HardwareX 11 (2022) e00295

Contents lists available at ScienceDirect

HardwareX

journal homepage: www.elsevier.com/locate/ohx

A low-cost push–pull syringe pump for continuous flow applications

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ARTICLE INFO

Article history:
Received 12 November 2021
Received in revised form 22 February 2022
Accepted 10 March 2022

Keywords:
Dual syringe pump
Push–pull
Continuous flow
3D-printing

ABSTRACT

Syringe pumps are very useful tools to ensure a constant and pulsation-free flow rate, however usability is limited to batch processes. This article shows an open-source method for manufacturing a push pull syringe pump, valid for continuous processes, easy to build, low-cost and programmable.

The push–pull syringe pump (PPSP) is driven by an Arduino nano ATmega328P which controls a NEMA 17 in microstepping via the A4988 stepper driver. The Push-Pull Syringe Pump setup is configurable by means of a digital encoder and an oled screen programmed using C ++. A PCB was designed and built to facilitate the assembly of the device. The continuous flow is guaranteed by four non-return valves and a dampener, which has been sized and optimized for use on this device. Finally, tests were carried out to evaluate the flow rates and the linearity of the flow. The device is achievable with a cost of less than 100 €.

Specifications table

Hardware name	Open-Source Push-Pull Syringe Pump (PPSP)
Subject area	• Engineering and materials science • Educational tools and open-source alternatives to existing infrastructure
Hardware type	• Biological sample handling and preparation
Open-source license	Creative Commons Attribution-Share Alike 4.0 International License (*CC-BY-NC-SA 4.0)*
Cost of hardware	70 €
Source file repository	*https://doi.org/10.17632/75w37bsh8d.1*

Hardware in context

Syringe pumps are devices in use in all those processes in which it is necessary to offer maximum precision for the delivery of known volumes of liquids, examples are given in [1,2]. The simple principle of operation and the easiness of

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https://doi.org/10.1016/j.ohx.2022.e00295
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use compared with the high costs that these devices have on the market, justify the proliferation of Open-Source projects. Starting from basic models that provide for the movement of a single syringe [3–7], more complex models have been proposed, in which the movement of two independent syringes is carried out [8,9]. Other configurations have been described for controlling several units simultaneously [10]. Open-source projects deals also with syringe pump with specific purposes, such as the touch screen syringe pump proposed in [11] useful to replace manual lysis for generating in vitro translation extracts, or the Poseidon Syringe pump[12] used in conjunction with a microscope. Another example is given from Darling et al. [13] in which a syringe pump able to host syringe of different size, has been replaced at the extruder of a 3D biomaterial-printer. With the advance of technological progress and the introduction of open-source microcontrollers such as Arduino, controlling sensors and actuators is nowadays less difficult. Furthermore, with the spread of 3D printing, prototyping no longer suffers from the long waiting times necessary for manufacturers.

Although the syringe pumps described in the literature could be used, in duplicate, to operate in continuous mode, it is useful to note that this approach is not trivial and not economical advantageous. Apart from the use of "one-way kits" (consisting of non-return valves i.e. https://www.zabdiresources.com/p-dkit-dual-pump-plumbing-kit) and a flow linearization system, it is necessary a synchronization between the two individual syringe pumps, as well as it is necessary to completely duplicate all the syringe pump pieces (i.e. molded parts, motors, drivers).

The development of open-source continuous syringe pumps could facilitate the use of processes that require maximum linearity of the flows, such as microfluidic and microfluidic-like processes for the formation of pharmaceutical nanocarriers [14–16]. In fact, the elimination of any fluctuation could be a key element for the investigation of how much the relationship between the flows involved affects quality and size of the nanoparticles.

Therefore, inspired by the publications offered by the network, having in mind the need to guarantee maximum linearity in continuous flow application, the aim of this project was to design, build and test a low-cost push–pull syringe pump for continuous flow applications. By using 4 non-return valves, a continuous flow was guaranteed and with the use of a dampener downstream of the two outlets, the oscillation was dampened, making the flow homogeneous even at high flow rates. The PPSP has been calibrated to work both in micro-step (1/4 step) and in full-step (where greater torque is needed) and has been made programmable and stand-alone to be versatile for laboratory purposes. To facilitate assembly and optimize volumes, a PCB has been designed.

Hardware description

The PPSP is mounted on a 450x50x4mm Plexiglas plate, a gasket has been glued on one side of the plate with the aim of both reducing vibrations due to stepping and improving adhesion. On the other side of the plate the 3D printed supports are fixed, precisely: the "Motor Holder & Electrical Cabinet" that serves to give stability to the stepper motor and contain the electronics; the two "Syringe Support" that serve to keep the body of the syringes still and in position.

All the three supports keep two 8 mm smooth bars still and locked on which the "Plunger Mover" is free to move between the two limit switches. The "Plunger Mover", by means of a flange, is moved by a NEMA17 motor piloted in micro-stepping and connected to a T8 worm screw.

A normal syringe pump on the market costs thousands of euros, a price that tends to double or even triplicate for push–pull devices, moreover in the Open-Source panorama a device has never been presented that would make the flow uninterrupted and linear.

Design files

CAD file and 3D-printing

All the pieces were made with the help of SOLIDWORKS 2017, the STL files were generated and prepared for printing using Ultimaker Cura 4.11.0 Software and made in polylactic acid (PLA) using Anet A8 printer. The files are available at the following repository: https://doi.org/10.17632/75w37bsh8d.1.

The **Plunger Mover** (Fig. 1, A) is the heart of the System, it is a piece that is moved by the rotation of the motor, slides on two smooth bars and, by blocking the plungers, guarantees the periodic loading and unloading of the syringes.

The **Screen Holder** (Fig. 1, B) is designed to support the screen and to cover the electronics and cables in the cabinet, leaving easy access to the system's USB port.

The **Motor Holder & Electrical Cabinet** (Fig. 1, C) is the main part of the system, it contains the PCB with driver and microcontroller and the NEMA17 motor is fixed to it

The **Syringe Support** (Fig. 1, D) is the piece that holds the syringe body fixed while the plungers are moved.

The **Plunger Holders** (Fig. 1, F.1 and F.2) are the pieces that keep the plungers fixed to the plunger mover.

The **Lateral Syringe Holder** (Fig. 1, E) and the **Top Syringe Holder** (Fig. 1, G) are pieces that hold the syringe body fixed together with the Syringe support.

