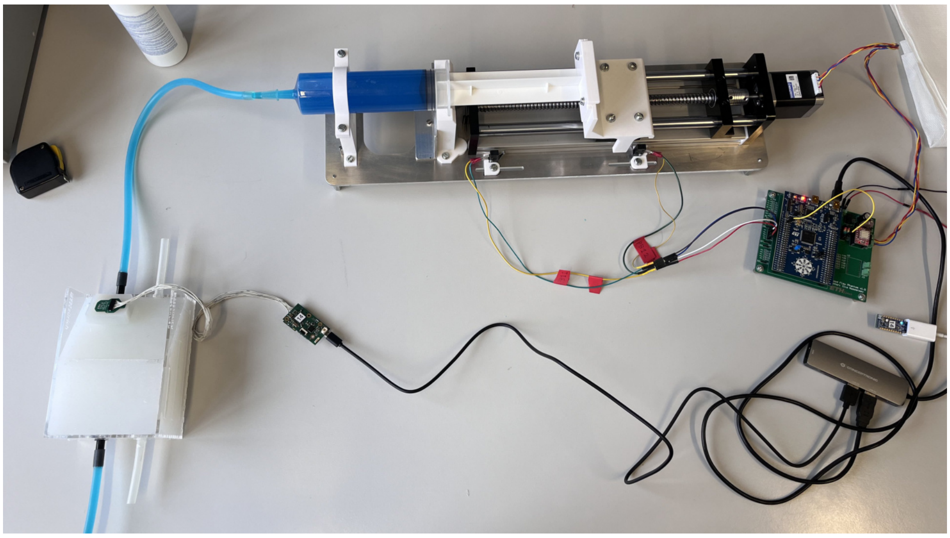
Integrated Systems Laboratory,
Department of Information Technology and Electrical Engineering

DOPFLOW User Manual



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Chapter 1

System Overview

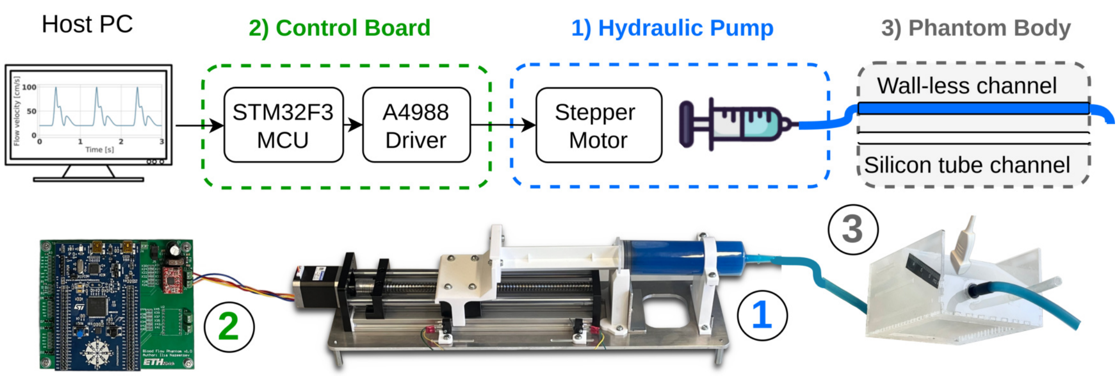


Figure 1.1: The DOPFLOW system diagram.

1.1 Introduction

This user manual provides the description of the design files and instructions required to replicate the DOPFLOW system, which was presented at the IEEE UFFC Joint Symposium 2024 [1].

DOPFLOW is an advanced Doppler Flow Phantom system designed to simulate the common carotid artery and surrounding tissue. The system enables users to define pulsatile flow patterns and achieve flow speeds exceeding 1 meter per second and has been validated with a commercial Doppler ultrasound machine (SONIXRP). With its affordability (under $400) and open-source design (see GitHub repository [2]), DOPFLOW presents a valuable research tool for advancing Doppler ultrasound technologies.

As shown in Fig. 1.1, the platform features a modular design, consisting of the following components:

1. A custom syringe-based hydraulic pump,
2. A control printed circuit board (PCB),
3. A phantom body with both walled and wall-less channels,
4. A graphical user interface (GUI).

This User Manual provides detailed instructions on how to use the system (see Chapter 3) and how to replicate it (see Chapter 2), including the manufacturing and mechanical assembly of the hydraulic pump, assembly of the control board and firmware flashing, and fabrication of the phantom body. The manual can serve as a starting point for modifying the DOPFLOW system and adapting it to specific research needs, as the system features a modular design and allows for local modification of individual components.

1.2 Specifications

The main technical specifications of the DOPFLOW system are available in the Table below.

Table 1.1: Specifications of the DOPFLOW system

Feature	Details
	Hydraulic Pump
Pump Type	Syringe-based flow pump
Supported Flow Patterns	Continuous, pulsatile, custom
Syringe Volume	**150 ml**
Motor Type	NEMA **17** stepper motor, **1.8°** per step, torque **0.1-0.8 N·m**, **2** phases, **1A** per phase, **24V** max
	Control Board
Type	Custom PCB for motor and limit switch control
Power	**12 V**, **2 A** from a lab power supply
Motor Driver	**A4988**, Max **1 A** cont. current per phase, **8-35 V**
Number of Drivers	**2**×A4988
Interfaces	USB (connection to the host PC), SPI, UART, I2C, 6xGPIOs, 2x inputs for mechanical end stops
	Phantom Body
Simulated Structure	Mimics the common carotid artery with walled and wall-less channels (**6 mm** diameter)
Tissue-mimicking material (TMM)	Ecoflex-30, acoustic velocity of **1015 m/s**, attenuation of **34.4 dB/cm** at **10 MHz**
Blood-mimicking fluid (BMF)	GP50140, acoustic velocity of **1800 m/s**, viscosity of **12 mPa·s**, density **1.15 g/cm^3**
	System Specifications
Maximum Flow Speed	Over **1 m/s** [1]
Total Cost	Under **$400**
License	Open source, all design files are publicly available [2]

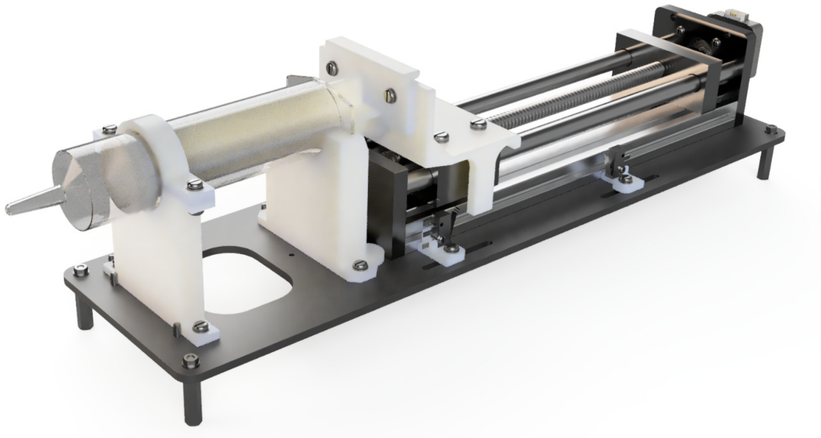


Figure 1.2: Design of the hydraulic pump. Render made in Fusion 360.

