

# An Open-Source Platform Enabling Continuous, Low-Flow Control for Long-Term Operation in Biotechnology Systems

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## Article

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# Abstract

Precise, programmable control of fluid flow over extended periods is essential for biotechnology applications, including continuous microbial culture, organ-on-chip systems, and dynamic cell-signaling experiments. Here, we introduce an open-source platform that enables continuous, low-flow control and long-term operation in biotechnology setups. The platform integrates hardware, firmware, and software into a unified system that allows users to define, execute, and adjust programmable flow behaviors. A reconfigurable pumping module supports two operating modes: continuous-motor operation for stable medium-to-high flow rates ( $> 85 \mu\text{L}/\text{min}$ ) and positional-motor operation for low-flow conditions ( $1.5\text{--}85 \mu\text{L}/\text{min}$ ), enabling compatibility with microfluidic applications. An integrated graphical user interface supports constant, pulsed, and oscillatory flow profiles, scheduled experiments, and external control scripts. We validate the platform through flow characterization and long-term bacterial culture experiments in microfluidic chambers, demonstrating stable programmable operation at  $1.5 \mu\text{L}/\text{min}$  over multi-day periods.

## Introduction

Microfluidic and milli-fluidic platforms enable controlled investigation of biological systems by regulating the delivery of nutrients, signals, and environmental conditions. In these settings, fluid flow plays a central role in shaping system behavior over time, particularly in experiments spanning hours or days<sup>1–8</sup>. Many biological processes require not only stable flow conditions but also dynamic control, such as switching media, introducing perturbations, or applying dynamic input profiles<sup>9–11</sup>.

Despite this need, current approaches to fluid delivery introduce trade-offs between precision, continuous operation, and programmability. Conventional syringe pumps provide accurate low-flow delivery but require periodic manual refilling, which interrupts long-term experiments. In contrast, peristaltic pumps generate flow through cyclic compression of flexible tubing and enable continuous operation, but the discrete nature of the actuation introduces pulsatile flow and limits stability, particularly in low-flow regimes relevant to microfluidic applications<sup>12,13</sup>. Pressure-driven systems offer an alternative approach based on feedback-regulated flow control, but operate at higher flow rates than required for microfluidic applications<sup>14–16</sup>. Although specialized micropumps have been developed to operate in lower flow regimes, these systems frequently require complex fabrication processes, high operating voltages, or specialized equipment, limiting their accessibility and integration into standard laboratory workflows<sup>14,15</sup>.

Open-source efforts have significantly improved the accessibility of fluid delivery systems by introducing low-cost and customizable designs. Buchhorn et al<sup>17</sup> developed an open-source peristaltic pump with multiple independently controlled channels and an automation-friendly software interface, enabling continuous and parallel fluid handling; however, the peristaltic mechanism introduces pulsatile flow and limits precision and stability in low-flow regimes, which are required for many microfluidic applications. Wijnen et al<sup>18</sup> demonstrated that syringe pumps can be fabricated using 3D-printed components and

readily available electronics, thereby substantially reducing costs and enabling broad adoption. However, these systems rely on single-syringe operation and require manual refilling, interrupting long-term experiments. To overcome this limitation, Lannone et al.<sup>19</sup> introduced a dual-syringe (push–pull) architecture that enables uninterrupted flow through coordinated actuation and valve switching, but the control structure is primarily focused on maintaining continuous delivery rather than supporting flexible definition and scheduling of flow profiles. More recently, Czech et al.<sup>20</sup> presented a multi-channel syringe pump platform with programmable microcontroller-based control, enabling parallelized operation across multiple channels. However, control is largely defined at the individual channel level without an integrated framework for coordinating experiment-level flow behaviors. Together, these systems demonstrate important advances in cost reduction, continuous operation, and automation, but do not simultaneously provide continuous operation, precise low-flow performance, and a unified control framework that supports real-time interaction, preprogrammed execution, and multiple flow behaviors.

To address these limitations, we developed a low-cost, open-source platform for continuous and dynamically controlled fluid delivery in long-term biotechnology experiments. The platform is structured as a layered architecture enabling flexible specification and adjustment of flow conditions over time. Built from 3D-printed components, an Arduino-based controller, and widely available fluidic and electronic parts, the platform is designed to be easily fabricated and adapted, with a total cost of approximately \$500. As illustrated in Fig. 1, the platform is organized around three complementary layers: hardware, firmware, and software. At the hardware level, the system is modular and reconfigurable, allowing different fluidic configurations to be assembled and adapted to specific experimental needs. At the firmware level, the platform is open-source, enabling users to modify the control logic and extend system functionality. At the software level, the system provides a unified interface for defining and executing flow behaviors over time. Together, these components form a customizable platform that defines and controls fluid delivery through integrated hardware and software. This structure enables precise specification and modification of flow conditions across diverse experimental configurations.

## Results

### Hardware and Firmware Implementation

The platform is implemented using a dual-syringe pumping architecture that enables continuous, programmable fluid delivery. The system consists of two syringes, solenoid pinch valves for flow routing and rectification, a servo-driven actuation mechanism, and an Arduino-based microcontroller that coordinates system behavior. The mechanical structure of the pump is fabricated from 3D-printed components, and the system is assembled from readily available fluidic and electronic components, resulting in a total cost of approximately \$500 (as of today).

At the core of the design is an alternating dual-syringe mechanism in which the two syringes operate in complementary phases. To guide the development of this system, we analyzed different valving

architectures using analogies between electronic circuits and fluidic networks. This fluidic–electronic design framework helped define a dual-syringe valving strategy that enables uninterrupted operation by dynamically switching the functional roles of the two syringes (Fig. 2A).

