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An open-source peristaltic pump with multiple independent channels for laboratory automation

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In recent years laboratory automation, high throughput characterization and self-driving laboratories have emerged as promising tools to accelerate the process of researching and developing novel materials. Many of these automated setups rely on precise and reliable liquid handling to perform their large-scale studies. Peristaltic pumps, with their simple and robust design, a low price point and only the tube itself being in contact with the fluid, are well suited to power these increasingly more complex liquid handling tasks. While existing open-source designs of peristaltic pumps already feature multiple channels to accommodate the need for more fluid lines, these channels are all powered by a single motor and can therefore not run independently of each other, reducing their usability and versatility. To overcome this limitation, we developed an open-source peristaltic pump with four fully independent pumping channels, a quick-swap cassette system and an automation friendly SiLA 2 interface. The design was created with lab automation and self-driving laboratories in mind and allows for flow rates from 0.3 µL min^{-1} to 8 mL min^{-1} with a repeatability of 0.2%. Another focus of the design was accessibility, with the pump built from 3D-printed parts and commonly available standardized and off-the-shelf hardware components, resulting in an affordable price point of around 280 USD.

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1. Introduction

Peristaltic pumps are positive displacement pumps, where a flexible tube is fixed between an arch-shaped tube guide and a rotor with multiple rollers. Those rollers push the tube against the guide. This creates a point, where the tube is pinched off, that moves along the tube as the rotor turns, pushing along any fluid inside the tube. This design results in simple and robust pumps that offer precise and well-controlled flows over a wide range of flow rates. Such pumps also have the advantage that the liquid is only ever in contact with the tube itself, making peristaltic pump inherently suited for applications with pure, sterile or highly reactive fluids.

For these reasons peristaltic pumps are popular in applications like microfluidics, (bio-)medicine and more generally in different characterization devices and setups.[1–3] Furthermore, since all these lab-scale peristaltic pumps feature integrated electronics controlling the pump's operation, they can easily be utilized in automated setups and self-driving laboratories (SDL). There they are often used for simpler tasks like filling and emptying reservoirs or pushing cleaning fluid through a liquid handling system.[4,5] Beyond that though, they can also take an essential role in such setups by for example generating the flow through a flow reactor or an inline characterization instrument, or by directly delivering the right volume and ratio of different reactants.[6–9]

With these applications, where liquid handling takes an essential role, often fluids are not just pumped from one reservoir to another one, but instead it is necessary to control multiple different complex flow paths. This can be achieved by combining a single pump with multiple valves to direct the flow in different directions. In applications though, that are sensitive regarding cross-contamination or ones that require fully independent flow paths, relying on just a single pump is not a feasible option. Instead, multiple individual pumping channels are used alongside each other within the same setup, as it can be seen in literature.[7–9]

A simple and common mechanism to implement more than one peristaltic channel within a pump is to axially arrange multiple tubing lines over a common rotor, powering them all by the same one motor. This results in all channels always having the same rotation speed, making it impossible to automatically enable or disable the flow of individual tubes or to run different lines at different speeds, rendering such pumps rather limited and inflexible.

In contrast, a pump that allows separate control over the flow rate and direction of each channel† offers multiple clear advantages, especially in the context of automated setups and SDLs. Most importantly, it can trivially pump different liquids

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† *E.g.* Ismatec's Reglo ICC pumps

independently of each other through a system, making it possible to, for example, sequentially screen different fluids or to create material libraries simply by mixing multiple stock solutions with arbitrary and varying flow rates and ratios.

Beyond that, independent channels also offer a great amount of flexibility. Instead of having to manually reconfigure which tube is attached to a pump, one can (automatically) select the desired tubing line in software and effortlessly switch between various lines. This allows for different fluids to be permanently accessible in an SDL, flexibly delivering fluid to different synthesis steps and characterization devices. With this, channels can also be individually calibrated, resulting in an overall greater accuracy and repeatability between different channels and tubes. It also enables easy parallelization of different (sub-)experiments or reactions within an SDL, without requiring multiple instances of the entire characterization hardware or even the entire setup. And finally, having multiple independent channels available creates the opportunity to implement a second redundant pumping channel for each *per se* required pumping line. This enables an SDL to continue operating with the second channel when the first tube reaches the end of its life span or in case a clog occurs. Afterwards the primary tubing can be fixed or replaced without the need to interrupt the entire experiment.

To further improve the process of changing tubes, many commercial peristaltic pumps use quick-swap cassette systems to attach individual tubing lines to the pump.‡ Such a system not only improves the usability of a pump, but it also significantly decreases the downtime required to change a tube. Without the need to disassemble parts of the pump, this makes it easy for non-specialist users to perform the process while reducing the risk of improper installations.

The major drawback of commercial pumps with such a cassette system and the above-mentioned ones featuring multiple independent channels is their high price point of typically above 1000 USD per pump channel. Also, due to their closed-source design, it is not possible for the user to easily modify or adapt them according to their own specific needs. And while there are several open-source designs that overcome these restrictions, they all lack these quick-swap systems and do not provide multiple fully independent channels.[10–15]

We therefore propose an open-source pump design that incorporates these two features, while still being significantly more cost-effective than the commercial options. It offers four independent pump channels in a compact footprint and uses custom cassettes that are compatible with commonly available 3-stop commercial tubing. Each channel can – depending on the selected tube diameter – deliver a flow rate between 0.3 μL min^{-1} and 8 mL min^{-1} with a repeatability of 0.2%. By using the automation-friendly SiLA 2 standard as programming interface, the pump is easy to integrate into state-of-the-art digitally driven setups.