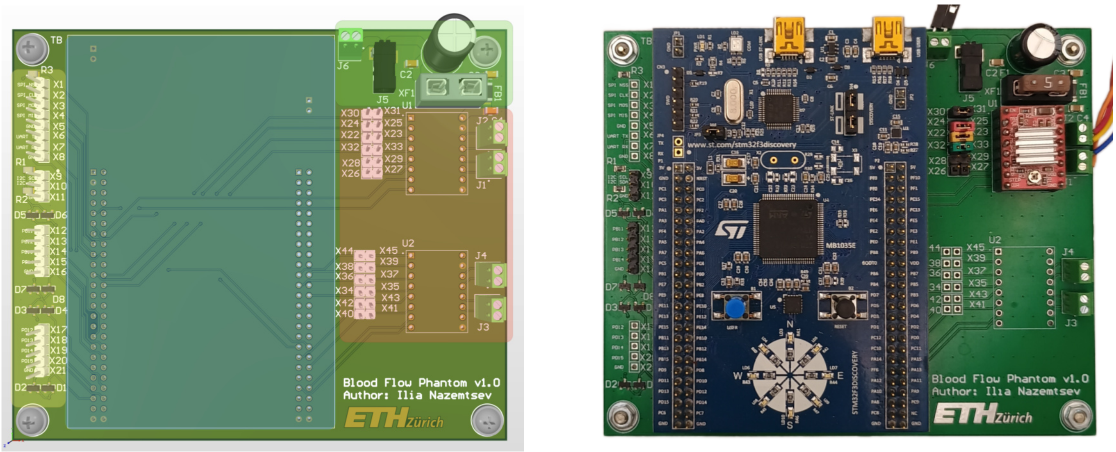
1.3 System Components

1.3.1 Hydraulic Pump

The custom pumping system is shown in Fig. 1.2. It uses a 150 ml syringe driven by a stepper motor SF2424-10B41 [3] mounted on an aluminum base plate. A screw-based transmission converts the motor's rotary motion into linear movement, pushing the content of the syringe (blood-mimicking fluid) through a silicone tube into the phantom body. A critical design choice is the use of a pre-assembled linear CNC guide SFU1204 [4] with an integrated ball screw. This single unit simplifies the mechanical alignment of the moving parts, reduces friction and wear, decreases vibrations and noise, and allows for a 200 mm effective stroke. Assembly instructions for the hydraulic pump are provided in section 2.1.

1.3.2 Control Board

The stepper motor is powered and controlled by a custom Control Board PCB (see Fig. 1.3) featuring an STM32F3 Discovery board [5] with the STM32F303 microcontroller and A4988 motor driver [6], with connection points for mechanical end-stop switches. The firmware enables USB communication with a Python-based GUI, allowing for speed control through a non-blocking timer in output-compare mode, updating motor speed every 20 ms. To ensure smooth operation, the MCU firmware checks and gradually increases speed if acceleration exceeds safe limits. The maximum speed step $\Delta\omega_{\max}$ is set to be 180 RPM, beyond which the motor may stall. Additionally, micro-stepping is activated when step intervals exceed 1.4 ms, improving movement smoothness at lower speeds.



(a) Render of the Control Board PCB.

(b) Photo of the Control Board.

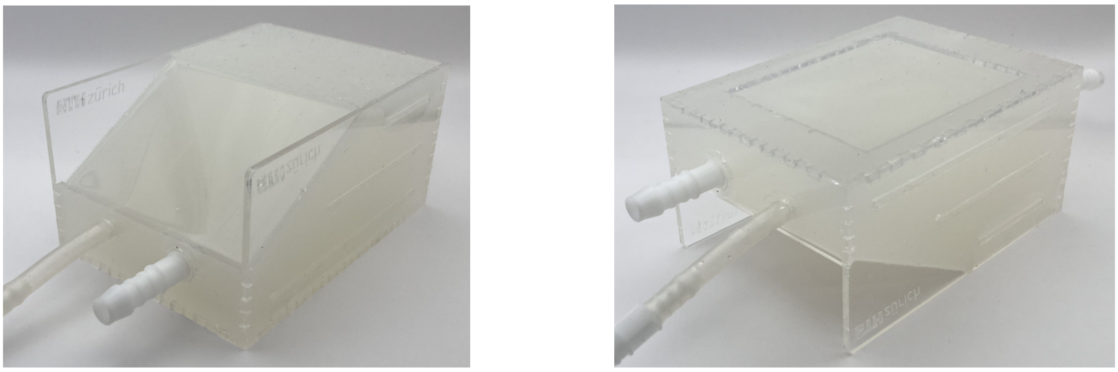
Figure 1.3: The component layout (a) and the photo (b) of the designed Control Board PCB: yellow: peripherals and additional pins, blue: board placement region, orange: driver placement region, green: power supply region.

The PCB exposes peripheral interfaces of the STM32F303, such as UART, I2C, and SPI (Fig. 1.3, a, yellow zone), which enable integration with external sensors (such as pressure sensors) that may be incorporated into the system in the future. Also, it includes eight additional GPIOs, while Schottky diodes protect all exposed pins against electrostatic discharge. The PCB's power supply offers a barrel jack and a terminal block for a 12V, 2A lab supply, with capacitors and a 5A fuse to protect against high currents (Fig. 1.3, a, green zone). Two motor drivers are mounted on the right side with 2 terminal blocks per driver for the motor wire connection (Fig. 1.3, a, orange zone).

Instructions for fabricating and assembling the Control Board can be found in Sect. 2.2.

1.3.3 Phantom Body

The hydraulic pump is connected via a silicone tube to the phantom body (Fig. 1.4), simulating a common carotid artery with two channels (wall-less and silicone, both 6 mm in diameter). The phantom is made from Ecoflex-30 silicone rubber, with an acoustic velocity of 1015 m/s and attenuation of 34.4 dB/cm at 10 MHz. The phantom includes an acrylic housing with rectangular holes to secure the Ecoflex block and two surfaces: 0° (flat) and 30° inclined for Doppler measurements, as shown in Fig. 1.4. Additionally, it features a scale to measure the distance from the surface to the channel center. To prevent blood-mimicking fluid leakage, the tube connector is inserted directly into the channel. The channels get connected to the syringe of the hydraulic pump (see above),



(a) 30° Inclined surface.

(b) Flat surface.

Figure 1.4: Artery-mimicking phantom with two imaging surfaces: 30° inclined (a) and flat (b).

which injects a GP50140 [7] blood-mimicking fluid (BMF), with an acoustic velocity of 1800 m/s and viscosity of 12 mPa·s, containing glass beads as scatterers.

Fabrication instructions for the phantom body are provided in section 2.3.

1.3.4 Graphical User Interface

The graphical user interface (GUI) connects to the STM32 MCU via USB, providing intuitive control over the motor through a Python-based interface built with the Tkinter library. Users can operate the system in two modes: manual control, where motor speed is adjusted via a slider, and automated pulse generation, which simulates blood flow patterns. The GUI also allows for custom pulse patterns to be loaded from a **.npz** file for tailored testing and experimentation, offering flexibility in configuring velocity profiles for the pump.

Section 3.2 includes instructions for installing the necessary software packages required to run the GUI, while Section 3.4 presents a detailed, step-by-step tutorial for navigating the GUI.

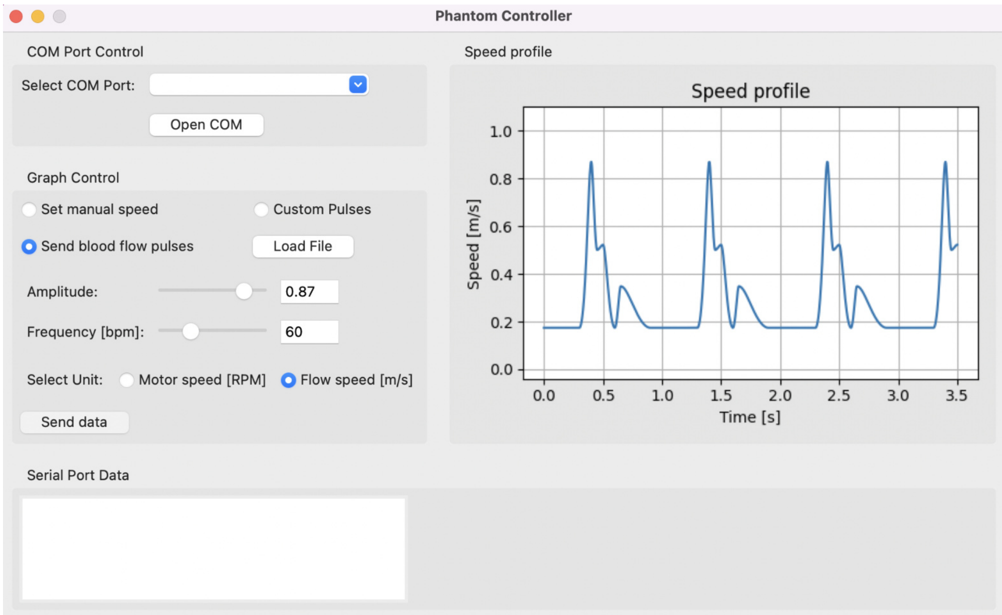


Figure 1.5: DOPFLOW graphical user interface (GUI) to set the speed profile.

Chapter 2

How to build your own DOPFLOW phantom?

