline flow.

Maintenance: If salt buffers (i.e. saline) or other chemicals are used with the pump, flush the system with water to remove salts or other chemicals that can precipitate and seize the pump. If precipitation of buffer salts does occur, it can be solved by flushing with water.

7. Validation and characterization

Flow rates produced by the pump were validated using Doppler ultrasound (Telemed Artus, Telemed, Lithuania) by the following method. The pump was set to pulse using an arterial waveform at 60 beats per minute (bpm) and 25 % pulse fraction with the pump outlet connected to a 3/16″ inner diameter silicone tube. The pulse rate and pulse fraction were then changed to the parameters shown in Table 2, and Doppler ultrasound was performed (representative image in Fig. 12). The peak systolic velocities were subsequently measured from saved images.

In separate experiments, flow rates were confirmed by weighing the fluid moved by the pump. The outflow tubing was placed into a beaker on a load cell balance with a 10 Hz sampling rate (ALAMSCN 1 kg Load Cell, Amazon, Seattle, WA). The average flow rate was measured across 10 pulse cycles at varying pulse rates and pulse fractions. Pulse volume was calculated by dividing this value by the number of pulses.

The output capabilities of the pump were assessed at varying pulse fractions (25, 50, 75, and 100 %) and pulse rates (60, 80, 100, and 120 bpm). These data show the pumping system can achieve stroke volumes of 2.6 to 15.8 ml (Table 2, which would would be inclusive of the cardiac output of a rabbit [13]. When coupled with an appropriately-sized phantom, flow rates physiologically-relevant to human lower extremity arterial vasculature can be generated (Table 2). When flow was directed through a 3/16″ silicone tube, flow rates of 4.8 to 17 ml/second were observed. These flow rates are higher than normal human lower extremity arterial vasculature [14], but these physiologic flow rates could easily be achieved by decreasing the waveform peak amplitude. Peak systolic velocities in the center of the tube by pulse-wave Doppler ultrasound were also measured (Table 2), and were within the range previously reported for human lower extremity vasculature [15].

Fig. 12 shows an example pulse-wave Doppler of water containing 0.05 % cellulose scatterers flowing in the center of a 3/16″ silicone tube on the outlet of the pump set at 60 bpm and a 25 % pulse fraction. Relative to the flow in a large-caliber human artery, this waveform exhibits mild spectral broadening, which may reflect turbulence in the outflow path from the complex geometry of the T-fitting.

Capabilities of the described hardware include:

- Pulsatile flow system which produces pulsatile flow with an arterial pulse waveform, and allows customization of flow pump parameters including the pulse rate, pulse fraction, and baseline flow.
- Programmable with the ability to specify custom waveforms
- On-the-fly changeable pulse rate, pulse fraction, and baseline flow rates
- Pulsatile flow rates up to 17 ml/second
- Inexpensive construction with off-the-shelf, readily available components, and open-source electronics and software

Limitations of the current hardware include:

- This pumping system is not designed for or tested in the high magnetic field environment of a magnetic resonance imaging (MRI) suite, where pulsatile pumps for cardiovascular flow studies are often desired. However, this system could with further testing be assessed for use in the lower magnetic field zones of an MRI suite.

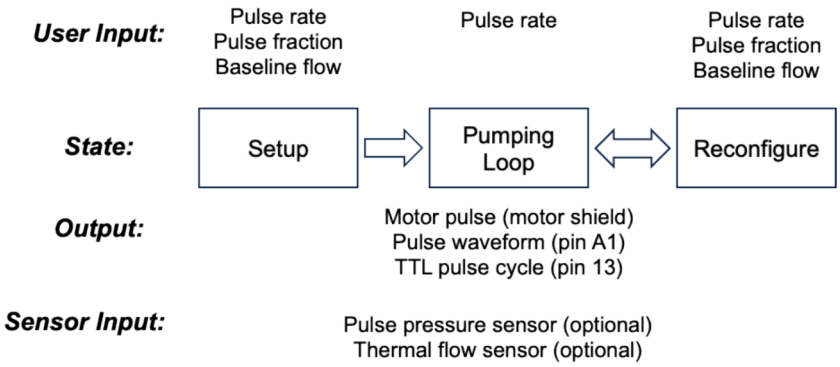


Fig. 10. Finite state machine of control program.