The pump is built from 3D-printed parts as well as standardized off-the-shelf components and can be built without requiring any specialized tools. Its design, including the CAD files, bill-of-materials (BOM) and build instructions, are released under a permissive Creative Commons Attribution 4.0 International license (CC BY), while the software is published under a comparably permissive Apache 2.0 license, enabling users to easily adjust everything according to their specific needs.§ A price of around 280 USD, one order less than comparable commercial products, makes it feasible to utilize multiple devices on the same setup or across different ones. In combination with the pump's precision and versatility this results in an attractive and accessible solution for the complex liquid handling tasks associated with automated setups and self-driving laboratories.

2. Design

The proposed peristaltic pump features fully independent channels and a tool-less quick-change cassette system, providing a capable and cost-efficient liquid handling solution that closes the functionality gap between open-source and commercial designs. This section will go over the different aspects of its design and explain the considerations behind it.

2.1. Overview and general design considerations

Fig. 1 depicts the pump and gives an overview of its major components. Generally, the pump itself provides four fully independent pump channels. All the electronics and mechanics powering these channels are fully integrated into the pump. Each channel is then completed by an easily exchangeable cassette.

These cassettes secure the tubes to the pump in the proper position, pushing them into the rollers. A latch firmly attaches the cassettes to the pump, where the pressure acting on the tube can be adjusted through an integrated compliant mechanism.

The channels themselves consist of four identical rotors, mounted on one shared axle, each driven by an individual stepper motor. Synchronous belts connect the motors to their respective rotors, forming a reduction stage that decreases the rotation speed between the motor and the rotors, increasing the provided torque and accuracy. The positions of the motors are stacked to achieve an overall compact design, resulting in a footprint of 126 mm by 146 mm, a height of 261 mm including the cassettes and a total weight of 3.8 kg. The design allows for multiple pumps to be placed right next to each other, allowing for compact and tightly integrated setups with up to 32 independent pump channels for each meter of space available.

The compact size of the pump also includes all the necessary electronics. Besides a control board with integrated stepper motor drivers and a microcontroller running a custom firmware for the low-level control of the pump, this also includes a Raspberry Pi single board computer hosting the user-facing SiLA 2 interface.

‡ *E.g.* Watson Marlow 205, Ismatec Masterflex, Heidolph hei-FLOW

§ Both the CC BY and the Apache 2.0 license allow unrestricted commercial use of both the original work as well as modified versions of them, as long as proper attribution is given. They are also both fully compatible with the popular GNU GPL v3 license.

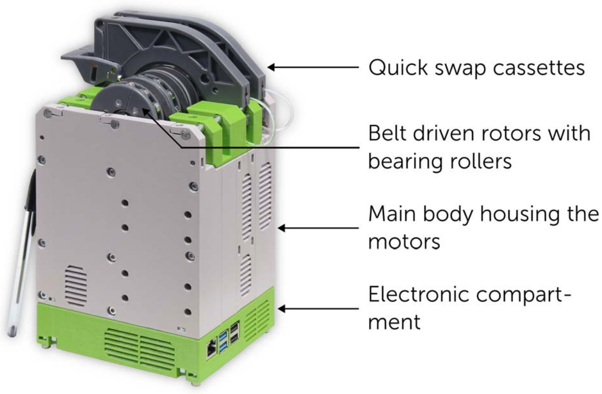

Fig. 1 Photograph of the assembled pump with labels pointing to the major components. The pen on the left is intended to provide a sense of scale.

Throughout the entire development emphasis was placed on proving a design that is cost-effective, accessible and can easily be replicated even by inexperienced users. All individual parts are either 3D-printed or commonly available off-the-shelf components. Assembling the pump does not require any special tools or machines and is laid out in a detailed build guide. To actually build the pump, a detailed bill-of-materials including cost estimates as well as the CAD-files including assemblies and readily exported STL-files of the printed parts are provided alongside this paper in Zenodo repository[16] under a CC BY license. In addition to that, the full software stack is available in another Zenodo repository,[17] published under an Apache 2.0 license. In there, also further documentation regarding setting up the different software components and on how to calibrate the flow rate is also available.

2.2. Mechanical design

The entire pump is built out of 3D-printed parts and readily available off-the-shelf components. The latter category includes standardized hardware for fasteners like nuts and bolts as well as functional parts like bearings, shafts, motors and belts. A detailed list of all these parts including the required quantities and price estimates can be found in the BOM.

Regarding the printed parts, two different printing techniques are utilized. For the cassettes, belt idlers, rotors and motor mounts, where higher precision and smaller feature sizes are required, resin printing (mSLA/SLA, (masked) selective laser annealing) is utilized. All other parts, including the pump's main body, are printed with the simpler and less labor-intensive filament-based printing process (FFF, fused filament fabrication). For the resin-printed parts a resin with a good ductility and low brittleness, often marketed under the term “ABS-like”, should be used, while for the filament printed parts any common non-flexible material like PETG or ABS is sufficient. The specific list of printed parts including recommended print settings can be found in the printed part sections in the BOM.

The physically largest part on this list are the four sections that together create the pump's main body. They form the structural backbone of the pump, onto which all the other components and subassemblies are attached. Additionally, they also enclose these components, protecting the internal mechanical and electronic parts from their surroundings. Down- and outwards facing slits in this cover avoid liquid ingress while letting all the heat generated by the motors escape freely.

Removing the outer section of the main body reveals the alignment of the pump's internal mechanical components. Fig. 2 shows a picture of the pump in this stage.