2.1 Hydraulic Pump Assembly Instructions

This section provides detailed, step-by-step instructions for assembling the syringe-based hydraulic pump. Before beginning the assembly, ensure that you have collected all the necessary materials listed in Tab. 2.2 and the tools outlined in Tab. 2.1. To find the suppliers of the key components, please explore the corresponding bill of materials (BOM) in the main repository [2]. For further assistance during the assembly, you can also refer to the visual guide in the assembly video: Hydraulic Pump Assembly Video.

Table 2.1: List of tools needed for the hydraulic pump assembly.

#	**Tool**	**Amount**	**Description**
1	3D Printer (PLA filament)	1 unit	For printing parts such as plunger pusher, puller, syringe holders
2	Screwdrivers	Various sizes	Flat head for M2, M3, M4, M5, and M6 screws
3	Allen keys	Various sizes	For tightening hex screws
4	Wrenches	Various sizes	For tightening nuts and bolts
5	Mallet	1 unit	For mounting the Dowel pins.
6	CNC Machine	1 unit	For machining the aluminum ground plate

Table 2.2: List of components needed for the hydraulic pump assembly.

#	Material	Amount	Description
1	Aluminum plate (5 mm thickness)	1 sheet (500x135 mm)	For building the ground plate where all components are mounted
2	Dowel pins (ISO 2338 ∅4 h6)	7x	For ensuring precise alignment of components on the ground plate
3	CNC rail SFU1204, 200 mm stroke	1 unit	The main component for linear motion of the plunger
4	Stepper motor (SF2424-10B41)	1 unit	Motor for driving the syringe plunger's
5	Motor coupling (6 mm, 8 mm)	1x	For coupling the stepper motor to the CNC rail
6	Syringe (150 ml)	1x	For pumping the fluid into the hydraulic line
7	Silicone tube (6 mm outer diameter)	2 m	For connecting the syringe to the phantom body
8	Plunger pusher (3D-printed)	1x	Connects the syringe plunger to the CNC rail
9	Plunger puller (3D-printed)	1x	Holds the plunger on the opposite side of the pusher
10	Syringe holder (3D-printed)	1x	Holds the syringe securely on the base plate
11	Barrel holder (3D-printed)	1x	Maintains the vertical position of the syringe barrel
12	Spacer (3D-printed, optional)	1x	Inserted if the motor shaft extends into the ball screw
13	Limit switch holder (3D-printed)	2x (1 mirrored)	Holds limit switches and adjusts their position
14	Screws (M6 x 15 mm)	4x	For securing the CNC rail to the ground plate
15	Screws (M5 x 15 mm)	4x	For securing the plunger pusher to the CNC rail
16	Screws (M3 x 12 mm)	4x	For mounting the stepper motor to the CNC rail
17	Screws (M2 x 15 mm)	2x	For securing the limit switches
18	Screws (M4 x 15 mm)	10x	For assembling the remaining components to the ground plate
19	Steel Hex Spacer (M4 x 12 mm)	4x	Support legs for the ground plate
20	Limit switches	2x	For limiting the plunger motion
21	Transparent tape	1 roll	For sealing open holes and ensuring mold alignment

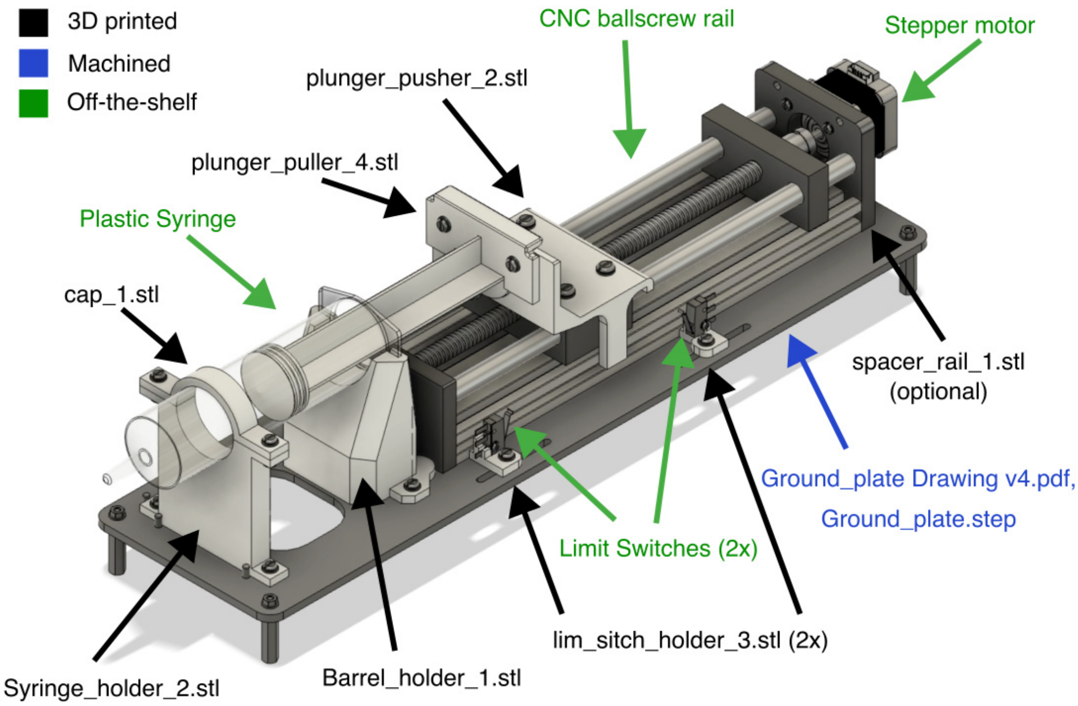


Figure 2.1: Hydraulic Pump Parts.

> **Note:** All the screws listed in Tab. 2.2 are stainless steel DIN EN ISO 1580 Slotted pan head screws.

When following the assembly instructions, use Fig. 2.1 as a visual reference. It maps the hydraulic pump components to their corresponding CAD design files, which can be found in the folder `./hydraulic_pump/` of the DOPFLOW GitHub repository.

I. Assemble the Ground Plate

a. **Prepare the aluminum plate**: Use the step file (`Ground_plate.step`) to machine the 5 mm thick aluminum plate (500 mm x 135 mm) the holes using the CNC machine. Refer to the technical drawings (`Ground_plate Drawing v4.pdf`) for tolerances and threads.

b. **Insert positioning pins**: Insert dowel pins (ISO 2338 ⌀4 h6 x 10 mm) in the bored holes using a mallet to ensure precise alignment of components on the plate.

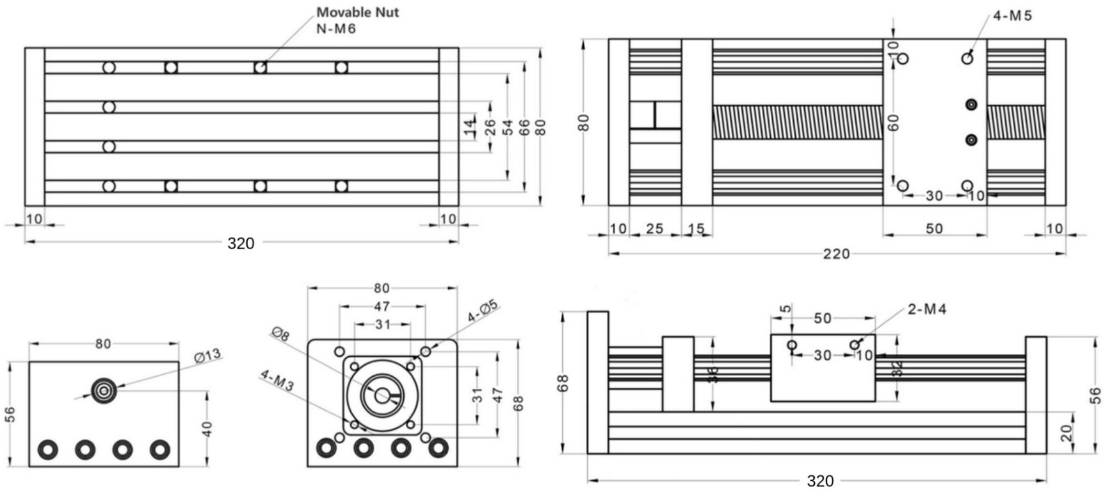


Figure 2.2: CNC rail technical drawings adapted from [4].

c. **Install supporting legs**: Screw in four hex spacers (M4 x 12 mm) to elevate and support the ground plate.