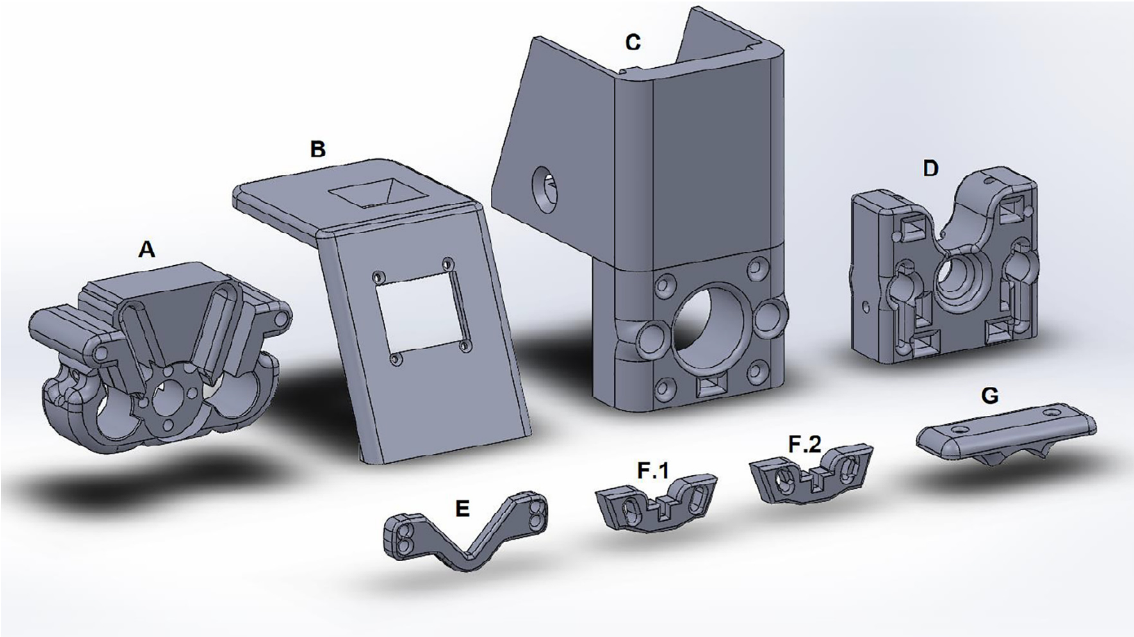

Fig. 1. 3D printed part of PPSP A) Plunger Mover; B) Screen Holder, C) Motor Holder and Electrical Cabinet; D) Syringe Support; E) Lateral Syringe Holder; F.1) Plunger Holder Front; F.2) Plunger Holder Back; G) Top Syringe Holder.

Design files summary

(See Table 1)

Table 1
Design files summary.

Design file name	Qnt.	File type	Open source license	Location of the file
Plunger Mover (Fig. 1, A)	1	STL	CC-BY-NC-SA 4.0	https://doi.org/10.17632/75w37bsh8d.1
Screen Holder (Fig. 1, B)	1	STL	CC-BY-NC-SA 4.0	https://doi.org/10.17632/75w37bsh8d.1
Motor Holder & Electrical Cabinet (Fig. 1, C)	1	STL	CC-BY-NC-SA 4.0	https://doi.org/10.17632/75w37bsh8d.1
Syringe Support (Fig. 1, D)	2	STL	CC-BY-NC-SA 4.0	https://doi.org/10.17632/75w37bsh8d.1
Lateral Syringe Holder (Fig. 1, E)	2	STL	CC-BY-NC-SA 4.0	https://doi.org/10.17632/75w37bsh8d.1
Plunger Holders (Fig. 1, F.1 and F.2)	2	STL	CC-BY-NC-SA 4.0	https://doi.org/10.17632/75w37bsh8d.1
Top Syringe Holder (Fig. 1, G)	2	STL	CC-BY-NC-SA 4.0	https://doi.org/10.17632/75w37bsh8d.1

Circuit diagram

The schematization of the circuit diagram is provided at the following repository: https://doi.org/10.17632/75w37bsh8d.1. The Arduino Nano board (rev 3.0) is the microcontroller used for the PPSP and it is powered directly on the VIN pin (and on the GND) from the DC connector (to which a 9 V DC, 1000mAh power supply must be connected).

The same GND and the 9 V are connected also to the driver A4988 at the specific pins (GND and VMOT). Between the positive (9 V) and the ground (GND) poles of the power supply, a capacitor (100 μF – 50 V) is placed, which has the purpose of stabilizing the current that reaches the driver, protecting the driver from noises caused by other parts of the hardware, and protecting other parts of the hardware from voltage drops caused by the driver.

The following parts are connected to the microcontroller: the 0.96" OLED screen (SDA on A4 and SCK on A5), the digital encoder (SW on D6, DT on D5 and CLK on D4), the two limit switches (for which a normally opened configuration and a 10 kΩ pull-down resistor are used) are connected to controller pins D10 and D9.

The A4988 pins 1A, 1B, 2A, 2B connect the stepper motor to the circuit; the DIR and STEP pins (connected to D2 and D3 respectively) are used to control the position and the steps of the motor; the SLP and RST pins are connected to each other (and to pin A1) and are used to disable the motor when the pump is put on pause (useful for limiting the consumption of electric current and delaying the deterioration of the internal components); finally the pins MS1, MS2, MS3 (connected to pins A6, A3 and A2 respectively) are used for microstepping control. The VDD pins of the various components are all connected to the 5 V of the microcontroller, in the same way, the GND pins of all the components are shared with the GND of the microcontroller. The pin-out of the microcontroller is reported in Table 2.

Table 2
Microcontroller pin details.

Microcontroller's Digital(D)/Analogic(A) pins	Component pin
A1	Sleep-Reset A4988
A2	MS3 A4988
A3	MS2 A4988
A4	SDA Oled Screen 0.96″
A5	SCL Oled Screen 0.96″
A6	MS1 A4988
D2	Dir A4988
D3	STP A4988
D4	DT Encoder
D5	CLK Encoder
D6	SW Encoder
D9	Limit switch 2
D10	Limit switch 1

PCB design

The Gerber files of the PCB are available at the following repository: https://doi.org/10.17632/75w37bsh8d.1 (See Fig. 2).

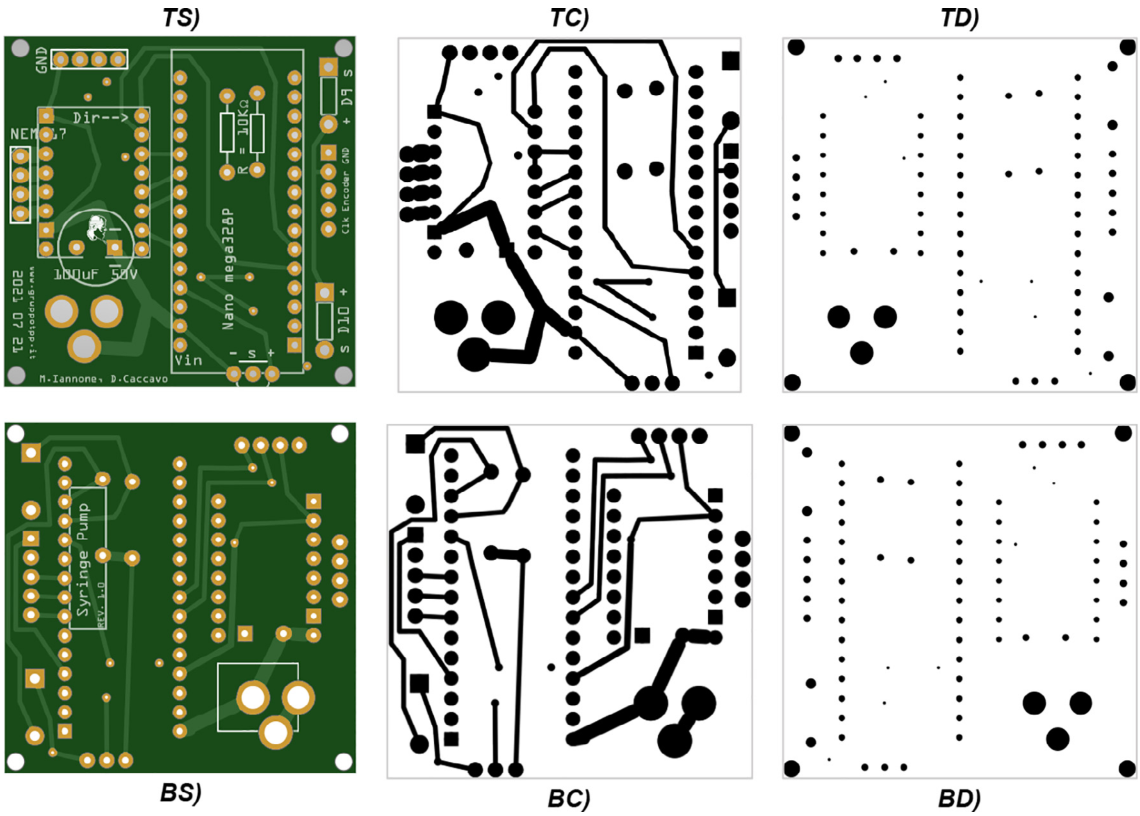

Fig. 2. PCB specify. TS) Top Silk; TC) Top Copper; TD) Drill position from Top; BS) Bottom Silk; BC) Bottom Copper; BD) Drill position from Bottom.