Starting at the top of this image, one can see one of the four rotors in dark grey. These rotors are running independently of each other on a common 8 mm hardened steel axle. A close-up image of one such rotor is depicted in Fig. 3. Each roller consists of two sections with the first one containing the rollers in the form of twelve miniature ball bearings. The bearings run on 5 mm steel pins, have an outer diameter of 11 mm and a height of 5 mm. The maximum supported outer tubing diameter of 3 mm is a direct consequence of this height, providing a compromise between a compatibility with larger tubes and a compact (axial) size of the rotors and therefore the entire pump. The circumference of the rotors, and therefore the number of individual rollers they hold, is a direct consequence of the standardized 72 mm long distance between the stoppers of the 3-stop peristaltic tubing.

The torque to turn the rotor underneath this tubing is provided *via* the second section of the rotor, where a GT2 pulley with 92 teeth is directly integrated into the part. Through this pulley, a belt with a width of up to 9 mm connects each rotor to

Fig. 2 Photo of the pump with the outer part of the main body and the electronic compartment removed to show the internal alignment of the motors, belt and idlers.

Fig. 3 Close-up picture of a rotor with the bearing rollers at the bottom and the pulley at the top. The SD card is intended to provide a sense of scale.

its respective stepper motor. Two idlers on each belt guide them downwards, where they are routed over an off-the-shelf metal pulley with 20 teeth mounted on the motor shaft. The resulting reduction of 1:4.6 is a compromise between achieving faster maximum pumping speeds and higher torques required for larger tube diameters.

Each motor position can be adjusted vertically by 10 mm to tension the belts. Located below the rotors, the motors are staggered both vertically and horizontally, as it can be seen in Fig. 2. With even a short motor being significantly longer than the width of a single rotor, these staggered positions enable the pump's compact length and ensure compatibility with NEMA 17 stepper motors with a length of up to 60 mm. The arrangement avoids complicated belt paths and makes it possible to place multiple pump units directly next to each other.

Further down below the main body of the pump is an additional compartment that houses the electronic components, making them easily accessible from the underside of the pump. Opposite to that, on top of the main body, two additional printed parts ensure the correct axial alignment of the cassettes. Two 8 mm steel rods identical to the rotor axle run parallely through these alignment parts to provide the mounting interface for the cassettes. The mounting mechanism that secures the cassettes to the pump unit can be seen in the side-view of a cassette provided in Fig. 4a.

When a cassette is attached to the pump, the small semicircular slot on the bottom right side in the image sits on one of these outer rods, while the latching mechanism on the left locks onto the other rod. To disengage the latch, the lever on the left side is pulled in the upper position as depicted in Fig. 4b. This way, the cassette can then be rotated upwards around the first rod in the semicircular slot and be pulled away from the pump once the opening of the slot is facing downwards. To install a cassette, these steps are simply repeated in reverse order.

We employed such a latch mechanism in the cassette's design, as it – compared to the screw-based fastening methods – allows to easily install and remove the cassette without the need for any tools. This enables novice and non-expert users to trivially change cassettes and tubes. We verified this by letting ten people, who previously never used the pump, install and remove a tube in a cassette and the cassette in the pump. All participants were able to do so after only a brief verbal introduction

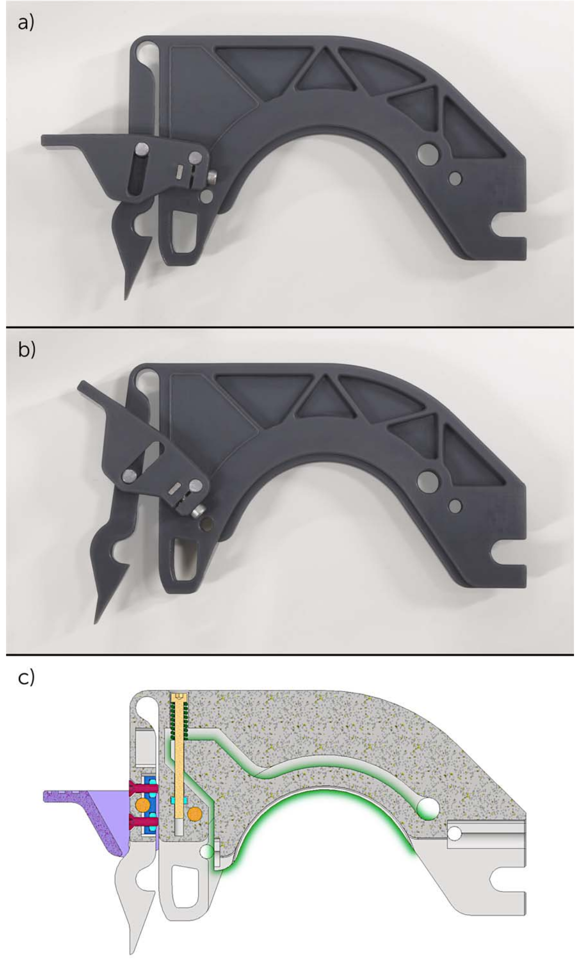

Fig. 4 Photographs of the cassette showcasing their general design including the latch mechanism in an closed (a) and open (b) position, as well as a cross-section of the cassette depicting the fully integrated tension mechanism (c). The green spring pushes downwards on the highlighted section of the cassette, pushing that section against the pneumatic tubing and the pump's rollers.

lasting about 2 min. On average, they required 30.2 s to perform this task compared to around 10 s for an already experienced user. Further details of this usability test can be found in the third section of the SI.

Apart from the latch mechanism, the pump is resin-printed as a monolithic part. The ribs in the upper part are intended to stiffen out the cassettes while reducing the amount of resin required to print them. With the cassettes being made from just printed parts and a few fasteners, they only cost around 4 USD.¶

Regarding tubing, the cassettes are designed to be compatible with all commonly available 3-stop peristaltic tubing, also referred to as MS/CA tubing, up to an outer diameter of 3 mm. Following this well-established standard gives the user access to a wide range of tubing sizes and materials from different reputable manufacturers. Additionally, the stoppers of these

¶ A detailed breakdown of the cost of the individual parts can be found in the BOM.