II. Install the CNC Rail

a. **Install CNC rail**: Attach the CNC rail to the ground plate using M6 x 15 mm screws and washers.

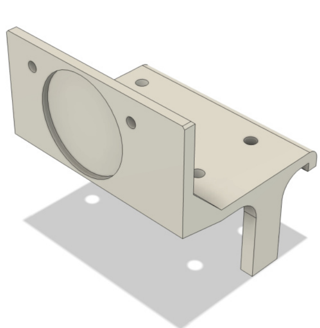
> **Note:** Ensure the three Dowel pins are in contact with the CNC rail to align it on the Ground Plate.

> **Note:** Technical drawings of the CNC rail are shown in Fig. 2.2. .

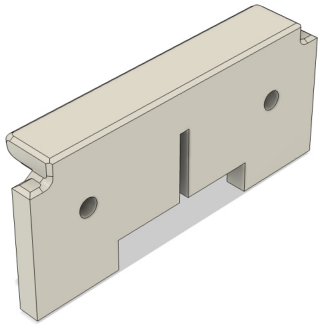
III. Attach the 3D-Printed Parts

a. **Print syringe holders**: 3D print the following parts shown in Fig. 2.3:

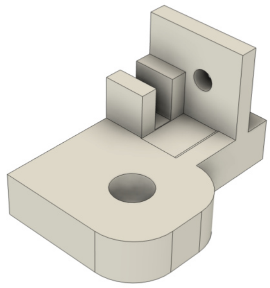
- Barrel flange holder (file `Barrel_holder_1.stl`)
- Syringe holder (file `Syringe_holder_2.stl`)
- Cap for the syringe holder (file `cap_1.stl`)



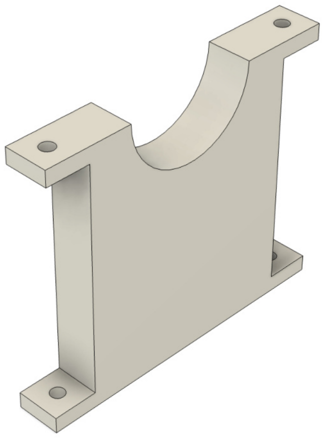
(a) Plunger pusher.



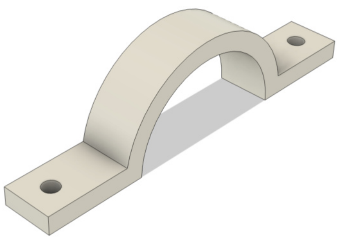
(b) Plunger puller.



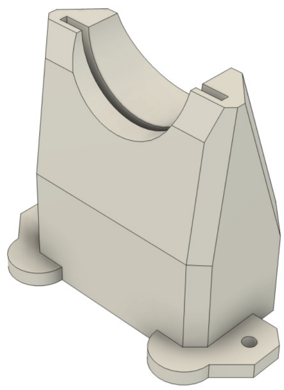
(c) Limit switch holder.



(d) Syringe holder.



(e) Cap for the syringe holder.



(f) Barrel flange holder.

Figure 2.3: 3D printed parts modeled in Fusion360 and printed with PLA, 20% infill. The models are available on the project GitHub page.

> **Note:** Use the PLA filament and 20% infill during the 3D printing.

b. **Install syringe holders and syringe:** Secure the syringe holders to the base plate and then install the syringe, ensuring the stability of the syringe barrel.

> **Note:** Use M4 x 15 mm screw, M4 hex nut, and M4 washer to secure these parts.

c. **Print and install plunger pusher and puller**: 3D print the following parts shown in Fig. 2.3:

- Plunger pusher (file `plunger_pusher_2.stl`)
- Plunger puller (file `plunger_puller_4.stl`)

After printing, connect the plunger pusher to the CNC rail. Then, install the plunger puller. These components connect the syringe plunger to the ball screw mechanism, allowing precise motion along the stroke.

> **Note:** Use M5 x 15 mm screws to install the plunger pusher and M4 x 15 mm screws for the plunger puller.

d. **Print and install limit switch holders**: 3D print the models (Fig. 2.3, c):

- Limit switch holder 1 (file `lim_sitch_holder_3.stl`)
- Limit switch holder 2 (file `lim_sitch_holder_3.stl`, mirrored)

After printing, mount the holders on the oblong holes on the side of the ground plate. These parts hold the limit switches and allow for stroke adjustment.

e. **Print spacer (optional)**: If needed, print `spacer_rail1.stl` to place between the motor side end plate and the aluminum extrusion if the motor shaft extends into the ball screw mechanism.

IV. Install the Stepper Motor and Coupling

a. **Install the motor**: Secure the stepper motor (SF2424-10B41) to the CNC rail.

> **Note:** Use M3 x 12 mm screws and washers.

b. **Motor coupling**: Mount the motor coupling (6 mm and 8 mm diameters) to properly connect the stepper motor to the CNC rail.

V. Mount the Limit Switches

a. **Install limit switches**: Secure the switches to their holders installed earlier.

> **Note:** Use M2 x 15 mm screws, hex nuts, and washers.

b. **Calibrate the limit switches**: Adjust the limit switch holders along the oblong holes of the ground plate. Manually move the ball screw until the syringe is almost empty, then adjust the switch holder so the switch is triggered by the pusher tail. Repeat for the full syringe position.

This process results in a fully assembled syringe-based hydraulic pump, capable of controlled linear motion for fluid displacement. For further visual reference, consult the assembly video at: Hydraulic Pump Assembly Video.

2.2 Control Board PCB Assembly

This section contains PCB Manufacturing and Assembly Instruction for the Control Board PCB. The hardware files, including Altium Nexus CAD projects, .pdf schematics, and .xlsx BOMs, can be found in the `control_board/hw/altium_project` directory of the DOPFLOW project repository.

2.2.1 Manufacturing Options

There are two primary approaches for assembling the PCB:

1. **Self-Assembly**: Order the PCBs, components and manually mount the components.
2. **Full-Service Manufacturing**: The manufacturer handles both PCB production and assembly of the components.

Self-Assembly

For self-assembly, you'll need to provide the following files to your PCB manufacturer:

- **Gerber Files**: These files describe the layout of the PCB, including copper layers, solder mask, and silkscreen. You can find them in `control_board/hw/altium_project/docs/fabrication_files/Gerbers`.
- **NC Drill Files**: These files define the locations and sizes of the holes to be drilled in the PCB, including vias and mounting holes. Located in `.../altium_project/docs/fabrication_files/NC Drill`.
- **PCB Stackup**: Defines the arrangement of copper layers and insulating materials in the PCB. Found in `.../altium_project/docs/fabrication_files/control_board_stackup.xls`.

Required Equipment and Skills

Self-assembly requires basic experience with soldering and minimal equipment such as soldering iron, solder wick, flux, and tweezers.

Full-Service Manufacturing

For full-service manufacturing, in addition to the files mentioned for self-assembly, you will also need to provide:

- **Pick-and-Place Files**: Although not provided, these files can be generated from the Altium project and are used by automated machines to accurately place components on the PCB.
- **Assembly Drawing**: This is a visual guide showing how components should be placed and oriented on the PCB. Found in `.../altium_project/docs/control_board.pdf`.
- **Bill of Materials (BOM)**: This detailed list includes all required components, their designators, and quantities. The BOM is located in `.../altium_project/docs/control_board_bom.xlsx`.

Final Considerations

We generally recommend **Self-Assembly**, as the PCB's design is simple, requiring minimal soldering skills and basic tools. However, for those who prefer to delegate the entire process, from fabrication to component assembly, **Full-Service Manufacturing** is a convenient alternative.

2.2.2 Flashing Firmware

After assembling the PCB, follow the steps below to flash the firmware to the control board PCB.

I. Install STM32CubeIDE

a. **Download and install**: Download version 1.12.1 of STM32CubeIDE from the ST website. Install the software on your system.

> **Note:** Ensure that version **1.12.1** of STM32CubeIDE is installed, as newer versions are currently not supported.

II. Create a New Project

a. **Create Project**: In STM32CubeIDE, go to
`File > New > STM32 Project from an Existing STM32CubeMX Configuration File (.ioc)`.