Unlike conventional single-syringe systems, which must pause fluid delivery once the syringe is depleted and require refilling, the dual-syringe strategy enables simultaneous refilling and infusion. At any given time, one syringe is connected to the target and actively delivers fluid, whereas the other is connected to the source and refills. As the active syringe approaches depletion, the system switches valve states so that the refilled syringe takes over fluid delivery while the previously active syringe transitions to the refill phase.

A key feature of this architecture is that passive rectifying elements do not maintain the direction of flow; instead, they are coordinated by valve actuation. In other words, the flow path is explicitly defined at each stage of operation through active control of the fluidic network, ensuring that fluid is directed toward the target during syringe exchange. This coordinated switching maintains a continuous and well-defined flow path throughout operation, thereby enabling uninterrupted fluid delivery (Fig. 2).

In dual-syringe pumping systems, rectification can be achieved using either passive or active strategies. Passive rectification relies on check valves, which allow flow in one direction based on pressure-dependent behavior, while active rectification uses coordinated valve states to define flow direction during operation. These approaches represent different strategies for controlling fluid routing during alternating syringe actuation (Fig. 2B). In the present system, flow direction is explicitly defined by synchronized control of solenoid pinch valves, enabling deterministic fluid routing during both steady operation and switching events. As illustrated in Fig. 3, the configuration consists of three valves: two three-way pinch valves that control whether each syringe is connected to the source or the target, and one two-way valve placed in series to prevent unintended flow during switching events. During operation, the firmware coordinates valve states with motor actuation such that one syringe is always connected to the target while the other is connected to the source. During transitions, the two-way valve is briefly closed to block fluid pathways and eliminate crossflow between branches. This actively controlled rectification approach removes dependence on pressure thresholds and enables deterministic control over flow direction during operation and switching events.

Actuation of the syringes is achieved using a goBILDA 2000-series servo motor operating in continuous mode, which provides sufficient torque and controllability across a range of operating conditions. The Arduino-based controller executes firmware that synchronizes motor motion and valve switching, ensuring consistent system behavior and coordinated flow generation. This tight coupling between actuation and flow routing is critical for maintaining continuous operation and stable fluid delivery. In this configuration, the motor provides smooth, uninterrupted displacement of the syringe plunger, resulting in continuous flow over time (see Supplementary Information, Section S1, for Flow Rate Calculation). The mechanical assembly process is demonstrated in **Supplementary Movie 1**.

Because the platform is open-source, users can modify the firmware to implement custom control strategies, enabling the addition of new flow behaviors or experiment-specific logic. This flexibility allows the system to be adapted to a wide range of experimental requirements. In this work, we have added control logic to the firmware to enable multiple flow behaviors by modulating motor actuation, for example, by adjusting rotation speed and introducing time-dependent actuation patterns. Using this approach, the system can generate a variety of temporal flow profiles, including constant, pulsed, and oscillatory behaviors, without requiring changes to the physical configuration. These implementations demonstrate the flexibility of the control framework, which can be extended to define additional flow behaviors tailored to specific experimental needs.

## Software Control

The platform is controlled by a software layer that enables real-time interaction, automated experimentation, and integration with external algorithms. As illustrated in Fig. 4, the software communicates with the hardware via a unified control pathway, in which user-defined commands are transmitted to the microcontroller and executed through synchronized motor actuation and valve switching. All control modes share this common communication pathway, differing only in how commands are generated.

Communication between the software and hardware is implemented through a serial protocol over USB. Upon initialization, the microcontroller transmits a ready signal over the serial connection, after which the software begins issuing control commands. Commands are encoded as instruction strings and transmitted to the microcontroller, which parses and executes them. This unified communication structure ensures consistent system behavior while allowing flexibility in how commands are generated. The platform supports three modes of software control that differ in how commands are generated. In manual control mode, the user interacts directly with the graphical user interface to define flow conditions and adjust parameters in real time. In preprogrammed mode, the user defines time-resolved command sequences that are automatically executed by a scheduling engine, enabling unattended operation during extended experiments. In externally controlled mode, commands are generated programmatically by an external script, allowing integration with adaptive algorithms such as feedback control or machine learning-based optimization. All modes share the same execution pathway and firmware, differing only in the source of the command. The graphical user interface provides a centralized environment for configuring and monitoring experiments (see Section S5 for more details). Users can define flow parameters, select flow behaviors, and control pump operation through an intuitive layout. In addition to real-time control, the interface allows users to create and execute time-resolved experimental protocols by either uploading command files or constructing sequences through an interactive dialog. The scheduling engine manages execution timing while supporting pause, resume, and restart operations without disrupting relative timing. Operation of the graphical user interface is demonstrated in **Supplementary Movie 2**. The software also enables users to select and deploy different flow behaviors via a simple, flexible interface. As shown in Fig. 5, the system supports multiple

predefined flow profiles, including constant, pulsed, and oscillatory behaviors, which can be configured by adjusting the corresponding parameters. These behaviors can be applied in real time or incorporated into scheduled experiments, providing dynamic control over fluid delivery throughout the experiment.

## Reconfiguring the Pump for Low-Flow Operation

While the continuous-motor regime enables continuous flow at medium to high flow rates, it is fundamentally limited by the motor controller's velocity bounds. In continuous mode, the GoBilda 2000 Series Servo is driven by a pulse-width modulation (PWM) signal that maps to a finite range of rotational velocities. Below a certain command threshold, the motor cannot sustain reliable motion and either stalls or produces irregular behavior. As a result, there exists a lower bound on achievable flow rates in continuous operation, preventing access to the microliter-per-minute regime required for many microfluidic applications.