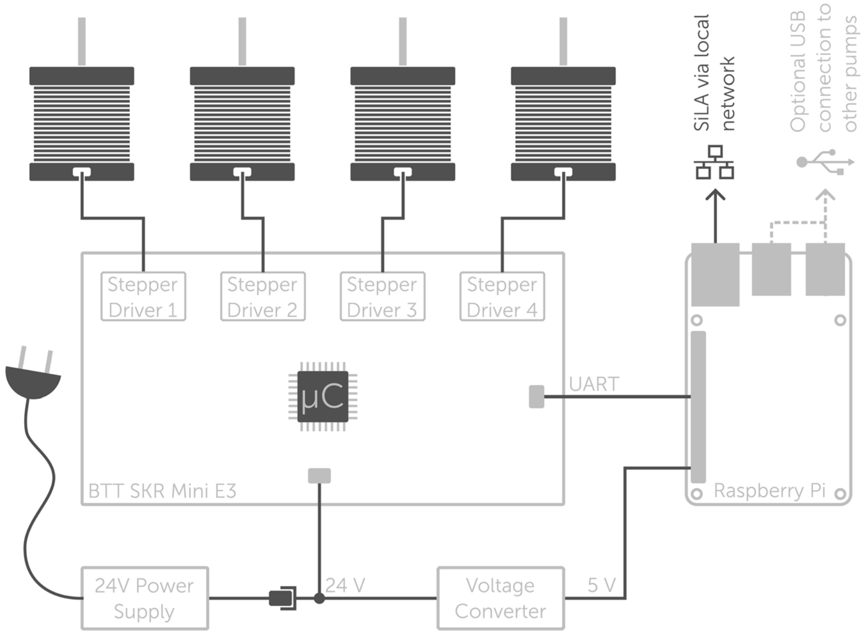

Fig. 5 Scheme of the pump's different electronic components and how they are connected.

peristaltic tubes make it easy to insert them into a cassette without requiring any tools. In the sideview of the cassette, these stoppers can be seen through two circular cutouts, showing the colors of the stops used by many manufactures to uniquely identify the different tubing variants available.

With the tube installed in the cassette and the cassette securely fastened to the pump, the tube is pushed by the pump's rollers against the arch shaped part of the cassette. As shown in the cross-section of the cassette in Fig. 4c, only the right end of this arch is connected to the rest of the cassette. Its other side is pressed into the roller by a compression spring. As the arch section highlighted in green can slightly flex along its length, this always ensures a good and reliable fit between the rollers and the cassette. To accommodate different tubing thicknesses and materials, the pretension of this spring and therefore the entire arch can be varied by adjusting a bolt accessible through the top of the cassette.

2.3. Electrical design

As mentioned in the previous section, the electronics are housed in a compartment at the bottom of the pump. They consist of a microcontroller-board with integrated stepper drivers, a Raspberry Pi single board computer and a step-down voltage converter. They are powered with 24 V supplied by an external power brick. Fig. 5 schematically shows how those components are connected to each other. It should be noted that not every pump necessarily needs to have its own single board computer, with one Raspberry Pi being able to control multiple neighboring pumps that then do not require a Pi on their own.‖

‖ Compared to a pump that does use its own single board computer, building one without one requires less wiring work and results in a cost reduction of approximately 50 USD.

In general, the idea behind the electrical design is to keep everything simple in order to achieve a robust and accessible design. We tried to minimize the required wiring work, choose widely available components and kept everything modular so that user can easily change out components for different ones they prefer or in case that the originally intended ones are no longer obtainable.

Starting with the power supply, an off-the-shelf 60 W 24 V power brick was chosen as it avoids any wiring work on the mains voltage side. This minimizes safety risks, makes the build feasible for non-experts and ensures regulatory compliance. The output barrel jack of the power supply is directly connected to the pump, where it internally splits up two ways: One side powers the Raspberry Pi running the SiLA server through a step-down-voltage converter, while the other side directly supplies the microcontroller-board.

For this, a control board for a Creality Ender 3, a common filament-based 3D-printer, is used. While there are multiple versions of Ender 3 boards with differing features available from different manufactures, they share common advantages. They are typically equipped with four integrated stepper motor drivers, are cheap and widely available, feature a compact board size and usually come preflashed with bootloaders such that users can easily install (custom) firmware on them. Also, with most NEMA 17 stepper motors equipped with a JST XH style connector, it is possible to plug them into these boards without requiring any wiring work.

As default option for the pump's control board, we choose the BIGTREETECH SKR Mini E3 V3.0 due to its availability, price and the embedded silent TMC2209 stepper motor drivers. Our firmware though is written in such a way that it supports many common microcontrollers, providing the option to also use other control boards.

In the default case with both a single board computer and the control board present, communication between the two is achieved through a serial UART interface. In case no Raspberry Pi is present in a pump unit, its printer board can be connected to the Pi in a neighboring pump with an USB cable. For this purpose, both the Raspberry Pi and the microcontroller board are mounted in such a way, that their USB ports are accessible from the outside. This is also the case for the Pi's Ethernet port as it is used to connect the SiLA 2 server to the local network. Alternatively, for newer models of the Raspberry Pi with a build-in wifi-chip, it is also possible to connect them to the network wirelessly.

2.4. Design of the software

The developed software stack consists of three main parts: a firmware for the microcontroller on the printer control board, a Python interface providing access to the pump's functionality and managing the serial communication with the microcontroller, and a SiLA 2 HTTPS-server as a wrapper around the Python interface providing network access to the pump.