   Select the `phantom_control/phantom_control.ioc` file and press **Finish**.

b. **Overwrite Folders**: Overwrite the files in the `Core/*` and `USB_DEVICE/*` folders from this repository. Drag and drop both folders to the new project located in `C:\Users\USERNAME\STM32CubeIDE\workspace_1.12.1\phantom_control`. Select **Copy files and folders**, click **OK**, and then select **Overwrite All**.

III. Build and Flash the Project

a. **Connect the PCB**: Connect the PC to the STM32F3DISCOVERY board (plugged into the control board PCB) via USB cable.

   > **Note:** The STM32F3DISCOVERY board is equipped with two USB connectors. Make sure to use the **User USB** connector located on the side of the PCB, rather than the centrally positioned **ST-LINK USB** connector.

b. **Power Supply**: There is no need to supply power to the motor power line; only USB power is required during flashing.

c. **Build and Flash**: Build the project, then flash it to the STM32F3DISCOVERY board.

The control board is now fully prepared to be used with the DOPFLOW graphical user interface for motor control and executing custom flow profiles. For step-by-step GUI setup and usage instructions, please refer to Sections 3.2 and 3.4.

2.3 Phantom Body Fabrication Instructions

This section contains step-by-step instructions on how to fabricate the DOPFLOW phantom body. Before beginning the fabrication, ensure that you have collected all the necessary tools outlined in Tab. 2.3 and the materials listed in Tab. 2.4.To find the suppliers of the main components, please explore the corresponding bill of materials (BOM) in the main repository [2].

Table 2.3: List of tools needed for the phantom body assembly.

#	**Tool/Equipment**	**Amount**	**Description**
1	Laser cutter for acrylic and plywood sheets	1 unit	For cutting the acrylic box and supporting frame components
2	3D printer (PLA filament)	1 unit	For printing lids
3	Vacuum chamber	1 unit	To degas the EcoFlex 30 mixture
4	Measuring cup	1 unit	For accurately measuring volumes
5	Stirring spoon	1 unit	For mixing the EcoFlex 30 components
6	Mixing bowl	1 bowl ($\geq$ 1 litre)	For mixing the EcoFlex 30 components
7	Vacuum chamber (min. 15-20 mbar)	1 unit	For EcoFlex degassing

Table 2.4: List of components needed for the phantom body fabrication.

#	**Material**	**Amount**	**Description**
1	Acrylic sheet (3 mm thickness)	1 sheet (300x300 mm)	For laser cutting the acrylic box components
2	Plywood sheet (3 mm thickness)	1 sheet (300x220 mm)	For laser cutting the supporting frame
3	Acrifix glue	1 tube	To glue the acrylic box
4	Silicone tube (6 mm outer diameter)	2 m	For the walled channel
5	Steel rod (6 mm diameter)	1x	For the wall-less channel
6	Steel rod (5 mm diameter, optional)	1x	For reinforcing the silicone tube
7	Petroleum jelly	10 ml	For coating the steel rod
8	EcoFlex 30	800 ml total volume	Tissue-mimicking material
9	Transparent tape	1 roll	To seal open holes
10	3D-printed lids	2x pieces	To cover holes in the mold
11	Plastic hose connector	2x pieces	For wall-less channel

(a) Assembled Plywood Support Frame

(b) Acrylic box mounted on support frame.

Figure 2.4: Plywood Support Frame with acrylic box

I. Assemble the Acrylic Body

First, fabricate the acrylic box and supporting frame, which provides structural support for the phantom body during the fabrication process. Follow the steps below:

a. **Laser cut acrylic box**: Use the technical drawings (file `AcrilicBoxV4.svg`) to laser cut the parts of the acrylic box for the phantom body from a 3 mm acrylic sheet.

b. **Assemble the box**: Glue the laser-cut acrylic pieces together using Acrifix glue [8], ensuring all edges are securely joined.

c. **Laser cut support frame**: Use the file `support_consturction_blocks.svg` to laser cut support blocks from 3mm thick plywood.

d. **Attach support frame**: Assemble and securely attach the support frame to the acrylic frame to provide stability during fabrication.

> **Note:** For a quicker assembly of the support frame, refer to Fig. 2.4 (a). It provides a clear visual guide.

II. Prepare the Mold

a. **Insert components**: Insert a 6 mm silicone tube and a steel rod (6 mm diameter) into the pre-arranged holes for the walled and wall-less channels.

> **Note:** We recommend inserting a smaller steel rod, approximately 5 mm in diameter, into the silicone tube for added structural support (see Fig. 2.5, a).

b. **Coat the steel rod**: Apply petroleum jelly to the 6-mm steel rod (wall-less channel) for easier removal after curing.

c. **Seal the mold**: Use transparent tape to seal all open holes or 3D-printed lids such as `phantom_hole_lid.stl` to cover the holes for the wall-less channel.

> **Note:** During the mold preparation, refer to Fig. 2.5 (a) for visual guidance.

III. Filling with Tissue-Mimicking Material

a. **Prepare EcoFlex 30**: the EcoFlex comes in two parts ("part A" and "part B") which need to be mixed to make a silicone mold. Mix parts A and B of the EcoFlex 30 in a 1:1 ratio, using a mixing bowl (> 1l volume)and a stirring spoon to ensure a smooth and even mixture for the best results.

b. **Degas the mixture**: Place the EcoFlex mixture under a vacuum at 15-20 mbar for approximately 60 seconds to remove air bubbles.

c. **Pour the silicone**: Carefully pour the degassed silicone into the acrylic frame, ensuring an even, smooth fill up to the boundaries of the inclined surface (Fig. 2.5, b).

d. **Allow to cure**: Let the silicone cure for 4 hours to solidify the phantom body. Don't move the phantom body during curing.

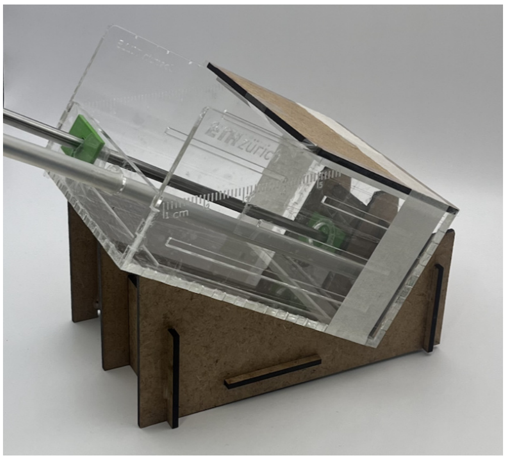
IV. Removing the Sacrificial Parts

a. **Remove the steel rod**: Once the EcoFlex has cured, carefully remove the steel rod, creating the cylindrical wall-less channel.

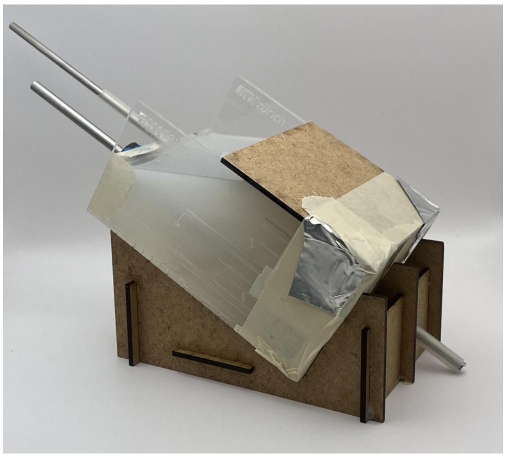
b. **Remove other sacrificial parts**: Remove the optional steel rod from the walled channel's tube and other sacrificial parts to free the channels.

c. **Insert the inlet**: Insert the plastic inlet to connect the wall-less channel to the silicone tube, ensuring a proper seal to prevent leakage.

These steps result in a phantom body depicted in Fig. 2.6.



(a) Prepared phantom body mold.



(b) Phantom body mold filled with silicon rubber.

Figure 2.5: Phantom body mold.