To overcome this limitation, the platform is reconfigured to operate in a positional-motor regime, where flow is generated through discrete angular steps rather than continuous rotation (Fig. 6A). In this mode, the motor is commanded to increment its position by small angular displacements, each corresponding to a fixed volume of fluid displaced by the syringe. By introducing controlled delays between successive position updates, the effective flow rate can be reduced independently of the motor's minimum continuous velocity. In this regime, flow is generated as a sequence of discrete volume increments separated by time intervals. If the time between successive increments exceeds this value, the flow no longer behaves as sufficiently continuous and instead results in periodic bolus delivery. Within this constraint, however, discrete actuation can approximate continuous flow, enabling operation in the low-flow regime.

Importantly, to evaluate the thermal stability of the pinch valve during prolonged operation, we conducted an independent test in which the valve was subjected to alternating ON–OFF cycles for at least 40 min while its temperature was continuously monitored. The results showed that the temperature increased initially, reached a steady-state plateau after approximately 15 min of operation, and remained stable thereafter, with no evidence of overheating under normal operating conditions (see SI Section S6 for additional details).

Direct measurement of such low flow rates using conventional flow sensors is challenging because the flow signal itself exhibits discrete spikes rather than a steady profile. As shown in Figs. 6A and 6B, the instantaneous flow rate exhibits periodic peaks associated with individual actuation events, making it challenging to infer a single effective flow rate directly. To address this, flow was quantified using an image-based method in which dyed fluid was infused into micro-bore tubing and tracked over time using edge detection (Section S8). Representative recordings used for this analysis are provided in **Supplementary Movies 3–7**. The extracted fluid position was converted to volume and differentiated to obtain the flow rate as a function of time, as illustrated in Fig. 6C. This approach allows the effective flow

rate to be determined from the average behavior over time, despite discrete fluctuations. Using a 10  $\mu\text{L}$  Hamilton syringe, the platform achieves flow rates as low as 1.5  $\mu\text{L}/\text{min}$ .

Overall, reconfiguring the platform to operate in positional-motor mode enables access to low flow rates that are not achievable in continuous operation. To evaluate the platform's applicability in a biological context, continuous culture experiments were performed in microfluidic devices with monolayer chambers. As shown in Fig. 6D, *Escherichia coli* cells remained viable and proliferated under continuous flow at 1.5  $\mu\text{L}/\text{min}$  over 24 hours. These results demonstrate that the generated flow is sufficiently stable to support long-term microfluidic culture.

## Discussion

This work introduces a low-cost (approximately \$500 as of today), open-source platform for programmable fluidic control that combines continuous operation with user-defined flow behaviors and straightforward integration into experimental setups. Existing fluid delivery solutions often lack adaptability, making it challenging to implement dynamic or time-dependent control within custom workflows. In contrast, the platform presented here enables users to define and execute a range of flow profiles, including constant, pulsed, and oscillatory behaviors, within a unified control framework. The system can be modified at both the hardware and software levels to accommodate different experimental requirements. This flexibility is further supported by the integration of complementary actuation regimes within the same architecture, enabling operation across a broad range of flow conditions without requiring hardware modification.

The platform is designed to operate across a range of flow conditions, enabling its use in both microfluidic and bioreactor-based setups. Low-flow operation supports applications such as microfluidic devices and monolayer chambers that require sustained, controlled delivery. In contrast, higher-flow operation enables integration into systems such as bioreactors that operate at larger volumetric scales.

Operation in the low flow regime highlights the trade-offs inherent to discretized actuation. In positional mode, flow is generated through discrete angular steps, each corresponding to a fixed volume determined by the syringe cross-sectional area and the mechanical resolution of the actuator. As a result, the flow signal consists of periodic increments separated by time intervals set by the control logic. This introduces a direct relationship among actuator resolution, syringe geometry, and achievable flow rates: smaller step sizes or longer time intervals yield lower effective flow rates. Although this results in transient spikes in the instantaneous flow profile, the system's effective behavior is governed by the time-averaged delivery. More generally, motor-driven fluid delivery is inherently discretized, and apparent continuity arises from sufficiently small increments relative to the system dynamics. At the same time, care must be taken in applications that are highly sensitive to instantaneous flow or shear variations, as the discrete nature of actuation may introduce perturbations that could affect system behavior. These effects may be more significant in systems involving shear-sensitive cell types or geometries that amplify transient flow variations.

The experimental validation demonstrates that the generated flow is sufficient to support sustained operation in microfluidic environments. Stable bacterial growth within monolayer chambers indicates that the system can maintain consistent conditions over extended periods, even in the presence of transient actuation and valve-switching effects. These results support the use of the platform in applications that require long-term operation and controlled fluid delivery.

Several limitations should be considered. The system operates in an open loop configuration, and performance may vary with changes in hardware properties or experimental conditions. In addition, implementing new control logic requires careful coordination between motor actuation and valve switching, as flow routing depends on their synchronization. Improper timing can result in unintended flow paths or transient backflow. The actuator's motion must also remain within its defined operating range. These constraints are primarily relevant when modifying or extending the firmware, as such changes require careful alignment between control logic and mechanical limits. For typical use, the provided firmware already implements a range of flow behaviors, allowing users to operate the system without modifying the underlying control logic.

Future work could improve robustness by integrating sensing and feedback, enabling closed-loop control and adaptive regulation. The modular design also allows extension to more complex configurations, including multi-unit systems or integration with automated pipelines. These directions would support the use of programmable fluidic control in increasingly complex experimental environments.