Together, they allow the user to either dispense a predefined volume or to let the pump run continuously. In addition to that, it is possible to change the pump's flow rate or rotational speed, change the direction of the flow, pause and resume pump operations, and enable or disable the individual motors.

All source code is provided in the project's Zenodo software repository.[17] It also contains a detailed and illustrated setup guide, leading users through the process of setting up the entire software stack, including the use of a SiLA client[18] to interact with the pump. Precompiled binaries for the firmware as well as a preconfigured system image for the Raspberry Pi are also available, vastly simplifying the setup process.

2.4.1. Microcontroller firmware. We developed the firmware specifically for the printer control board used in the pump, namely a BIGTREETECH SKR MINI E3 V3.0 featuring a STM32G0 microcontroller.** Alongside the source code for this firmware we also provide ready-made binaries for this platform, enabling users to program this board without the need to interact with any form of source code.

Architecture-wise, the major challenge associated with a multi-channel pump lies in maintaining concurrent yet precise step timings for four different motors while at the same time communicating with the single-board computer over a serial interface. This is overcome by limiting the size of all individual communication messages to 6 bytes, hence minimizing the disruptions to the time-critical step generation. In each message, a 1 byte checksum is included to validate the transmitted information. Additionally, each command to the pump is acknowledged by the microcontroller, ensuring reliable communication.

2.4.2. Python interface. Thanks to the vast number of open-source libraries, ease of syntax, and cross-platform support, Python is one of the most popular programming languages in the context of laboratory automation. Therefore, a comprehensive yet lightweight interface to control the pump was developed in Python, with only minimal external library dependencies (NumPy and pySerial) to ensure lasting compatibility over the coming years.

The task of this code is, on one side, to communicate with the firmware running on a microcontroller through a serial interface. In addition to that, it provides a high-level interface, hiding the details of this communication and the necessary conversions. The library also supports event-based callbacks, for example, when a target volume is reached, removing the need to continuously query the current state of the pump.

Especially with automated and parallel experiments where multiple pumps are being integrated in the same SDL, it is necessary to concurrently run and orchestrate multiple devices. The Python interface supports the control of multiple pumps, with all commands being able to be executed in a blocking or non-blocking manner. Additionally, it was also ensured that the entire program is thread-safe, such that even with simultaneous calls to the same pump, only one command is executed at a time.

Typically, the user only interacts with the SiLA server, which then calls the corresponding functions within the Python library. With it acting as an interface and an abstraction layer, it is also possible for the user to control the pump directly through the Python program, enabling full control over the pump while bypassing the SiLA server. Especially for smaller and less complex setups, this provides the user with more flexibility when it comes to integrating the pump into an (existing) software stack.

2.4.3. SiLa integration. SiLA 2 [19,20] is an open-source standard that aims to tackle some of the key challenges in laboratory operation, namely providing means of standardized communication to devices, interoperability and IT security. SiLA acts as an additional software layer wrapping around the actual device software and supports multiple common programming languages.

We therefore developed such a SiLA 2 wrapper in Python, covering nearly all the features supported by the pump's previously discussed Python interface. With the pump's Raspberry Pi acting as a SiLA 2 device server, the pump can be easily integrated into automation workflows over the network through Ethernet or a wireless network connection.

Besides the programming interfaces for SiLA enabled devices, non-coder scientists also have the possibility to use universal SiLA user interfaces,[18,21,22] allowing them to control the pump's functionality simply through a web browser.

While the SiLa 2 interface is not strictly necessary to operate our pump, it does enable a hardware-agnostic standardization of the communication with different laboratory devices and inherently includes modern features such as encrypted communication, accessing devices over the network and easy scaling when it comes to adding new devices. Moreover, while these benefits bring along additional complexity in the software stack, we believe this trade-off is well worth the additional

** We also developed additional versions of the firmware that are compatible with Arduino environment and both initial generations of Raspberry Pi Picos. While these versions can also be found in our software repository, those are not intended to be used for this peristaltic pump.

effort, especially in the context of increasingly more complex, automated and digital setups.

3. Performance

We measured the flow rate of the pump for all four pumping channels and for different rotation speeds between 0.1 and 100 rpm. Based on this we derived the pump's repeatability and how the delivered flow rate scales with the rotation speed. Before presenting these performance characteristics, the following section first introduces the measurement setup we used to obtain the results.

Finally, we also performed a durability test with the pump and the cassette to show their reliability. There, they were running for a total of 300 operating hours and were subjected to 800 opening and closing cycles of the locking mechanism, both without causing any fatigue or issues, proofing the long-term viability of our design for automated research setups. The description of this test and its results can be found in the first section of the SI.

3.1. Gravimetric measurement setup

Generally, we determined the flow rate by pumping water from one reservoir into the other one and observing the weight change of the second reservoirs as it is filled. To do this, we place this reservoir on a laboratory balance (Mettler-Toledo XPR106DUH). The reservoir, depicted in Fig. 6, was designed specifically to ensure that we only measure the weight difference caused by the changing amount of liquid in the reservoir. It has a volume of around 1.7 mL and is made from a piece of silicone tubing held in a flat spiral shape by a 3D-printed part. The outer end of the tube extends beyond the printed part and is directly connected to the pump while the inner end curls upwards and remains open.

Using the tube itself as reservoir avoids the possibly inconsistent process of droplet formation as the liquid drips from a tube into an open container. Furthermore, the small opening of the tube also minimizes the effects of liquid evaporation compared to an open container like a beaker. At the filling level used to measure the smaller flow rates, our approach showed a 2.9 to 63 times lower evaporation rate compared to three different open containers. The details of this measurement can be found in the second section of the SI.