Software and firmware

The software was written in C ++ language and it was implemented on the microcontroller using Arduino IDE. The code is available at the following repository: https://doi.org/10.17632/75w37bsh8d.1.

Bill of materials

(See Table 3).

Table 3
Bill of materials.

Designator	Component	n°	Cost unit [€]	Total cost [€]	Source of Materials	Material type
M2x8mm Countersunk metric screw	M2x8	4	0.10	0.40	https://tinyurl.com/2p95n7n6	Metal
M2X2mm Nut	M2x2	4	0.10	0.40	https://tinyurl.com/2p9f9db6	Metal
M3x10mm Countersunk metric screw	M3x10	9	0.10	0.90	https://tinyurl.com/3ddwc6nb	Metal
M3x16mm Countersunk metric screw	M3x16	8	0.10	0.80	https://tinyurl.com/2p8fbmcx	Metal
M3x20mm Countersunk metric screw	M3x20	4	0.10	0.40	https://tinyurl.com/5cxh7ek9	Metal
M3x25mm Countersunk metric screw	M3x25	4	0.10	0.40	https://tinyurl.com/3d32b4zn	Metal
M3x35mm Countersunk metric screw	M3x35	2	0.10	0.20	https://tinyurl.com/4be34d9d	Metal
M3x40mm Countersunk metric screw	M3x40	2	0.10	0.20	https://tinyurl.com/53pjfc8p	Metal
M3x2.2mm Nut	M3x2	29	0.05	1.45	https://tinyurl.com/4j5278dz	Metal
M3x10mm Self-tapping screw	ST3x10	7	0.10	0.70	https://tinyurl.com/2p98r7pf	Metal
M3x9mm Washer	MW3x5	4	0.10	0.40	https://tinyurl.com/seafdn74	Metal
Steel smooth rod D = 8 mm	MC-01	2	2.00	4.00	https://tinyurl.com/ycv2w7mz	Metal
T8x350mm threaded rod + threaded brass flange	MC-02 & MC-03	1	9.99	9.99	https://tinyurl.com/2p85jc59	Metal
P-type self-adhesive gasket	PL- 01	1	1.00	1.00	https://tinyurl.com/2p8v2wda	Metal
Plexiglas slab (450x50x4mm)	PL-02	1	1.00	1.00	https://tinyurl.com/3trze2bd	Polymer
connector joint 5–8 mm	MC-04	1	1.39	1.39	https://tinyurl.com/bdecdhrm	Metal
Syringe	PL-03	2	0.58	1.17	https://tinyurl.com/2p97dkha	Polymer
Self-lubricating plastic bearing (ID = 8 mm OD = 15 mm)	MC-05	2	1.12	2.25	https://tinyurl.com/bdfkmzws	Polymer
One-way valve	FD-01	4	1.64	6.55	https://tinyurl.com/w3ac228w	Polymer
Silicon Cap	FD-02	1	0.2	0.20	https://tinyurl.com/4mvp3xkr	Polymer
Tubes (different dimensions)	FD-03	2	0.3	0.60	https://tinyurl.com/4mvp3xkr	Polymer
Y fitting 3–4 mm	FD-04	3	0.10	0.30	https://tinyurl.com/4mvp3xkr	Polymer
T fitting 3–4 mm	FD-05	1	0.10	0.10	https://tinyurl.com/4mvp3xkr	Polymer
Tube reduction 8–3 mm	FD-06	1	0.10	0.10	https://tinyurl.com/4mvp3xkr	Polymer
Cable ties	FD-07	22	0.02	0.44	https://tinyurl.com/4fdt9tay	Polymer
Hose clamps	FD-08	2	0.50	1.00	https://tinyurl.com/2p84rb8c	Metal

(*continued on next page*)

Table 3 (*continued*)

Designator	Component	n°	Cost unit [€]	Total cost [€]	Source of Materials	Material type
Electronics						
Elegoo nano ATmega328P	EL-06	1	4.66	4.66	https://tinyurl.com/2ckf6kk8	Electronic
Quimat Nema 17 stepper motor 1.7A 0.59Nm	EL-10	1	15.00	15.00	https://tinyurl.com/vt6ec5m7	Electronic
Stepper driver A4988	EL-07	1	1.60	1.60	https://tinyurl.com/muy64ncc	Electronic
Oled screen 128x64 0.96″	EL-11	1	4.00	4.00	https://tinyurl.com/2u8kh8n7	Electronic
Digital Encoder	EL-09	1	1.40	1.40	https://tinyurl.com/4hjbcv4c	Electronic
Stop sensor	EL-12	2	1.16	2.32	https://tinyurl.com/yckuz6yz	Electronic
DC plug in power supply 5.5 mm	EL-03	1	1.00	1.00	https://tinyurl.com/4w98ekay	Electronic
10KOhm Resistor	EL-02	2	0.20	0.40	https://tinyurl.com/m5zkbtxw	Electronic
100 V electrolitic condenser	EL-01	1	0.20	0.20	https://tinyurl.com/m5zkbtxw	Electronic
male pin	EL-04	1	0.20	0.20	https://tinyurl.com/m5zkbtxw	Electronic
Female pin	EL-05	1	0.20	0.20	https://tinyurl.com/m5zkbtxw	Electronic
Wires	EL-06	1	1.00	1.00	https://tinyurl.com/m5zkbtxw	Electronic
PCB	EL-08	1	2.20	2.20	https://tinyurl.com/3nfxwzjm	Electronic

Build instructions

Additional instruments, devices, and materials:

Screwdrivers, calibrated pipettes, graduated cylinders, pliers, Soft Tip Hammer, Screwdriver, Drill, Soldering Iron, Tin, Multimeter, some 2 mm Self Tapping Screws for PCB Fixing, Hot Glue, Lubricating Oil.

Preparation of electronic components

The PCB (El-00) was designed by our Research Group and built by PCB-Way (www.pcbway.com, website through which, by uploading the gerber files provided in the supplementary materials, it is possible to order PCBs for this project), the characteristics are listed below:

- Dimensions = 46.8 × 46.8 × 1.6 mm,
- Material = FR-4 (TG 130–140);
- Finished copper = 1 oz.
- Layers = 2;
- Surface finish = HASL with lead;

Additional information: The tracks directly connected to 9 V DC, as they carry loads of the order of Ampere, have been oversized (70mils) to avoid overheating problems.

Mount the PCB

- Solder the 47uf (100 V) electrolytic capacitor (EL-01), the 10kOhm resistors (EL-02) and the connector for the 9 V-DC (EL-03) using the appropriate holes
- Solder the female pins (EL-05) (15x2 Arduino board, 8x2 Stepper Driver A4988, 4x1 Oled Screen 128x64px) and the male pins (EL-04) (4x1 NEMA17 motor, 2x2 Limit switches, 5x1 Digital Encoder)
- Insert Microcontroller (EL-06), Stepper Driver A4988 (EL-07) in the female pins paying attention to the indications on the PCB face (see Fig. 3)
- Fix PCB (EL-08) to the internal wall of the *Motor Holder & Electrical Cabinet*, insert the encoder (EL-09) in the side of the same piece and fix it with the nut (Fig. 4).
- Fix the Oled screen (EL-11) to the *Screen Holder* using M2x8 pins and nuts (M2x8 and M2x2) (Fig. 4).