## Methods

### Platform design and implementation

The fluidic platform consists of a dual-syringe actuation mechanism integrated with solenoid pinch valves, controlled by a microcontroller-based system. Structural components were designed in Autodesk Fusion 360 and exported as STL files, which were sliced using Ultimaker Cura and fabricated using fused deposition modeling from thermoplastic filament on a Creality Ender 3 printer. The actuation mechanism uses a rack-and-pinion configuration to convert rotational motion into linear displacement of syringe pushers. Actuation was provided by a goBILDA 2000 series dual-mode servo motor capable of both continuous rotation and positional control, and system control was implemented using an Arduino Uno microcontroller. Fluid routing was controlled using two three-way and one two-way solenoid pinch valves. The electronic control circuit was assembled to interface the microcontroller with the servo motor and solenoid valves, including appropriate switching elements and protection components for stable operation. The fluidic network consists of two syringes connected through silicone tubing and pinch valves configured to control flow routing between source and target. Hamilton glass syringes were used for flow generation, and connections were established using standard Luer fittings, Y connectors, and tubing adapters. The system was designed to enable continuous fluid delivery through coordinated syringe actuation and synchronized valve switching, while maintaining controlled routing and preventing unintended flow during valve transitions. The platform supports a range of syringe sizes from 1  $\mu\text{L}$  to 1

mL, enabling access to different flow regimes by varying syringe geometry. Detailed information on mechanical design and assembly is provided in the Supplementary Information (Section S2), with additional details on circuit implementation and fluidic integration in Section S3 and the bill of materials in Section S9.

## Control system and software architecture

The platform is controlled by a layered software architecture comprising Arduino firmware and a Python-based graphical user interface. The desktop application was implemented using PyQt5, with serial communication handled through the pyserial library, enabling operation across standard desktop environments that support Python-based applications. Communication between the software and hardware is achieved via a serial protocol operating at 9600 baud, in which commands are transmitted as ASCII strings to define flow rate, direction, and temporal flow behavior. Flow behaviors are implemented through time-dependent control of actuator motion and valve states, enabling constant, pulsed, and oscillatory profiles. The system supports manual control, preprogrammed execution, and external programmatic control, allowing integration into automated or adaptive experimental workflows. The Arduino firmware is configured in two stages, where an initialization configuration is used to set and store system parameters, including actuator limits, syringe geometry, and calibration parameters in non-volatile memory, and a second operational configuration is used for normal pump operation, where stored parameters are retrieved and used to execute flow control. Calibration is required to relate control inputs to physical flow outputs and to ensure accurate operation across different hardware configurations, including actuator response, syringe dimensions, and control signal behavior, allowing the platform to be adapted to different syringe sizes, motor characteristics, and experimental conditions. Detailed calibration methods and parameter definitions are provided in the Supplementary Information (Section S4).

## Flow characterization

Flow characterization was performed using two distinct measurement approaches corresponding to the platform's two actuation regimes. Due to the different temporal characteristics of the two modes, separate methods were used to capture flow behavior accurately.

In continuous actuation mode, flow rate was quantified using a Sensirion SLF3S-0600F flow sensor. Data acquisition was performed using Sensirion Control Center software (version 1.49.1) using the default configuration, including a measurement frequency of 10 Hz and liquid mode set to water. The sensor was connected in series with the fluidic system, and flow measurements were recorded directly from the sensor output. The relationship between the control input and flow rate was established through calibration, in which actuator motion was mapped to plunger velocity and converted to volumetric flow using the syringe's cross-sectional area. The calibration procedure and the mapping between the control input and the flow rate are described in the Supplementary Information (Section S4).

In positional actuation mode, flow was characterized using an image-based method. The system was configured to infuse fluid into Tygon Non-DEHP microbore tubing (0.030" inner diameter), which was secured against a uniform background to enhance contrast. Water with blue food coloring was used as the working fluid, and a defined segment of the tubing was recorded using a smartphone camera. Movie data were processed using a custom algorithm that analyzed each frame with a vertical edge-detection kernel to track the fluid front's position along the tubing over time. The extracted position was converted to infused volume using the known inner diameter of the tubing, and the flow rate was obtained by differentiating the volume with respect to time. During data collection, the pump was controlled through a serial connection from a computer.

## Microfluidic cell culture and imaging

Biological experiments were performed using microfluidic devices containing monolayer chambers (MCs) for cell trapping and growth. The design and fabrication of the microfluidic devices are described in the Supplementary Information (Section S7). *E. coli* cells engineered to express cyan fluorescent protein (CFP) constitutively were used. The expression plasmid was obtained from Addgene, and transformations were performed prior to experiments.

Cells suspended in M9 media were introduced into the main channel of the microfluidic device. To facilitate loading into the monolayer chambers, the device was centrifuged with the chambers oriented outward from the axis of rotation, thereby driving cells into the trapping regions. Following loading, the DIY pumping platform was sterilized and connected to infuse fresh media from a reservoir into the device using a 10  $\mu$ L Hamilton syringe.

Media was continuously delivered at a flow rate of 1.5  $\mu$ L/min for 24 hours while the device was maintained on an inverted microscope (Nikon Eclipse Ti2). Time-lapse imaging was performed using NIS-Elements software (version 5.30.00), capturing phase-contrast images every 5 minutes and CFP fluorescence images every 3 minutes. This flow rate was selected to ensure sufficient nutrient delivery while minimizing shear stress within the monolayer chambers.

## Declarations

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### Author contributions

H.R. and S.M.D.O. conceived and H.R. implemented the DIY dual-syringe pumping platform, including hardware construction, Arduino-based continuous-mode control, and experimental validation. K.A.W. and T.O. designed and fabricated the DIY pump, developed Arduino control in positional mode, and contributed to experimental design and validation. B.A.A. developed the graphical user interface. T.O. produced assembly tutorial movies. Y.H.P. contributed to data analysis. S.M.D.O. supervised the project, acquired funding, and guided the overall research direction. All authors contributed to writing, editing, and reviewing the manuscript.