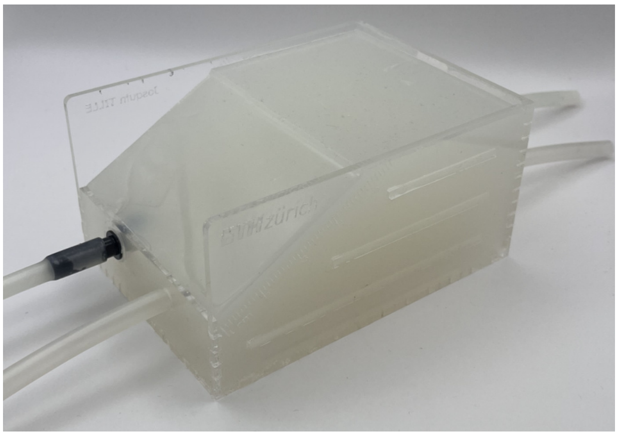


Figure 2.6: Final phantom body with wall-less and walled (silicone tube) channels.

Chapter 3

How to use the phantom?

This chapter explains the necessary steps to get started with the DOPFLOW phantom.

The first section focuses on the hardware requirements and describes the equipment you need to take the first measurements. The second section discusses necessary software installations, and the third focuses on the DOPFLOW graphical user interface (GUI).

3.1 Hardware requirements

To start functional tests with the DOPFLOW phantom, you will need the components listed below:

1. Hydraulic Pump
2. Control Board
3. Phantom Body
4. Blood Mimicking Fluid
5. USB cable
6. Windows (or Linux) computer/laptop with USB port
7. Power supply: lab supply (12 V, 2A)

Note: Please refer to Chapter 2 for the instructions on how to manufacture and assemble the Hydraulic Pump, Control Board, and Phantom Body.

3.2 Software requirements

The DOPFLOW GUI uses the following key technologies (among others):

1. **Python** 3.11.5
2. **Tkinter** Python binding to the Tk GUI toolkit.
3. **Matplolib** visualization library
4. **Pyserial** for serial communication
5. **Scipy** for data processing

The following steps guide the user through installing the graphical user interface of the DOPFLOW phantom:

1. Install the Anaconda package manager from https://docs.conda.io/en/latest/miniconda.html.
2. Find the **requirements.yml** file in the `./software/` directory of the repository.
3. Open a terminal (Windows: Anaconda Prompt) and navigate to the directory containing the **requirements.yml** file.
4. Execute the following command to create the python environment:
```
conda env create -f requirements.yml
```
5. In a new terminal, activate the environment:
```
conda activate phantom_env
```
6. Launch the GUI by running:
```
python speed_control.py
```

3.3 Preparing the DOPFLOW Phantom for Operation

3.3.1 Connecting the Hydraulic Pump to the Control Board

To control the hydraulic pump with the control board, connect the following components:

1. **Stepper motor cables** to connectors J2 and J1 on the control board. The correct color order is: red, yellow, blue, orange, starting from the pin closest to the C2 capacitor.

2. **Limit switch 1** (Contact NO) to the PB11 GPIO of the STM32 MCU via pin header X12.
3. **Limit switch 2** (Contact NO) to the PB12 GPIO of the STM32 MCU via pin header X13.
4. Connect the **Contact COM** of both limit switches to the GND of the control board (e.g., via X11 and X16).
5. Connect the **12V, 2A power supply** from the lab power supply to connector J6 (both power and ground wires).
6. Connect the **STM32 Discovery kit** to the host PC using a mini USB cable.

For visual guidance, please refer to Fig. 3.1.

3.3.2 Connecting the Hydraulic Pump to the Phantom Body

After assembling the hydraulic pump and control board, proceed to connect the hydraulic pump to the phantom body.

First, select the desired channel (either wall-less or walled), then connect one end of the silicone tube to the syringe nozzle and the other end to the phantom body. If needed, use the plastic tube connector listed in the bill of materials.

Additionally, connect the phantom's outlet to another silicone tube and submerge its end into the fluid tank.

3.4 Using the GUI and operating the phantom

3.4.1 Filling in the Syringe and Running the Basic Flow Pattern

After completing the preparations, launch the GUI by following the steps outlined in Section 3.2.

After launching the GUI, you will see the DOPFLOW graphical user interface, as shown in Fig. 3.2. Follow the steps below to run the system:

1. Ensure that the control board is powered on by the lab supply and the USB cable is connected to the PC. Use the Fig. 3.1 for visual reference.
2. Click on the **Select COM Port** dropdown menu to select the control board's COM port, then press **Open COM**. You should see a message in the *Serial Port Data* window indicating a successful connection. Refer to Fig. 3.3 for reference.

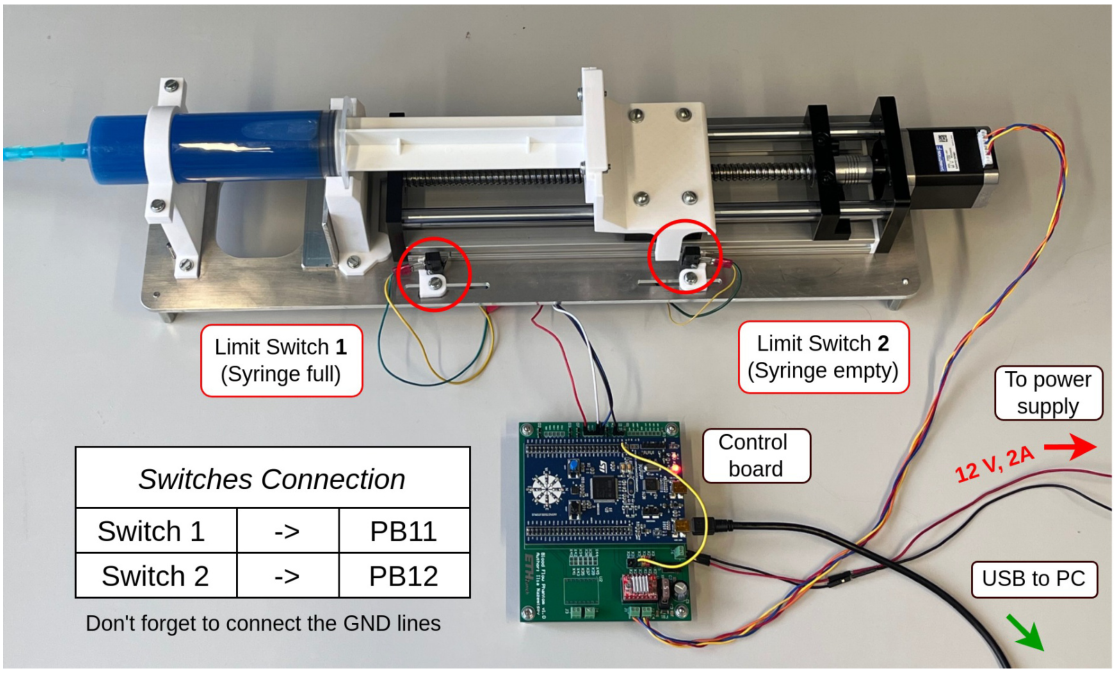


Figure 3.1: Connection of the Control Board to the Hydraulic Pump.

Note: If you selected the wrong COM port, push **Close COM** button and repeat the port selection step.

3. After successfully connecting to the Control Board, select the **Set Manual Speed** mode and input an amplitude of **0.1**, which sets a flow speed of **0.1 m/s**. If the motor does not start immediately, press the **Start** button. Refer to Fig. 3.4 for guidance.

4. Manually press **Limit Switch 1** (refer to Fig. 3.1 for switch location). The system will enter the *Refill* state, and you will see *Refill in progress* in the *Serial Port Data* window (Fig. 3.5). The motor will move the syringe plunger backward, drawing the blood-mimicking fluid into the syringe.

   Note: Once the plunger hits **Limit Switch 2**, the system will exit the *Refill* state, displaying *Refill done!*. The motor will reverse direction and begin executing the user-programmed pattern.

5. Allow the hydraulic pump to perform a few refill-emptying cycles to remove bubbles and completely fill the syringe volume with the blood-mimicking fluid.