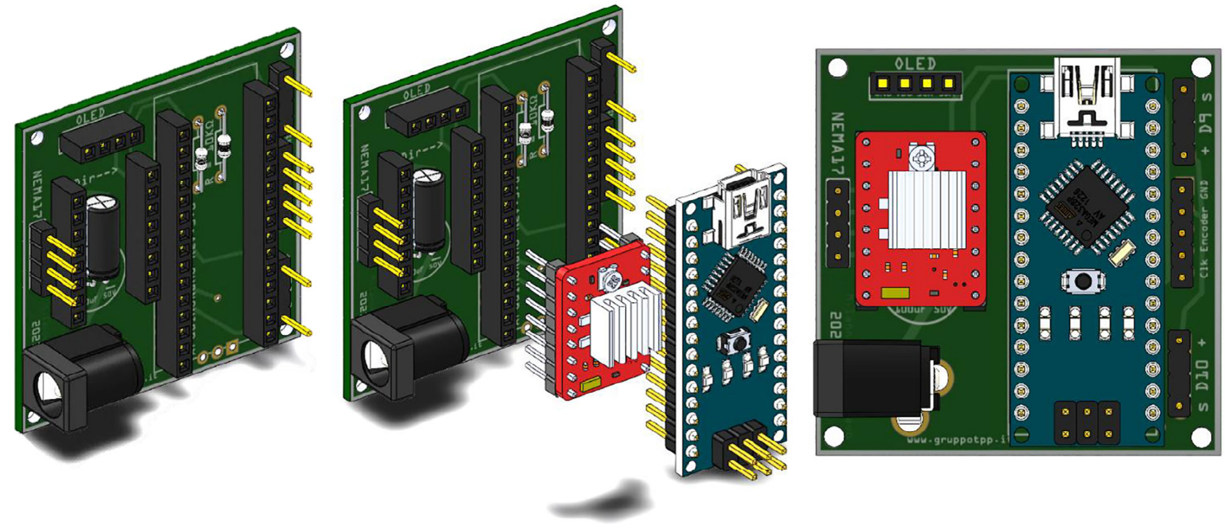

Fig. 3. PCB assembly.

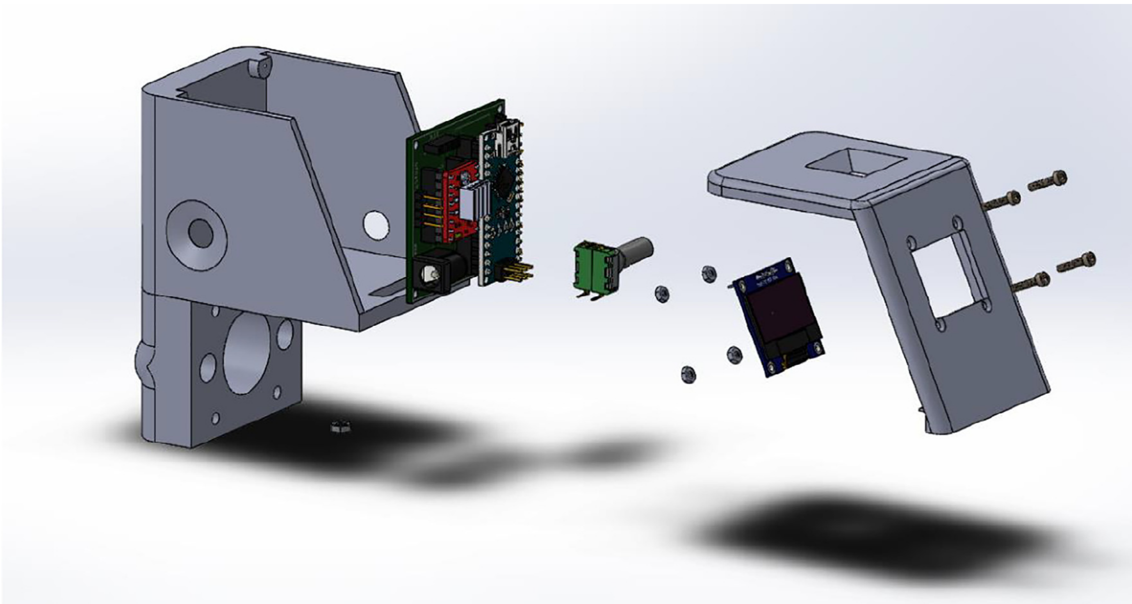

Fig. 4. Motor Holder & Electrical cabinet and Screen Holder Assembly.

- Fix the PCB using hot glue or 2x10mm self-tapping screws.
- Connect the NEMA17 (EL-10) motor by passing the wires through the rear hole of the Motor Holder and Electrical Cabinet, connect the screen and encoder using FF wires and connect free FM wires on the corresponding pin-headers, close the cover by passing these cables through the rear hole. Of the piece.

Preparation of NEMA17 with A4988 stepper-driver

If the motor current is not tuned, it may happen that the motor doesn't move correctly and starts pulsating. To adjust the input current to the NEMA17 motor it is necessary to calibrate the A4988 stepper driver using the potentiometer on-board mounted. The A4988 allows you to set a target current by adjusting Reference Voltage (V_{ref}) turning the potentiometer present on board [17].

In our case, having a 1.5A NEMA17 motor (considering a real maximum load equal to 80% of the theoretical maximum load) and an A4988 driver with a 0.1 Ω sense resistor, we calculate [17,18]

$$I_{Max,Real} = I_{Max,Theoretical} * 0.8 = 1.5A * 0.8 = 1.2A$$

The actual value of Vref can be calculated using the formula [17,18]:

$$V_{ref} = I_{Max,Real} * 8 * R_s = 1.2A * 8 * 0.1\Omega = 0.96V$$

Using a multimeter, measure the voltage at the top of the potentiometer head and at any ground point on the board, or alternatively, measure the current flowing in one of the motor cables downstream of the driver. Using a multimeter, measure the voltage at the top of the potentiometer head and at any ground point on the board, or alternatively, measure the current flowing in one of the motor cables downstream of the driver. Useful guides are given in [17,18].

It is suggested to use the "sleep" pin on the A4988 driver to limit the current consumption and therefore limit the overheating and wear of the electronic components crossed by high loads, in this way, the power request goes from about 8 W to about 0.2 W when the pump is paused.

Preliminary operations

- Cut and drill the Plexiglas sheet, calibrating the distance between the holes according to the size of the used syringes, the cut can be made using a circular saw (e.g., Dremel), while the holes can be drilled with a drill and a 3 mm bit, alternatively a perforated sheet of any material can be used
- Insert the 3 mm nuts (M3x2) fully and in each orifice provided on the 3D printed pieces.
- Fix the limit-switches (EL-12) using self-tapping screws 2x10mm (ST2x10) on the sides of the *Syringe Support* marked with holes (Fig. 5).
- Fix the syringe body to the two *Syringe Supports* using *Lateral Syringe Holder* and M3x16mm pins, *Top Syringe Holder* and M3x20mm pins (Fig. 5).
- Fix the threaded flange (MC-03) to the *plunger mover* using M3x16mm pins and nuts (Fig. 6).
- Insert self-lubricating bearings (MC-05) in the dedicated holes and fix their position with M3x25mm pins (Fig. 6).
- Position the two syringes (PL-03) and fix the plungers to the *Plunger Mover* using the *Plunger Holders.*

Global assembly

- Fix the 5–8 mm connector joint (MC-04) to the NEMA17 motor and fix the T8x350mm threaded bar (MC-02) to the connector by tightening the side screws (Fig. 7).
- Fix the motor to the *Motor Holder and Electrical Cabinet* using M3x25mm pins (Fig. 7).
- Insert the 8x400mm smooth bars (MC-01) into the dedicated holes on the *Motor Holder and Electrical Cabinet* (Fig. 7).
- Insert by sliding, in sequence, the first *Syringe Support*, *Plunger Mover* and the second *Syringe Support* (as seen in Fig. 8 the limit switches must both face towards the center).
- Lubricate the stroke of the *Plunger Mover*