Fig. 6 Photo of the spiral reservoir. The changing weight of this reservoir is tracked during the gravimetric measurements. The SD card is intended to provide a sense of scale.

The challenge with this approach lies in the part of tube between the reservoir on the balance and the pump. To eliminate small movements of this tubing section and their influence on the weight measurement, this section is attached to a laboratory stand right outside the balance. The weight of this part of the tube and how much of it is carried by the balance, the laboratory stand and the pump is unknown and depends on the amount of liquid inside this section. By ensuring that the reservoir is at least 10% filled before each measurement, this section is always filled with liquid and its weight remains constant even as the reservoir fills up during a measurement. This way all the weight change observed is actually caused by the liquid added to the reservoir. The pump's flow rate itself is then obtained by dividing this weight difference by the density of the liquid and by the time the pump was in motion.

3.2. Repeatability

To determine the repeatability of the pump's flow rate, the measurement outlined in the previous section is repeated six times for each channel with identical pump settings.

Using a PVC tube featuring an inner diameter of 0.38 mm (PerkinElmer N8145148), 100 rotations of the rotors filled the reservoir from roughly 10% before each measurement to a fill level of around 95% afterwards. The pump was running at a speed of 31 rpm and the calculated flow rates are based on a density of 0.989 g mL^{-1}. This density was measured at room temperature of 20.8 °C with a manual pipette (BRAND 705880) calibrated directly before the measurement with the same balance used to track the weight of the reservoir throughout the measurements.††

Table 1 shows the results of these measurements. Across all four channels an average flow rate of 540.3 μL min^{-1} was recorded. The channel deviated a maximum of 1.9 μL min^{-1} or 0.35% from this average, while the flow rates within each channel have standard deviations of up to 1.1 μL min^{-1}, corresponding to 0.20% of the measured flow rate.

Repeating the measurement performed on channel one while reseating the cassette in between every individual measurement resulted in a decrease in the flow rate by 0.2 μL min^{-1} with the repeatability remaining at ±1.0 μL min^{-1} or 0.18%.

3.3. Linearity

In addition to the 0.38 mm tube already used for the repeatability measurements also a Tygon tube with an inner diameter of 0.13 mm (Saint Gobain Life Sciences 070535-00-ND) and one made from PVC with an internal diameter of 1.02 mm (Agilent 5005-0020) were used for the linearity measurements. These additional tubes represent the smallest one commonly available as well as the biggest one supported by the pump.

†† We measured the density of the liquid instead of using the literature value for the density of water because ink was added to water in order to improve the visibility of the liquid column in the reservoir.

Table 1 Flow rates and their corresponding repeatability achieved across the pump's four channels. The pump was running at a rotation speed of 31 rpm while using a peristaltic tube with an inner diameter of 0.38 mm

Channel	Measured flow rate	Relative repeatability	Relative deviation from average of all channels
Channel 1	(538.6 ± 1.0) μL min^{-1}	0.18%	−0.32%
Channel 2	(542.2 ± 0.9) μL min^{-1}	0.17%	+0.35%
Channel 3	(539.4 ± 1.1) μL min^{-1}	0.20%	−0.18%
Channel 4	(541.1 ± 0.7) μL min^{-1}	0.14%	+0.15%

For the higher rotation speeds of 10 rpm and above, the measurement was based on adding and removing around 1 mL of fluid from the reservoir. For the remaining lower rotations speeds the pump always moved 10 rotations even though this results in different amounts of fluid transported across the three tube sizes. This was done to limit the duration of the individual measurement both due to practicability and avoiding the influence of long-term drifts of the balance.

The weight difference was recorded for both emptying and filling the reservoir. The flow rates presented here are the average of both flow directions.

Fig. 7 shows the result of the flow rate measurements for the different peristaltic tubes and rotation speeds. The flow rates range from 0.34 μL min^{-1} achieved by the tube with an internal diameter of 0.13 mm at a rotation speed of 0.1 rpm to 8.2 mL min^{-1} based on a rotation speed of 100 rpm in combination with the 1.02 mm inner diameter tube.‡‡ Generally, within the same tube, the flow rate scales proportionally with the pump's rotational speed.

Linear functions were fitted to the data points to emphasize this relationship. In Fig. 7 they are represented as dashed lines. They have the form $f = a \cdot \omega$, where f and ω represent the flow rate and the pump's rotational speed. Each tubing sizes was fitted separately through parameter a, where we obtained values of 3.15, 18.1 and 87.3 μL per revolution of the rotor for the three tubes.

Averaging over the entire range of pumping speeds, the measured flow rates deviated from the expected linear relationship by 2.5% for the 0.13 mm tube, by 1.5% for the 0.38 mm tube and by 1.6% for the 1.02 mm one. When only the more common range from 5 to 50 rpm is considered, these deviations decrease to 0.6%, 0.6% and 0.7% respectively. With the flow rate delivered by a tube at 50 rpm already being greater than the one delivered by

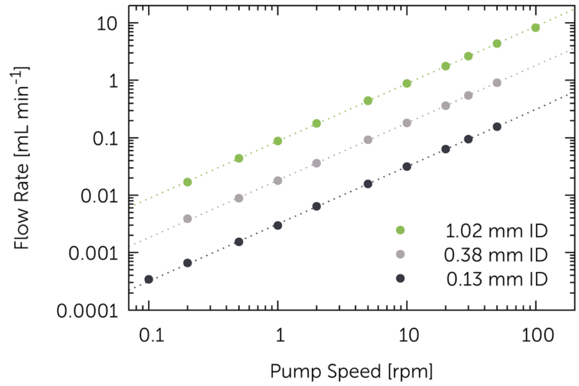

Fig. 7 Measured flow rate of the pump across different rotation speed and sizes of peristaltic tubes. The dashed lines represent linear functions without vertical offset, that were fitted to the measurements.

the next larger one at 5 rpm, the pump is still able to deliver all flow rates between 16 μL min^{-1} to 4.3 mL min^{-1} within this range across the three tubing sizes used here.