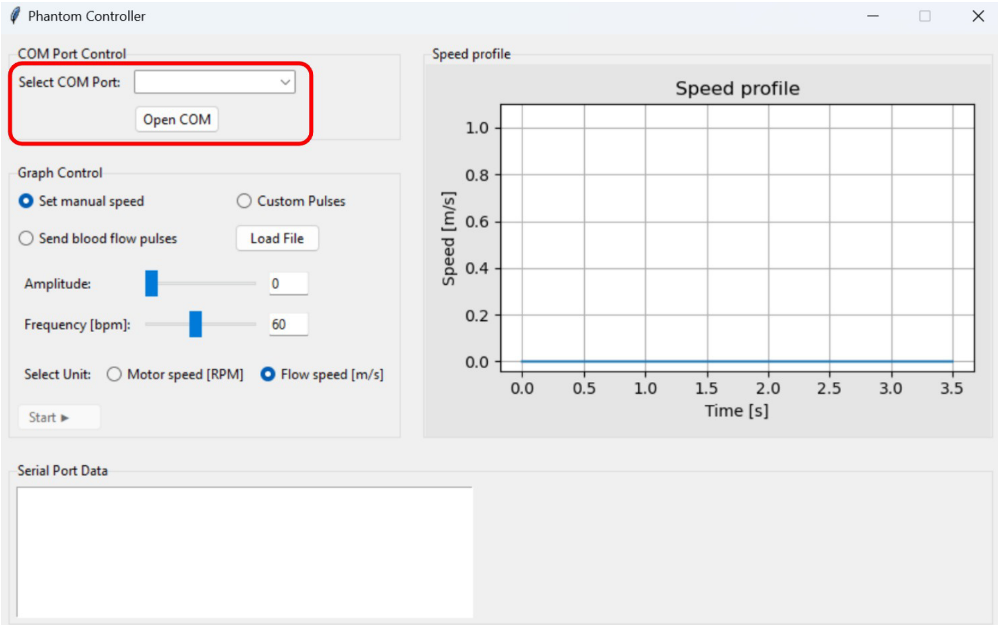


Figure 3.2: GUI COM port connection. Select the port and click *Open COM*.

Note: If needed, press the **Stop** button in the GUI to stop the pulse execution.

After all these steps, the DOPFLOW phantom is finally ready for operation.

3.4.2 Phantom calibration

In the GUI (Fig. 3.4, 3.6 and 3.7), the graph displays the flow rate through the phantom channels in meters per second (m/s). This estimate assumes a fixed channel diameter, the lead screw pitch, incompressible fluid, and rigid hydraulic lines to calculate the average flow rate. The user can also change the units to RPM (motor speed).

In reality, the hydraulic lines interconnecting the pump with the phantom are not rigid and are affected by the Windkessel effect. Calibration of the phantom, including compensation for the Windkessel effect, is not covered in this manual, as an A-mode ultrasound measurement system is required to acquire the impulse response. For detailed calibration instructions, please refer to the original paper [1] (Sect. II B).

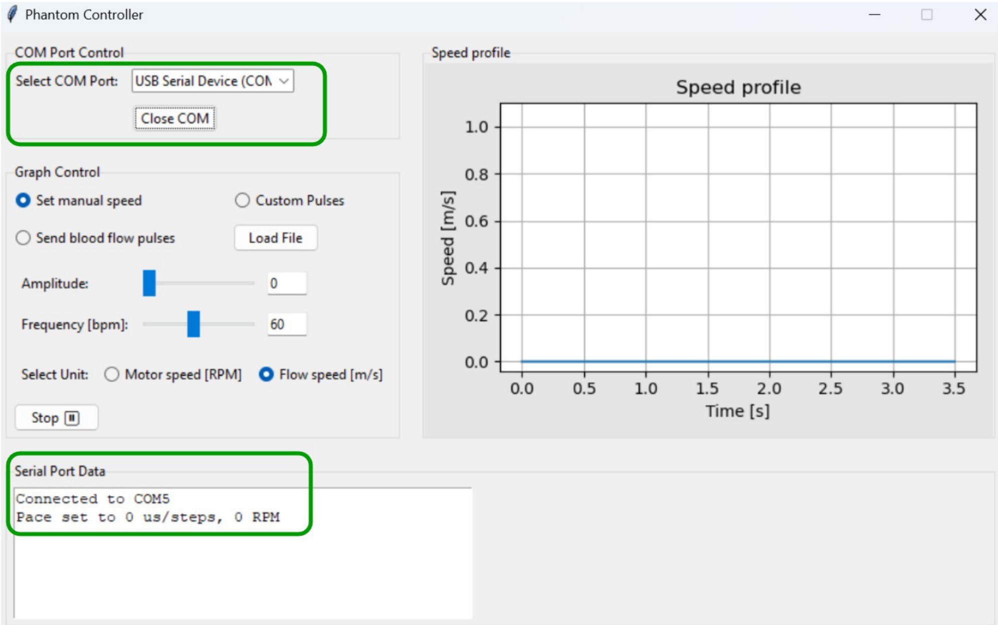


Figure 3.3: GUI Serial Port Data window shows messages from the control board and confirms a successful connection.

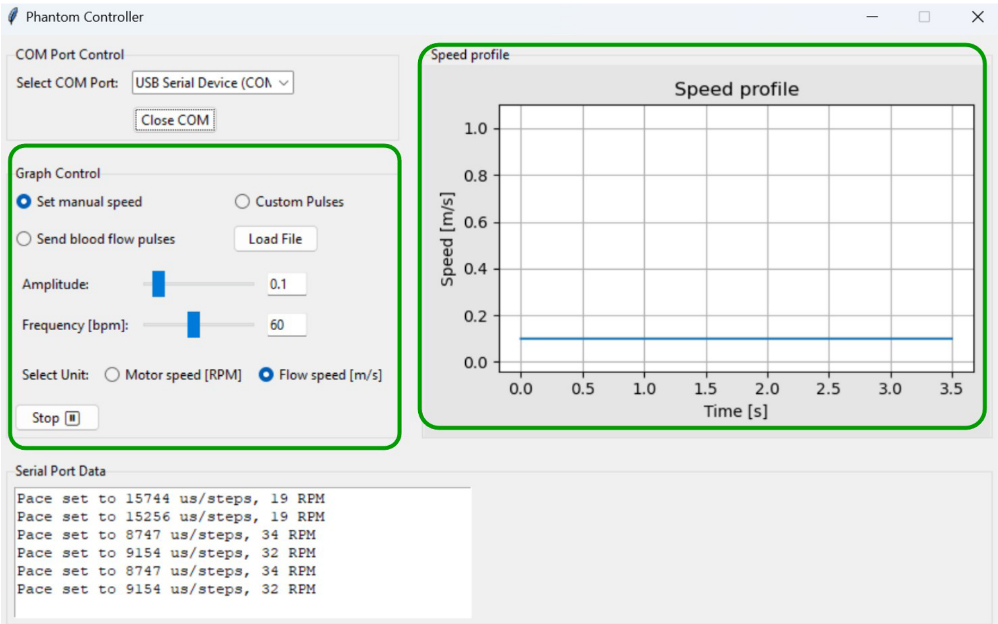


Figure 3.4: GUI Graph Control window for setting up manual constant speed. Adjust the amplitude, and the speed profile will update.

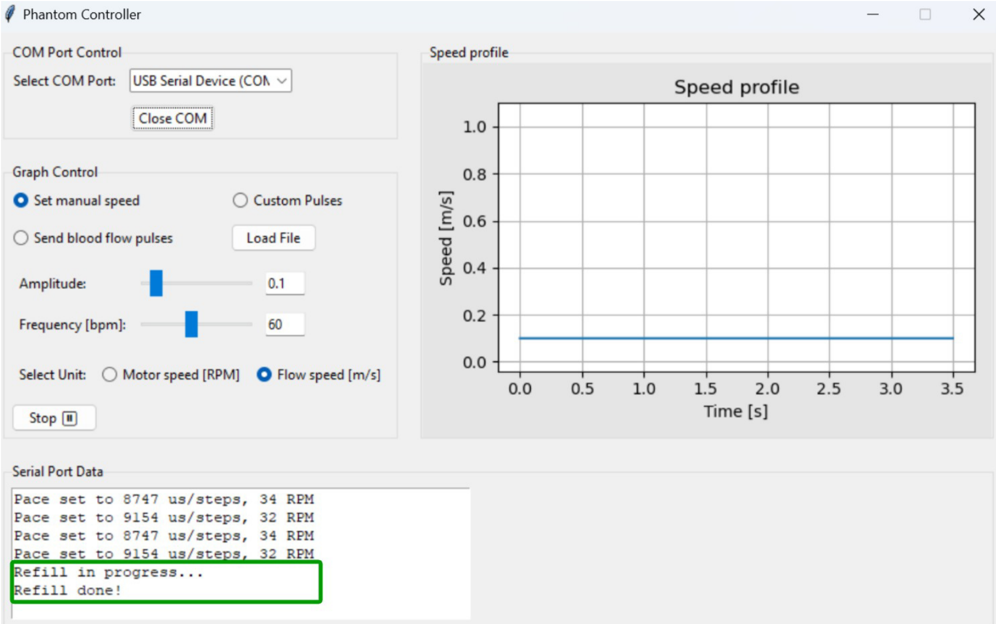


Figure 3.5: GUI showing the state when syringe refill is completed.