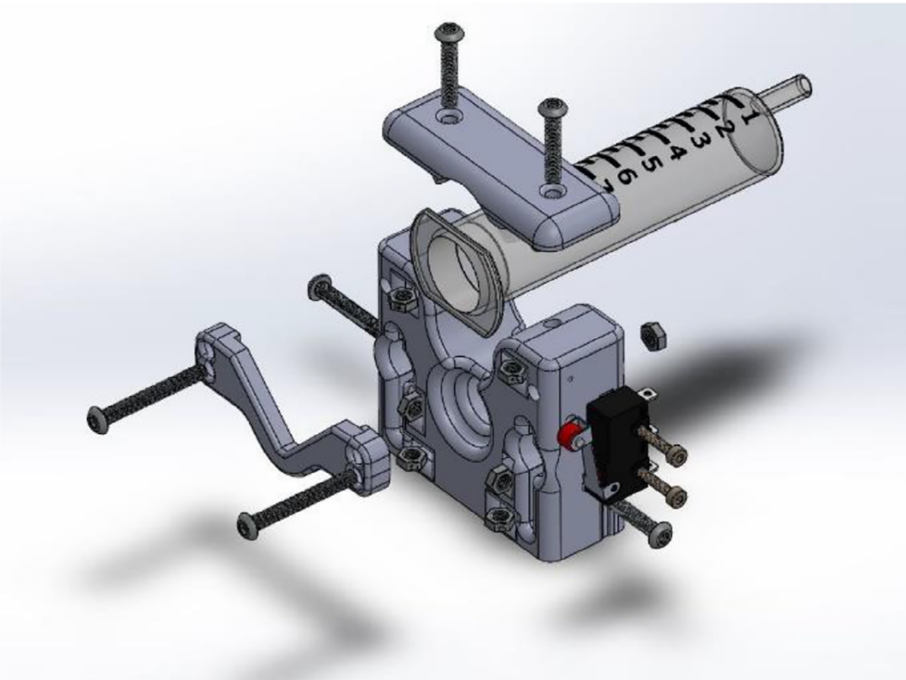

Fig. 5. Syringe Support assembly.

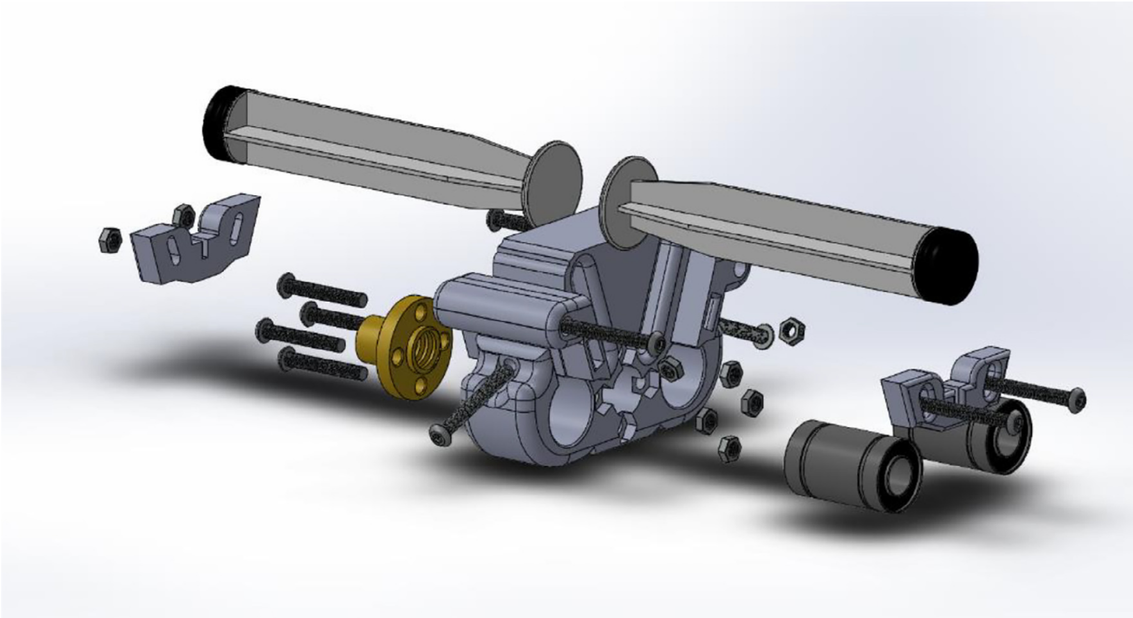

Fig. 6. Plunger mover assembly.

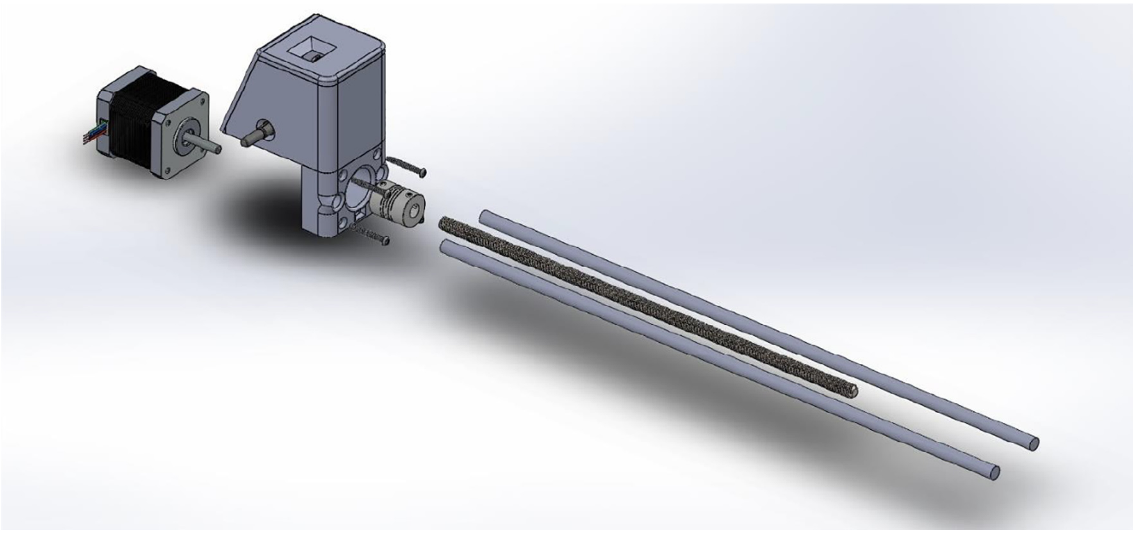

Fig. 7. Mechanical assembly.

- Connect the two limit switches by soldering (or using FASTON terminals) and wires by passing the cables adjacent to the lower face of the Plexiglas. The limit switch closest to the PCB is connected to D9 while the farthest to D10
- Glue the P-type self-adhesive gasket (PL-01) along the sides in the lower part of the Plexiglas sheet.

In this work 10 mL syringes (L = 12 cm, D = 1.3 cm) have been used as a reference, and calibration has been carried out on these syringes. However, during the building phase, a different type of syringe can be chosen, but it will be necessary to recalibrate the instrument following the procedure outlined in the manuscript.

Fluid-dynamic piping preparation and assembly

To ensure flow continuity, 4 one-way valves (FD-01) were used connected as shown in Fig. 9.