4. Discussion

Precise and well-defined liquid control plays a fundamental role across diverse research fields, including chemistry, materials science, microfluidics, biology, and medicine. In these domains, liquid handling tools are essential for experimental workflows, enabling the accurate mixing and transfer of reactants and solutions. They also allow seamless and flexible transport of liquids between different laboratory instruments such as stirrers, heaters, reactors, coating devices and characterization tools. By linking these various laboratory devices and experimental stages, liquid handling systems act as key enablers in automating such measurement setups.

Commercial liquid handling systems offer a pathway to automation but often come with high costs and limited adaptability. The increasing popularity of the maker movement in recent years has led to the development of different open-source projects, providing more flexible and cost-effective alternatives. Those include all different kinds of liquid handling solutions, which, besides the already mentioned peristaltic pumps,[10–15] also include automated pipettes,[24–27] pressure pumps,[28,29] syringe pumps,[30–32] liquid dispensers,[33] full liquid handling workstations[34–37] as well as proposals where robot arms handle liquids by pouring them with regular laboratory glassware.[38,39]

The pump presented in this work expands the repertoire of open-source liquid handling solutions, offering a versatile and scalable option for automated setups that require multiple independent peristaltic pumping channels. With its intended use case, it is not suitable for applications better served by different liquid handling techniques, coming with their own set of capabilities, advantages and limitations.

To provide some context for the design we developed, we therefore choose to focus solely on other open-source and commercial peristaltic pumps and asses their performance relative to our system. An overview, over these other peristaltic

‡‡ It should be noted though, that we measured an evaporation rate of 0.049 μL min^{-1} for our spiral tube reservoir at the same fill level that were used to measure the lowest flow rates with the 0.13 mm tube and rotations speeds of below 10 rpm. This evaporation rate corresponds to around 14% of the lowest observed flow, limiting the quantitative accuracy of the lower flower rates reported here. It should be noted though, that by averaging over the filling and the emptying of the reservoir, the influnce of the evaporation is further reduced and should in practice actually be significantly lower than this value.

Table 2 Comparison of the technical specifications of our design against similar commercial and open-source peristaltic pump designs

	This work	**Ismatec Reglo ICC - 12 roller** model[23]	**Fast pump** Jönsson *et al.*[10]	**User-centric 3D-printed mod. peristaltic pump** Cataño *et al.*[13]	**Customizable 3D-printed peristaltic pump kit** Ching *et al.*[11]
Min. flow rate [μL $\min^{-1}$]	0.33	0.1	0.7	3.58	0.022
Max. flow rate [mL $\min^{-1}$]	8.2	24	6	1.75	0.73
Repeatability / accuracy	0.2%^{a} / 0.4%^{b}	1% tot. acc.	0.15%^{a} / 1.5%^{b}	0.9%^{b}	5%^{b}
Total channels	4	Up to 4	8	3	Up to 4
Independent channels	4	Up to 4	1	1	1
Quick-swap cassettes	✓	✓	✗	✗	✗
Same hardware usable for all tube sizes	✓	✓	✗	✓	✗
Open-source hardware	✓ *CC BY*	✗	✓ *GPL v3*	✗	✓ *CC BY-SA*
Open-source software	✓ *Apache 2.0*	✗	✗	✗	✓ *CC BY-SA*
Price [USD]	280	Up to 5730	360	175	50

Values marked with *a* describe the repeatability within one channel, while those marked with *b* describe the repeatability across different channels. If multiple repeatability values for different rotation speeds or different tubes were provided, the best option was used in this comparison.

pumps,[10,11,13,23] their key technical specifications and how they compare with our design can be found in Table 2. In there, a clear feature discrepancy between the commercial option and the other open-source designs can be seen.

The general goal of our design was to close this gap and develop a pump that is specifically suited for automated setups with complex liquid handling task requiring multiple independently controlled flow paths.

The most important features in this regard are the four independently controlled channels. All open-source peristaltic pumps previously published offer only one single channel or interdependent channels driven one common motor. With our design each channel has its own rotor, each powered by an individual motor, offering a great advantage regarding capabilities, versatility and flexibility. Another novelty in an open-source design is the cassette system that allows tubes to be changed quickly and without requiring any tools, greatly enhancing the general usability and serviceability. While common in commercial pumps, such a system was not yet implemented in an open-source design. Instead, for those the pump usually needs to be partially disassembled in order to access the tubing, where different tube sizes often even require hardware changes within the pump. With our pump all supported tubes, as in 3-stop tubes with an outer diameter of up to 3 mm, can be used with the same cassettes. With this we can achieve wider ranges of flow rates than the designs from Jönsson *et al.* and Cataño *et al.*,[10,13] with the pump from Ching *et al.*[11] specifically designed for microfluidic applications achieving an order of magnitude lower flow rates. Beyond that, in regards to the repeatability and the linearity across different rotation speeds as well as concerning the price point, our design can compete with or surpass the performance of those other pumps.

It should be noted that due to the independent channels, the cassette system and the integrated electronics, our pump is significantly larger and heavier than those other projects, possibly limiting the usability in space-constrained environments. Unlike the design by Cataño *et al.*[13] our pump also doesn't feature a built-in user interface and can therefore not be operated directly on the unit itself. And while the pump is designed from the ground up to be built by the user without any prior experience or special tools required, our build process is more involved than that of the other DIY options. In contrast to these other designs ours requires both resin and filament printed parts, which could act as an entry barrier to some users.