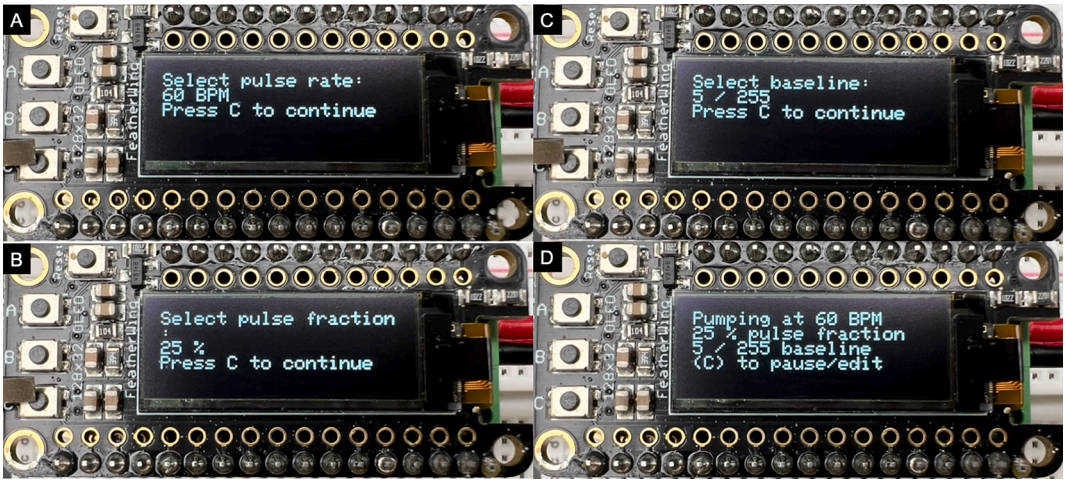


Fig. 11. Control interface of the pump, with selection/interface buttons on the left of the PCB. (A) Pulse rate selection in beats per minute (BPM). (B) Pulse fraction selection. (C) Baseline flow selection. (D) Pumping loop status.

Table 2
Flow rates, pulse volumes, and peak systolic velocities achieved in a 3/16″ silicone tube by varying pulse fraction and pulse rate.

Pulse Rate (bpm)	Pulse Fraction (%)	Flow Rate (ml/s)	Pulse Volume (ml)	Peak Systolic Velocity (cm/s)
60	25	4.8	4.8	58.9
80	25	4.9	3.6	47.4
100	25	5.3	3.2	44.3
120	25	5.2	2.6	42.7
60	50	6.0	6.0	67.2
80	50	6.6	5.0	61.5
100	50	6.7	4.0	51.6
120	50	6.9	3.5	47.4
60	75	8.9	8.9	82.3
80	75	8.9	6.7	77.6
100	75	9.3	5.6	75
120	75	9.9	5.0	71.4
60	100	15.8	15.8	90.6
80	100	16.4	12.3	82.8
100	100	17.0	10.2	82.3
120	100	15.7	7.9	77.1

- In the current study, we did not evaluate the pumping system for use with liquids of different viscosities, which are often used in flow studies to mimic biological materials such as blood.
- We did not specifically assess the wear and tear of the pump caused by running it in pulsatile fashion, but we have been using the same pump for several years without notable degradation in performance.

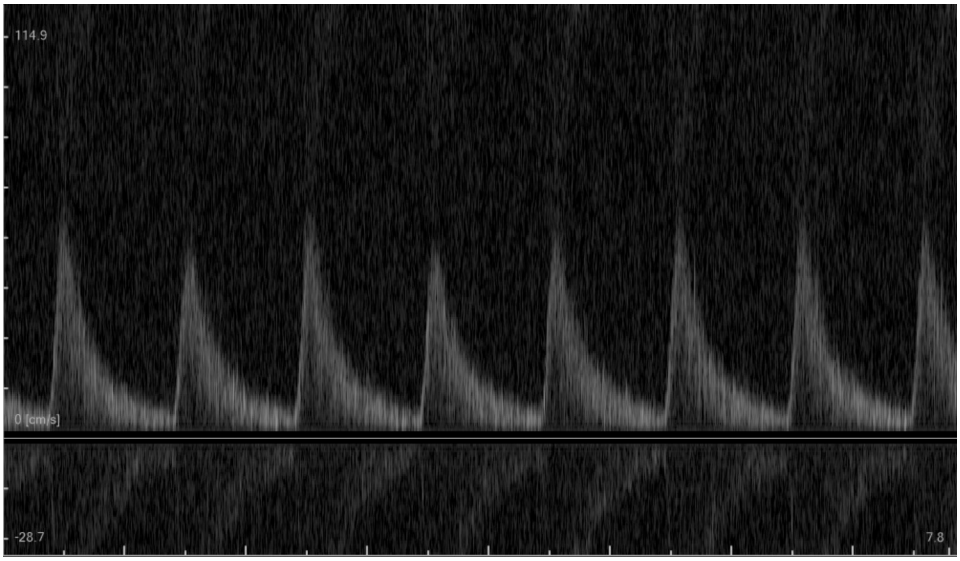


Fig. 12. Pulse-wave Doppler ultrasound showing the spectral features of pulsatile fluid flow in straight outflow tubing. Centimeters per second are depicted on the y-axis, and time in seconds is depicted on the x-axis.

Future directions include exploring the limits of complex hemodynamics this pump can replicate (e.g., mimicking hepatic vein or other venous flows), assessing the suitability of this technology for use in an MRI environment, making pulse cycles triggerable via an input on the microcontroller, and potentially exploiting the wireless capabilities of the selected microcontroller to stream data using Bluetooth or WiFi.

8. Ethics statements

Not applicable. No human or animal experiments were involved with the current work.

CRediT authorship contribution statement

Sanna E. Herwald: . **Daniel Y. Sze:** . **Daniel B. Ennis:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Alexander M. Vezeridis:** Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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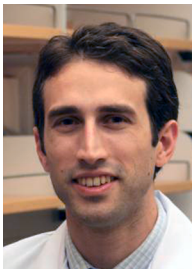
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