The system globally provides 2 inlets and 1 outlet. The flows coming out of the syringes, after being joined (by means of a Y junction FD-04), are sent to a damping area where there is a dampener. The dampener is composed of a silicone tube

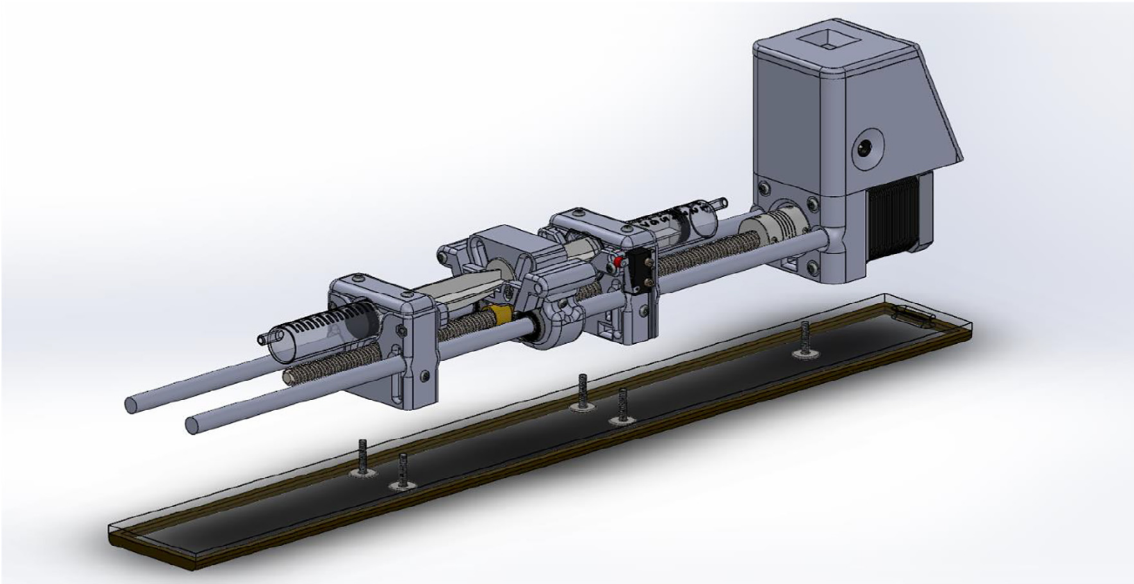

Fig. 8. Support assembly.

(OD = 10 mm, ID = 8 mm, L = 50 mm), a silicone cap (FD-02), and two metal hose clamps (FD-08), to tighten both the cap and a reduction (8–3 mm) which is connected to a T-junction (FD-05) and downstream of which there is a necking. The purpose of the dampener is to regulate the flow where there are spikes, it acts as a reservoir, which pours its contents when the pressure drop allows it.

Software setup

To write and implement the software Arduino IDE was used equipped with the U8g2lib library for the management of the OLED screen. The sketch is divided into 5 tabs, in the main one, named PPSP_Software (supplementary materials) runs the main loop, the other 4 are additional functions, one for the autohome function at startup, one for screen management and two others for the management of the digital encoder. The NEMA17 is driven in ¼ step (microstepping), the power supply voltage is 9 V DC and is supplied by a 220 V AC – 9 V DC (1000 mA) transformer.

Autohome

The first operation carried out by the pump at the start up is the autohome, the code is placed inside the autohome function (‘‘Autohome.ino”). The motor moves the Plunger Mover until it reaches the first limit switch. At this point the rotation is reverted and the Plunger Mover is moved until it reaches the second limit switch. While doing this movement the number of steps necessary to move from one switch to the other (full stroke) are recorded. These steps will be used to control the position of the Plunger Mover in the normal operation of the pump.

Pumping control system

After the autohome, the position of the Plunger Mover is known. At this point, by using two for loops, it is possible to control the movements of the Plunger Mover. In particular, a for loop moves the Plunger Mover from right to left, by sending digital HIGH and LOW signals to the driver of the NEMA motor, interspersed by a certain delay. The other for loop moves, in a similar way, the Plunger Mover from left to right. The delay between HIGH and LOW signals is function of the flow rate set by the user, that is in millisecond for low flow rate and in microseconds for high flow rates (this choice is performed in the ‘‘Start_selection.ino” function). The whole control logic is present in the ‘‘step_function.ino”.

User interface

The other part of the software has been developed to allow an easy interface between the pump and the human action. In particular, the file ‘‘Msg_to_Oled.ino” contains the code necessary to show on screen the flow rate and a command to pause or restart the pump. The interaction between the pump and the user is performed by a digital Encoder whose logic of control is reported in the ‘‘Encoder_sel.ino” function.

Operation instructions

The pump will be started with the connection of the power plug, at each start the system will perform an AutoHome to re-evaluate the position and distances (the maneuver is valid even if the pipes are empty), at the end of the auto-

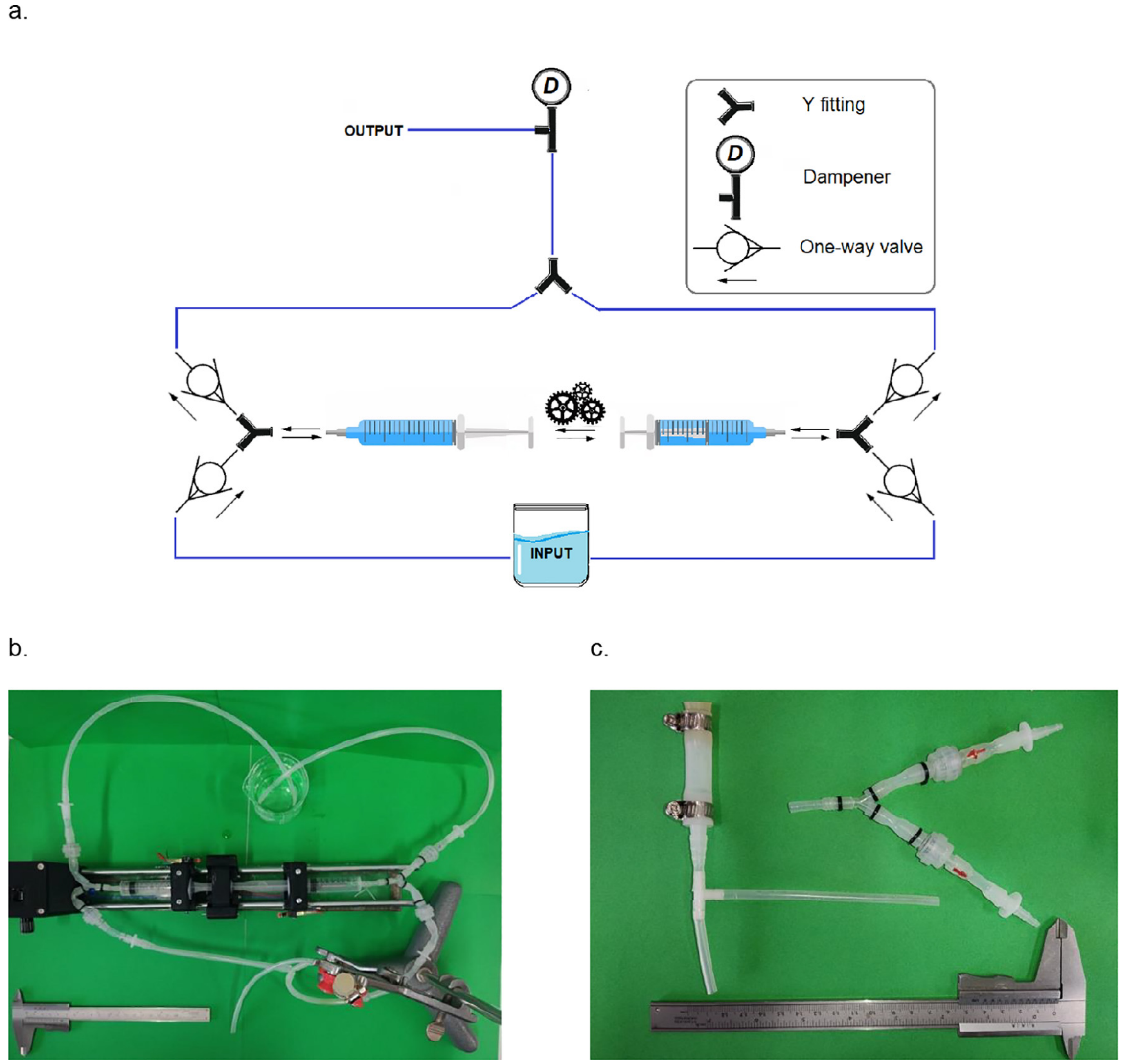

Fig. 9. a. Schematization of the piping; b. top view of the pump with the tubing; c. focus on the connection of the dampener (in-line mounting, inlet from below) and of the 2 one-way valves.