### Competing interests

The authors declare no competing interests.

### Data availability

The data supporting the findings of this study, including flow characterization measurements and design resources, are publicly available at [https://github.com/SamOliveiraLab/DIY\\_DSCPM](https://github.com/SamOliveiraLab/DIY_DSCPM). Additional guidance, including setup instructions, supporting materials, and **Supplementary Movies 1–7** are available at [https://samoliveiralab.github.io/DIY\\_DSCPM/](https://samoliveiralab.github.io/DIY_DSCPM/).

### Code availability

The firmware, graphical user interface software, analysis scripts, and supporting resources used in this study are publicly available at [https://github.com/SamOliveiraLab/DIY\\_DSCPM](https://github.com/SamOliveiraLab/DIY_DSCPM)

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## Figures

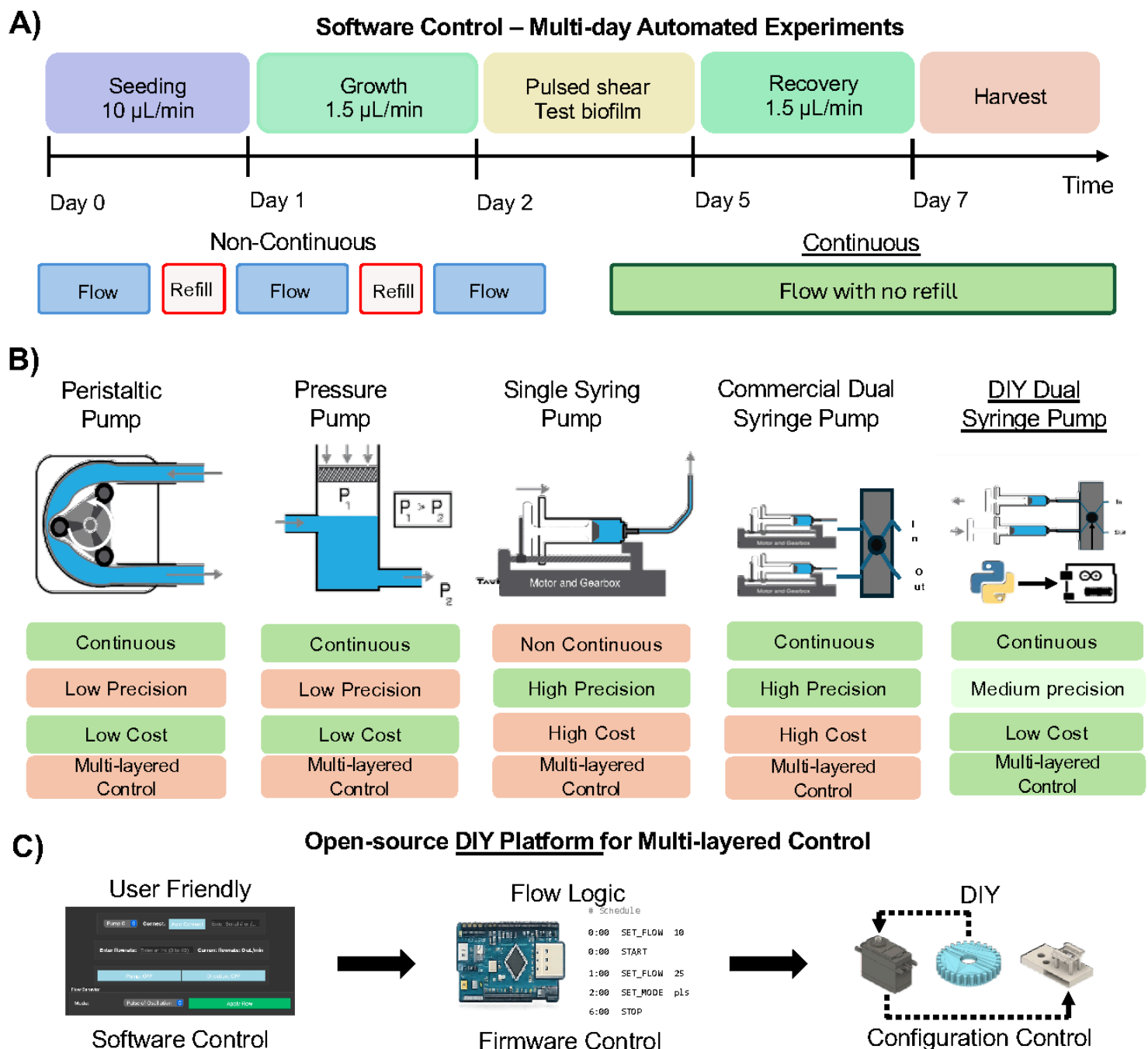


**Figure 1**

**Overview of the DIY pumping platform.** (A) Example of a multi-day automated biological experiment in which distinct phases, including seeding, growth, perturbation (pulsed shear), recovery, and harvest, require different flow conditions over time, motivating the need for programmable and time-dependent fluid delivery across extended durations. (B) Comparison of common fluid delivery approaches, including peristaltic pumps, pressure-driven systems, single-syringe pumps, and commercial dual-syringe pumps. Peristaltic and pressure-driven systems enable continuous flow but have low precision, while single-syringe pumps provide high precision but are non-continuous due to refill requirements. Commercial dual-syringe pumps enable continuous operation with high precision but at high cost. The DIY dual-

syringe pump enables continuous operation with medium precision, low-cost, and multi-layered control. (C) System architecture of the DIY pumping platform illustrating the integration of software, firmware, and hardware layers. The software layer provides a user interface for defining flow logic and experimental sequences, the firmware layer translates these commands into coordinated control signals, and the hardware layer executes fluid delivery through a dual-syringe mechanism with active flow routing. Continuous operation is achieved through alternating syringe actuation, in which one syringe delivers flow while the other refills, enabling uninterrupted fluid delivery during long-term experiments.