But even with these limitations of our design, we are nonetheless confident that our pump offers a capable, accessible and affordable liquid handling option specifically designed for automated setups. With the independent channels and the quick-swap cassette system we bring features that can so far only be found on commercial offerings into an open-source project, closing the gap between these closed-source products and their DIY counterparts.

Regarding these commercial options, there are lots of different pumps available for all kinds of different applications and use-cases. We choose Ismatec's Reglo ICC product line for a closer comparison, as they have similar features to our pump, using the same 3-stop tubing and a quick-swap cassette system for the up to four independent channels.

The biggest difference lies in the general industrial design and the price point of multiple thousand dollars associated with a closed-source commercial product compared to our budget- and DIY-friendly design that's intended to be built by users without the need for special tools or parts. For once, this allows a user to adapt our design to their own requirements and needs. Additionally, for the same budget, it also allows them to implement significantly more independently controlled pump channels and all the capabilities they open up, even when considering the time necessary to source and build our pump.

Generally, both pumps deliver an overall similar performance, with the Ismatec being able to deliver a higher flow rate due to supporting tubes with an outer diameter of up to 5 mm, while our design supports up to 3 mm. This can limit our pumps usability for applications that require high flow rates, like bioreactors. This trade-off was made to reduce the footprint of the pump as well as due to the limited availability of wider bearings that would be required for the wider rollers necessary for supporting larger diameter tubes.

To control the pump, Ismatec offers both a user-interface built directly into the pump as well as a serial interface for remote operations. While our pump lacks such build-in controls, we also support a serial connection through the previously described Python interface in addition to the capable SiLA 2 interface. This makes the pump accessible over the network, offers both browser-based graphical user interfaces as well as connections for most common programming languages and is directly compatible with some laboratory-device management software[22,40,41] and SDL orchestrators.[42] Additionally, its also possible to easily integrate our pump into many of the recently emerging modular automation platforms.[43–45] Even with them not directly supporting SiLA devices, its easy to integrate such devices like our pump due to the capable programming interfaces provided within the SiLA ecosystem.

This allows for effortless integration into modern data-driven laboratory ecosystems utilizing simulation-driven workflows, machine-learning and AI based decision-making, iterative closed-feedback protocols, and autonomous exploration. The built-in networking capabilities of this hardware-agnostic and modular interface also enable trivial scaling as the amount of required pumping channels within a setup changes and makes the pump well suited for remote- and cloud-accessible laboratories.

Finally, compared to Ismatec's four channel variant (MLX78001-82), our pump has a 32% smaller footprint, which in combination with a more optimized cable placement allows for around twice the amount of independently controlled fluid lines within the same space.

When looking at other commercial offerings besides those from Ismatec our pump compares equally well, with again similar advantages and drawbacks. We are convinced, that our pump is able to bridge the current feature gap between commercial peristaltic pumps and their open-source counter parts and that it is a highly capable yet cost-efficient tool for the liquid-handling challenges of modern automated and data-driven material research.

5. Conclusion

We developed a cost-efficient peristaltic pump that bridges the gap between commercial offerings and other open-source projects. It is designed from the ground up with modern automated and digitally driven setups in mind, featuring four fully independent pumping channels as well as quick-swap cassettes that are compatible with all commercial 3-stop peristaltic tubes up to an outer diameter of 3 mm. It can easily be built for around 280 USD with only 3D-printed parts and off-the-shelf hardware components. The entire design, documentation and manuals are published under a CC BY license, while the full software stack is released under an Apache 2.0 license.

To characterize the pump's flow rates, we used a custom gravimetric measurement setup. Across the entire range of supported tube diameters and rotation speeds from 0.1 rpm to 100 rpm the pump is able to deliver flow rates from 0.3 $\mu L\ min^{-1}$ to 8 $mL\ min^{-1}$. We furthermore found the flow rate to be repeatable within 0.2% for each channel individually and a general repeatability of 0.4% across different channels.

With its capable SiLA 2 interface, the possibility to easily combine multiple pumps and the inherent benefits and flexibility of independently controlled channels, this pump offers the complex liquid handling capabilities often required in highly automated data-driven setups. This makes it possible to power elaborate microfluidic devices including organ-on-chip systems or to easily select, dose and combine different solutions or reactants, enabling the creation of large material libraries and the investigation of high-dimensional composition spaces. In addition to accessing various solutions this can also be used to connect multiple reactors or characterization devices within one setup. Such non-trivial non-linear fluid paths can improve the utilization of expensive measurement equipment, increase a setup's throughput, allow hardware-level redundancies and enable highly parallelized experiments. At a fraction of the cost of comparable commercial offerings it can be an affordable solution for personalized medical devices, used in an education context or become a part of a frugal twin.[46] In combination with the option to easily adapt and modify the design, our pump is a vital tool to expand the accessibility and capabilities of high-throughput setups, self-driving laboratories and other sophisticated automated liquid handling workflows.

Author contributions

Buchhorn: conceptualization, methodology, writing – original draft, writing – review and editing, Akkoc: software, writing – original draft, writing – review and editing, Dworschak: supervision, writing – review and editing, funding acquisition.

Conflicts of interest

There are no conflicts to declare.

Data availability

The software for the pump can be found at **https://github.com/gunakkoc/HiPeristaltic** with **https://doi.org/10.5281/zenodo.15001197**. At the time of submission version 1.1.02 was the latest version. The full CAD model of the pump as well as exported STL-files for the printed parts, the bill-of-materials and detailed build instructions can be found at **https://doi.org/10.5281/zenodo.15223798**. The same repository also includes the data of the measurements shown in the submitted manuscript and the SI. See DOI: **https://doi.org/10.1039/d5dd00157a**.

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