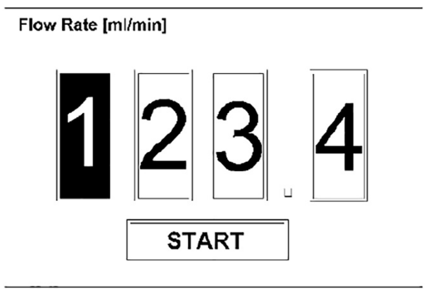

Fig. 10. Main menu screen representation.

home process the pump will remain stationary while waiting for commands, a menu will appear on the screen (an example is given in Fig. 10) in which it will be possible to choose the flow rate in a range that goes from 0.5 to 500 mL/min and then start the system.

In the main menu it is possible to set the range by navigating between the values of hundreds, tens, units and tenths shown on the screen, which are highlighted by rotating the encoder clockwise (right) or anticlockwise (left), by pressing the switch of the encoder, on the other hand, it is possible to modify the selection.

Positioning on "start" and pressing the encoder switch, the pump is started and will deliver the set flow rate. While the pump is running, by pressing the encoder switch, the pump will stop, and it will be possible to set a new flow rate

In the enclosed software the calibration was carried out with 10 mL syringes and ¼ step in micro-stepping modes with a Nema17 1.5A.

Validation and characterization

Calibration

NEMA17 has been programmed to carry out one step (or ¼ of step) every time interval Δt which is defined each time by the chosen flow rate: the greater the flow rate, the lower the Δt that will elapse between two consecutive steps. In Fig. 11 the experimental calibration curves obtained for high and low flow-rate are reported. At fixed delay step-step the output of the pump was collected for a certain amount of time and measured, the flow rate was calculated as the ratio of the volume and the time of collection of the sample. In particular for high flow rate ($\dot{Q}$) (5–500 mL/min or equivalently Δt 0–1000 μs) the relation between flow rate (mL/min) and Δt (in μs) is $\dot{Q}\left[\frac{mL}{min}\right] = 49300\frac{1}{\Delta t(\mu s)}$, whereas for low flow-rate (0.5–5 mL/min) the relation is $\dot{Q}\left[\frac{mL}{min}\right] = 54.5\frac{1}{\Delta t(ms)}$.

Pump calibration took place by correlating the delay set between one step and another and the volumetric flow rate, the latter was obtained by measuring the volume delivered (through graduated containers) and dividing this value by the metered delivery (through chronometer). Two calibrations were carried out, one based on microseconds, and one based on milliseconds, the differentiation was necessary for the low flow rates, where the delay between one step and the other is much greater, and, since the use of micros is reliable in a range from about 3 to 16000 μs [19] it was decided to operate with the milliseconds to avoid instability problems.

Dampener effect evaluation

As mentioned, the dampener is used to dampen any fluctuations in the volumetric flow; the presence of a compressible fluid such as air inside a closed volume and placed through a tree-way fitting along the line where the flow to be damped streams, acts as a shock absorber by accumulating liquid when the piping is under pressure, and giving up a flow rate when pressure drops are recorded in the piping. When making a dampener, it is necessary to consider the operating pressure, the desired percentage of damping, parameters that will define the volume of the dampener itself. In our work a dampener with-

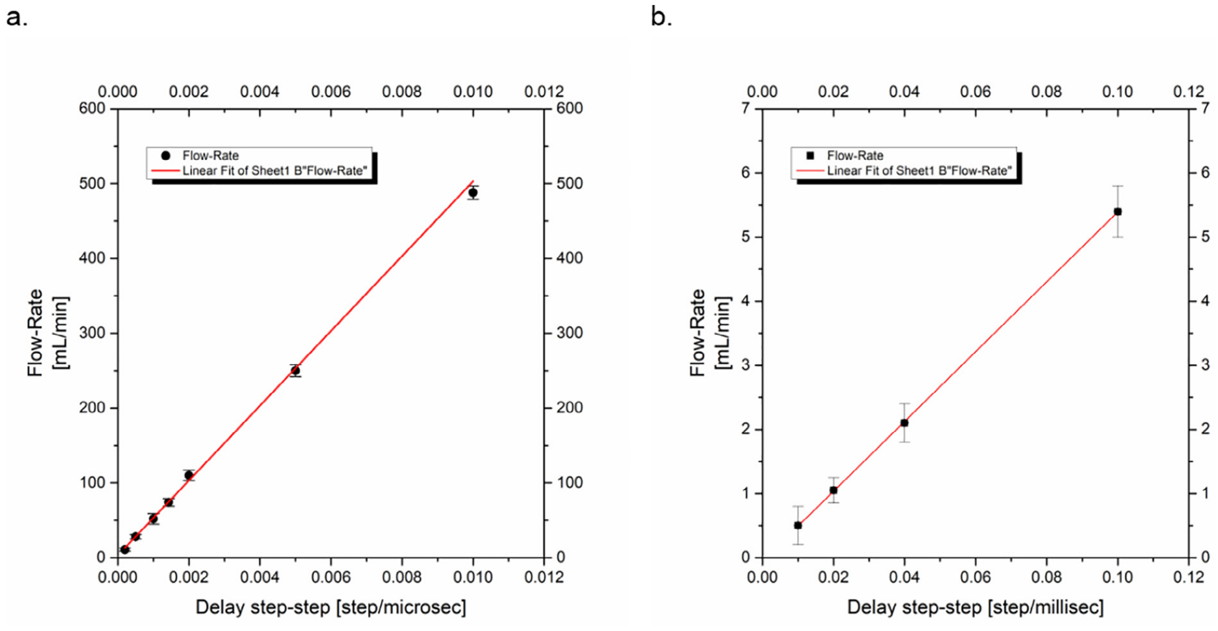

Fig. 11. Calibration line: a. relationship between volumetric flowrate [mL/min] and delay between two consecutive steps in microseconds (for high flow-rate); b. relationship between volumetric flowrate [mL/min] and delay between two consecutive steps in milliseconds (for low flow-rate).

out a separating membrane was created, for the dimensioning the law of the adiabatic transformation was used: $P_0V_0^\gamma = P_1V_1^\gamma = P_2V_2^\gamma$, where P_0 and V_0 are the atmospheric pressure and the total volume of the dampener; P_1 is the working pressure; V_1 is the volume of the compressed gas above the liquid level inside the dampener during normal operation of the pump; P_2 is the pressure recorded during the switch between the two syringes and V_2 is the volume of air present in the dampener at the switch (Fig. 12).