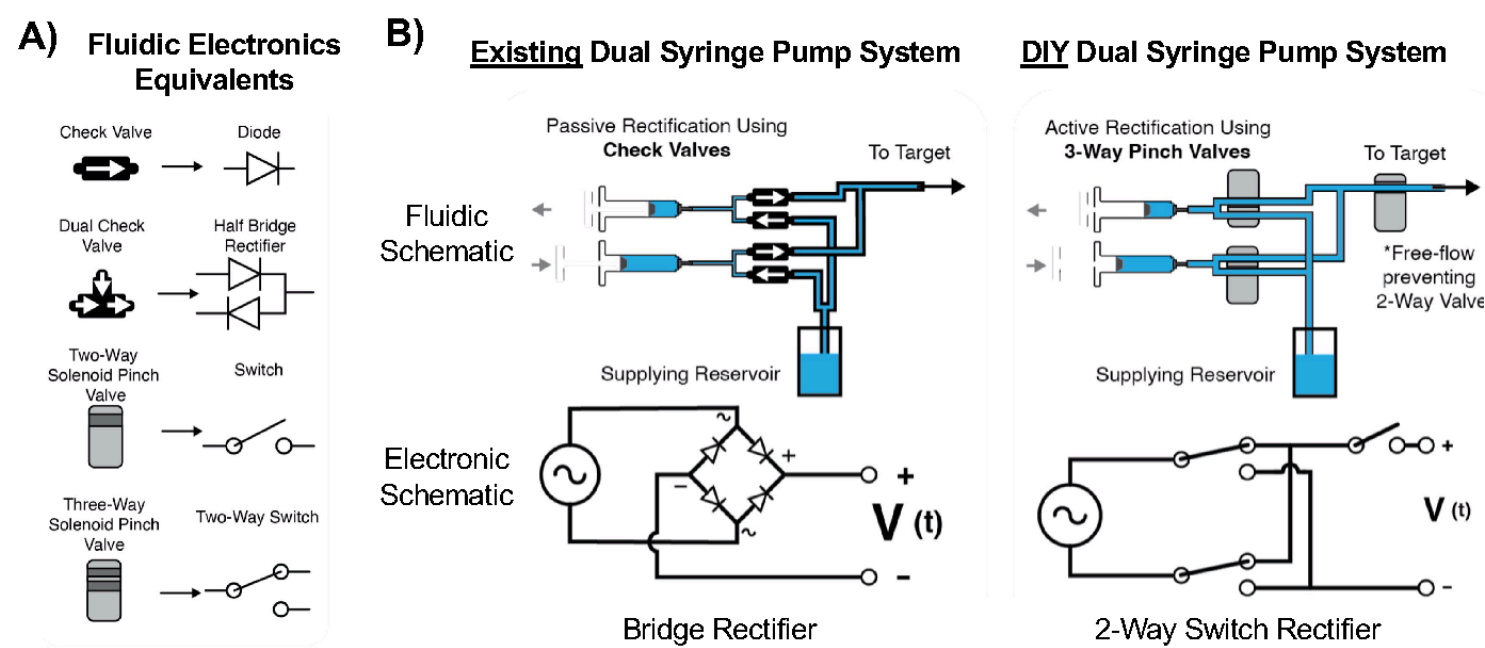


Figure 2

**Fluidic rectification using valving strategies inspired by electronic analogies.** (A) Mapping between fluidic components and their electronic equivalents, illustrating how valves can be interpreted as switches and rectifiers. (B) Illustration of rectification strategies in dual-syringe systems, including passive rectification using check valves and active rectification using solenoid pinch valves.