3.4.3 Advanced Flow Patterns

To simulate blood flow pulses in the carotid artery, you can use preprogrammed pattern. Select **Send Blood Flow Pulses** in the *Graph Control* window, as shown in Fig. 3.6. Adjust the maximum amplitude and pulse frequency as needed.

Additionally, users can load custom pulse patterns by selecting **Custom Pulses**, clicking on **Load File**, and choosing the desired pattern file. An example of a sawtooth pattern is shown in Fig. 3.7 from the file
`/dopflow/blob/main/software/custom_pulses/saw_tooth1.npz`.

To prepare a custom pulse pattern in Python, first create a NumPy array for time points ranging from 0 to 1 second (50 values total), which corresponds to a sampling frequency of 50 Hz. Then, generate another array for amplitude values representing relative flow velocity. Fig. 3.8 illustrates an example of a custom pulse discretized at 50 Hz sampling frequency. For implementation details, refer to the example script `make_custom_pulse.py`.

> **Note:** The amplitude values in the custom pulse **.npz** files are automatically normalized to $[0, 1]$ m/s by the DOPFLOW GUI after loading. The waveform's maximum amplitude is then adjustable through the **Amplitude** slider in the GUI. Similarly, the time array is normalized to $[0, 1]$ s, and the user can set the beats per minute (bpm) frequency using the corresponding slider.

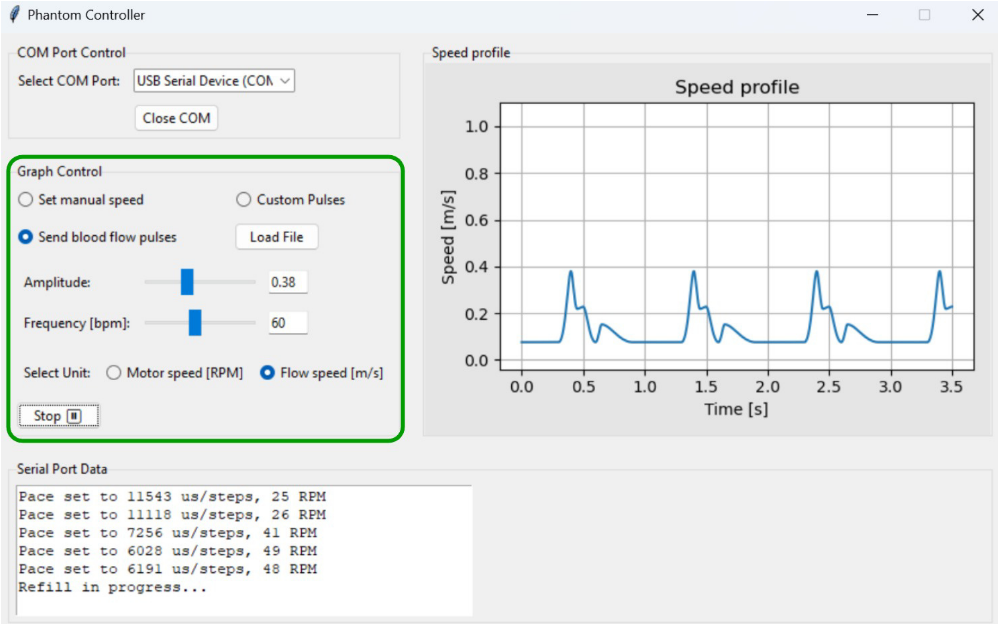


Figure 3.6: GUI with pre-programmed blood flow pulse mode enabled.

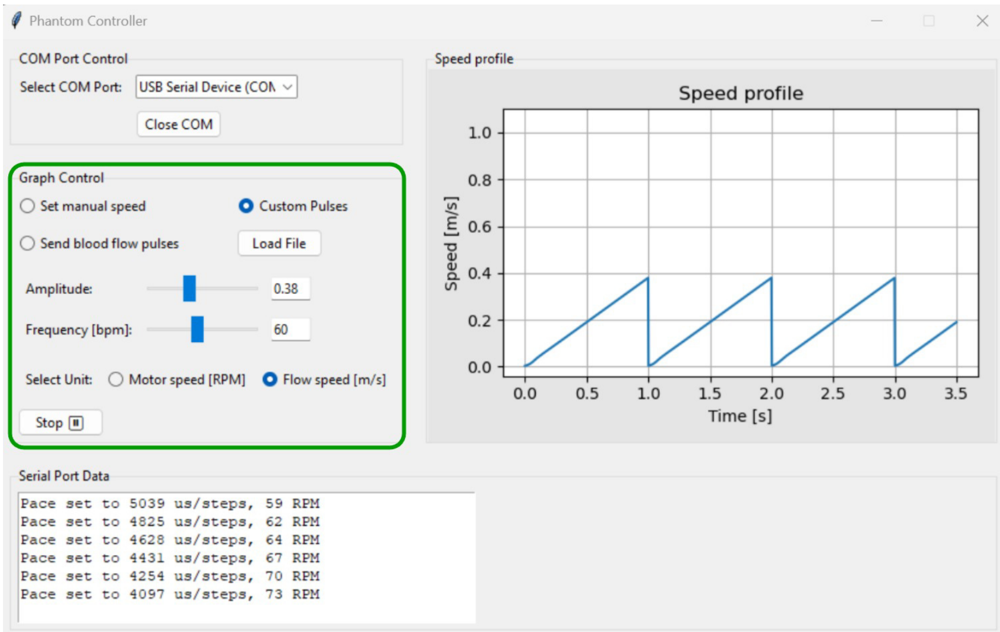


Figure 3.7: GUI Custom Pulses mode showing the execution of a sawtooth waveform.

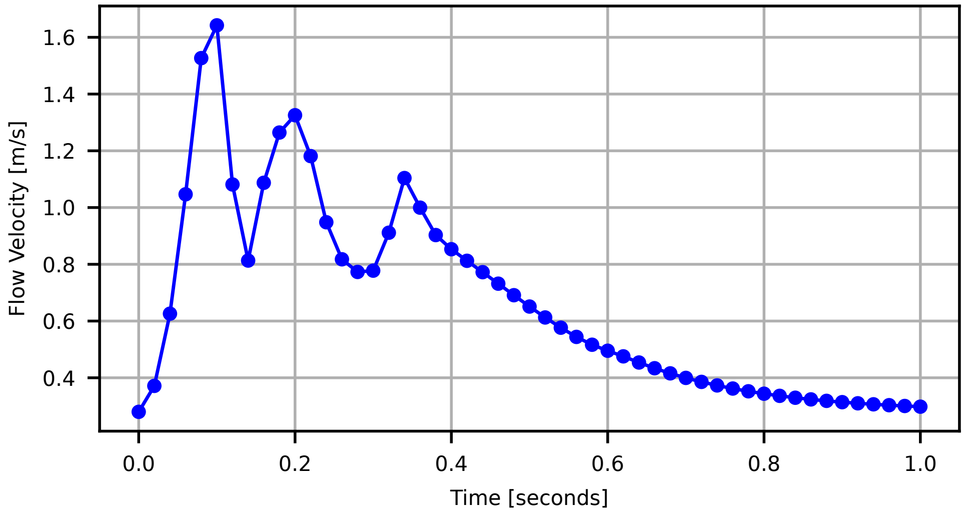


Figure 3.8: An example of a custom user-defined pulse, discretized with 50 Hz sampling frequency.

Chapter 4

Revision history

Date	Revision	Changes
05-Nov-2024	1	Initial release.

Bibliography

[1] S. Vostrikov, J. Tille, I. Nazemtsev, L. Benini, and A. Cossettini, “Open-source fully-programmable flow phantom for doppler ultrasound,” in *2024 IEEE Ultrasonics, Ferroelectrics, and Frequency Control Joint Symposium (UFFC-JS)*. IEEE, 2024, pp. 1–4.

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