Considering that the more it is necessary to reduce a pulsation, the closer the value of P_1 must be to P_2: i.e. $P_2 = 95\%P_1$, so as to have a damping factor equal to 5%, $\varepsilon = 0.05$. Considering that $V_1 = V_2 - \delta V_{liq}$ (see Fig. 12) and combining these considerations with the adiabatic transformation $P_0V_0^\gamma = P_1V_1^\gamma = P_2V_2^\gamma$, it is possible to obtain the equation to estimate the volume V_0 of the dampener:

$$V_0 = \left[(1-\varepsilon)\frac{P_1}{P_0}\right]^{1/\gamma}\left[\frac{\delta V_{liq}}{(1-(1-\varepsilon))^{1/\gamma}}\right]$$

Equation 1. Dampener volume estimation

It is fundamental to know the δV_{liq}, which is a characteristic of the pump. To estimate its value, in this work an analog pressure transducer was connected after the dampener, measuring the pressure inside the system at 10 different flow rates. Knowing that for air the expansion coefficient is $\gamma \approx 1.4$, and using the the maximum (P_1) and minimum (P_2) pressure values it was possible to estimate the damping factor ($P_2/P_1 = (1-\varepsilon)$). Knowing the volume of the dampener used, from Eq. 1 it was possible to calculate δV_{liq} at the different flow rates. The values obtained are reported in Fig. 13, along their fitting with an exponential function that allows to calculate the characteristic δV_{liq} of the pump at different flow rates:

$$\delta V_{liq}[mL] = A + B * e^{\left(-\frac{\dot{Q}\left[\frac{mL}{min}\right]}{C}\right)}$$

where A = 0.421 mL, B = -0.445 mL, C = 144.883 mL/min

Equation 2. Equation to relate the δV_{liq} to the volumetric flowrate (coming from fitting of experimental data)

As it can be seen from Fig. 13, at flow rates lower than 20 mL/min the δV_{liq} is very small, meaning that there is no need to install a dampener in the systems. When the flow rate increases, the inertia of the system at the switch produces higher value of δV_{liq}, in other words the flow at switch is not constant, and the use of a properly sized dampener is needed.

Obviously, in order to have the effect of the dampener, a minimum pressure must be recorded in the piping which can be estimated starting from the consideration that, at the moment of minimum pressure in the dampener there must be liquid for at least 20% of the total volume of the dampener, i.e. $V_{2,min} = 0.8V_0$, from this, considering that $V_{1,min} = V_{2,min} - \delta V_{liq}$, substituting in the formula of the adiabatic transformation we obtain:

$$P_{1,min} = \left(\frac{V_0P_0}{0.8V_0 - \delta V_{liq}}\right)^\gamma$$

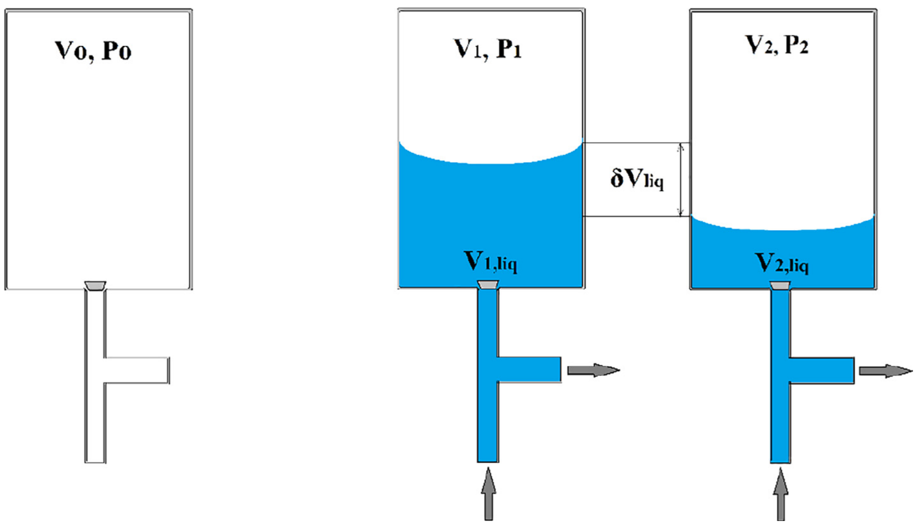

Fig. 12. Operating dampener example.

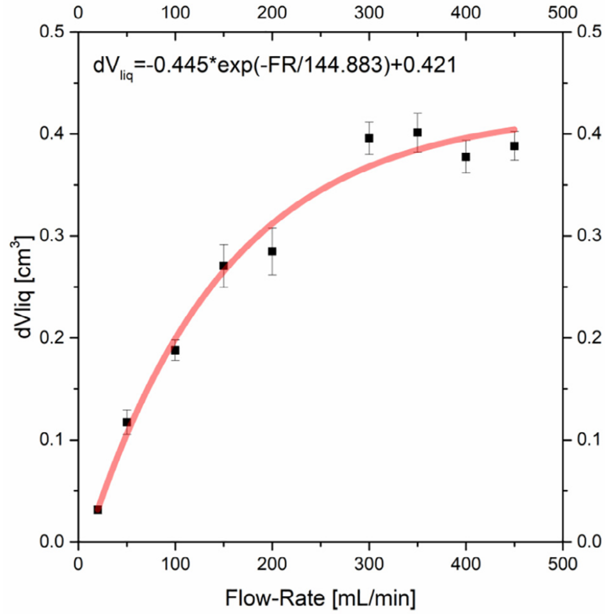

Fig. 13. Experimental data fitting to correlate δV_{liq} to the flowrate.

Equation 3. Equation for the estimation of the minimum working pressure ($P_{1,min}$) to obtain an effective damper effect

When designing the volume of the dampener without membrane (bladder) it is convenient to work, if it is possible, at the minimum pressure to assure the functioning of the dampener and its smallest volume. Is the downstream does not produce a sufficient back pressure, so that $P_1 \geq P_{1,min}$, a concentrated pressure drop (such as a restriction or a needle valve) should be installed downstream the dampener.

Fig. 14 shows a demonstration of the damping effect by comparing the pressure recorded on the pump delivery, at the flow rate of 300 mL/min, without and with three dampeners of different sizes (the pressure was measured by connecting an analog pressure transducer downstream of the dampener and an Arduino MEGA 2560 board).

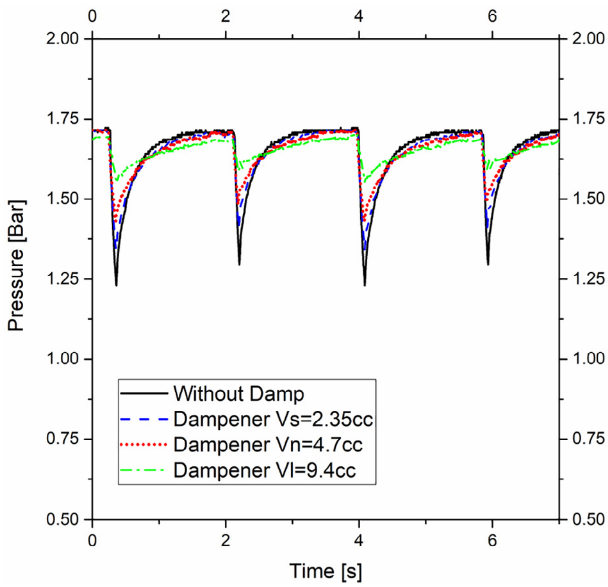

Fig. 14. Demonstration of the dampener effect on a flowrate of 300 mL/min tested in 4 different configurations: without dampener-black line, Small Dampener (V_s = 2.35 cm^3)-blue dashed line, Normal Dampener (V_n = 4.7 cm^3)-red dotted line, large dampener (V_l = 9.4 cm^3)-green point dashed line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

When a dampener of a certain volume is installed on the line, the Eq. (1) can be used to estimate the damping factor (ε) once the working pressure and the flow rate (so that δV_{liq} from Eq. (2)) are known.

CRediT authorship contribution statement

Marco Iannone: Data curation, Software, Methodology, Investigation, Writing – original draft, Visualization. **Diego Caccavo:** Conceptualization, Investigation, Validation, Writing – review & editing. **Anna Angela Barba:** Supervision, Writing – review & editing. **Gaetano Lamberti:** Supervision, Writing – review & editing.

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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