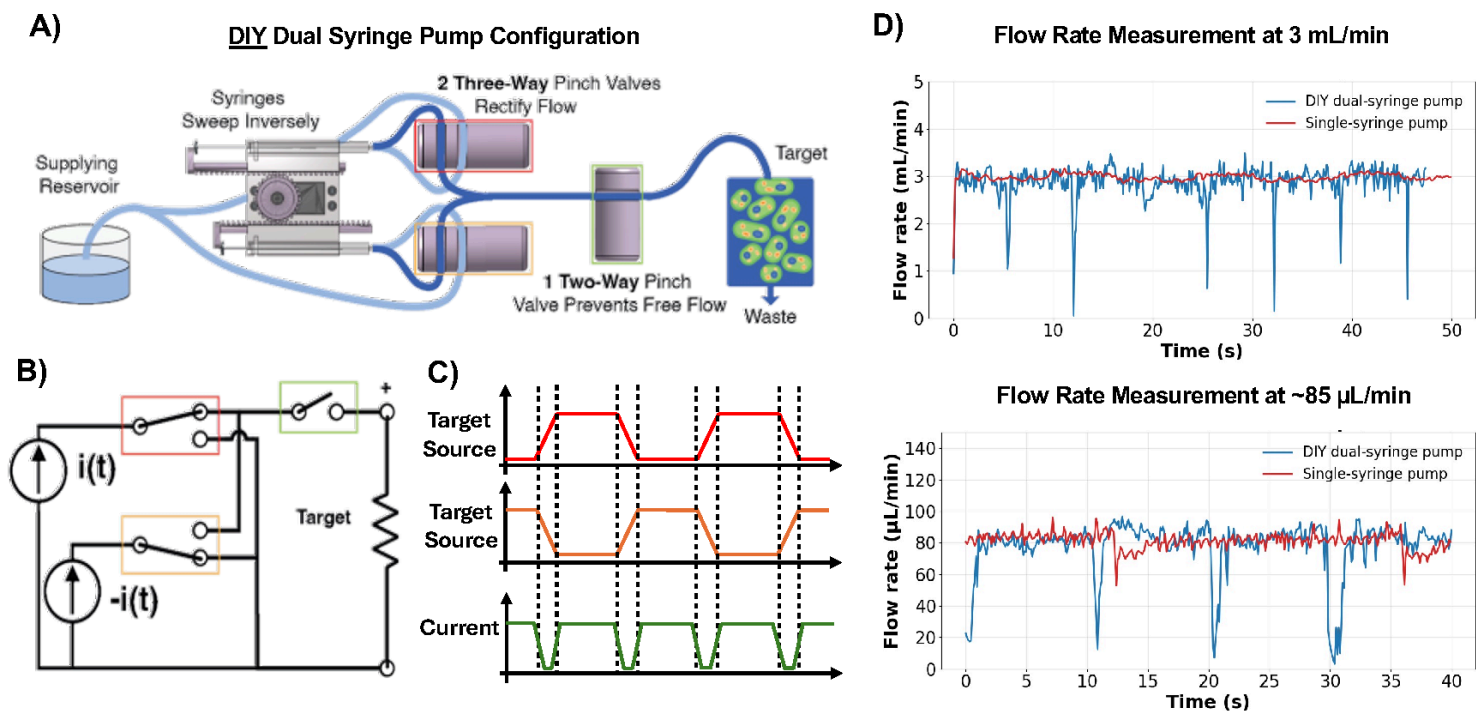


**Figure 3**

**DIY pump configuration and flow comparison with a commercial single-syringe pump.** (A) Schematic of the DIY pumping platform showing the dual-syringe configuration, fluid routing from the supplying reservoir to the target, and flow rectification using solenoid pinch valves. A two-way valve is included to prevent transient free flow during switching. (B) Electrical analogy of the mechanism, where alternating syringe actuation is represented as time-varying sources and valve logic enforces unidirectional flow. (C) Timing diagram illustrating coordinated valve switching and the resulting net flow, including a transient “danger zone” that occurs during switching events. (D) Flow rate comparison between the DIY pump and a commercial single-syringe pump (NE-1000 One Channel Programmable Syringe Pump) under two conditions: 3 mL/min using a 1 mL syringe (top) and 84  $\mu$ L/min using a 50  $\mu$ L syringe (bottom). The DIY pump exhibits increased fluctuations and transient drops associated with switching, compared to the smoother output of the commercial system, while maintaining continuous operation and enabling programmable flow behaviors described in subsequent sections.

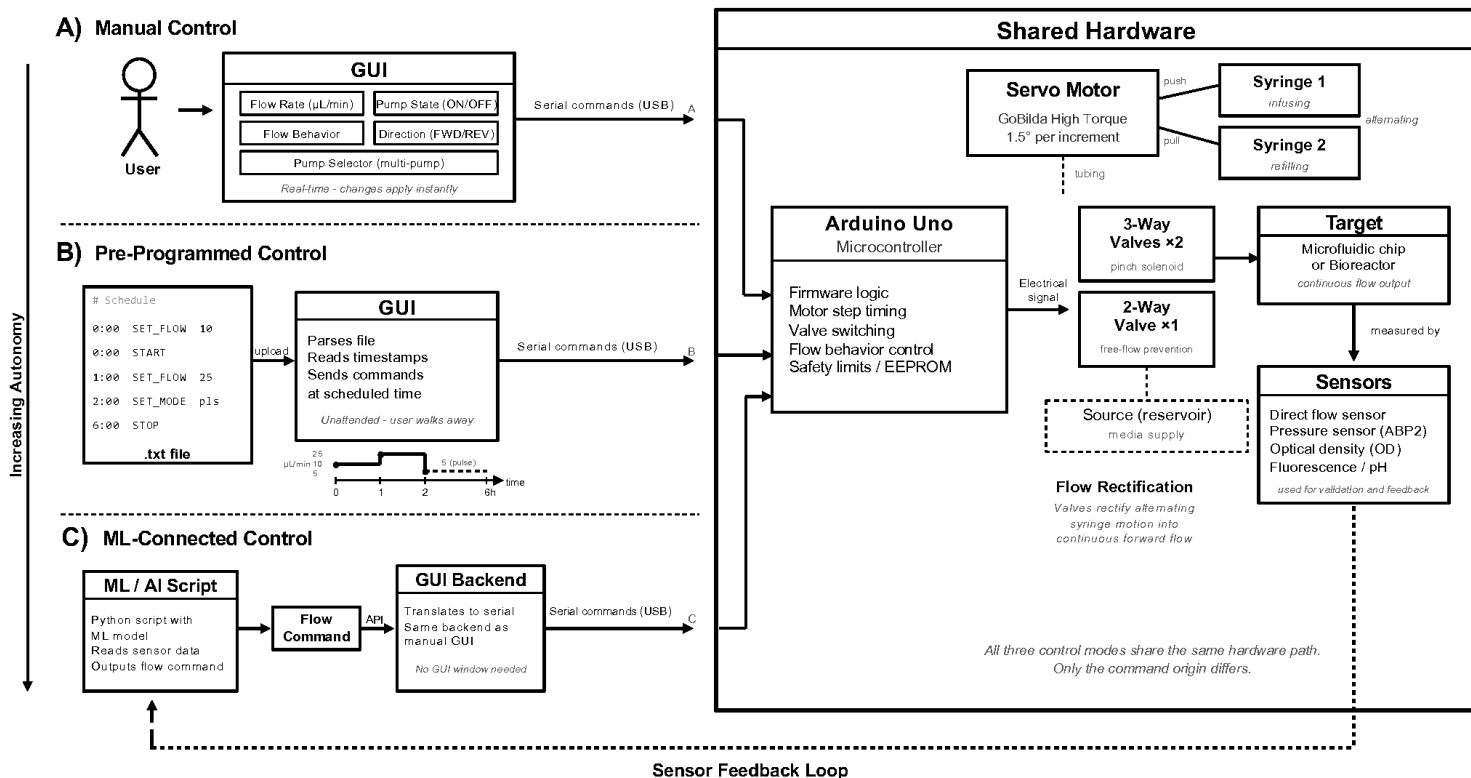


**Figure 4**

**Software control architecture and shared hardware pathway.** Three control modes are shown: (A) direct user interaction through the GUI, (B) scheduled execution from a command file, and (C) programmatic control via external scripts. The right panel illustrates the shared hardware layer, including the dual-syringe mechanism and active flow rectification.

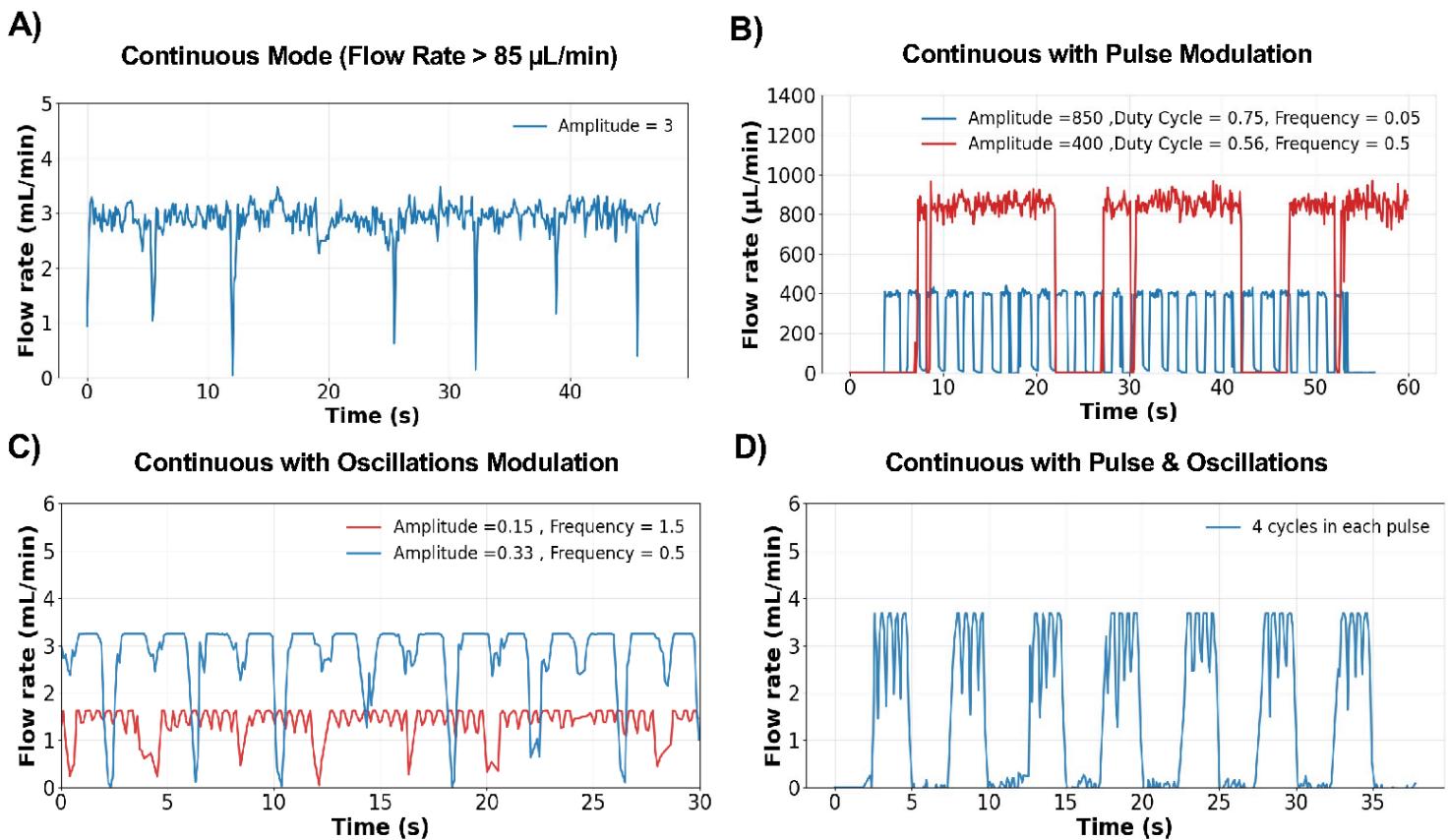


**Figure 5**

**Flow behaviors in continuous operation (flow rate > 85  $\mu\text{L}/\text{min}$ ).** Flow sensor measurements demonstrating system performance under different user-defined control modes. Each flow behavior is generated by selecting a mode in the software interface and specifying the corresponding parameters. (A) A fixed flow rate defines a constant flow rate. (B) Pulsed flow is defined by flow rate, duty cycle, and pulse frequency. (C) Oscillatory flow is defined by flow rate, oscillation amplitude, and frequency. (D) Combined pulse–oscillation behavior is defined by flow rate, duty cycle, pulse frequency, oscillation amplitude, and oscillation frequency.

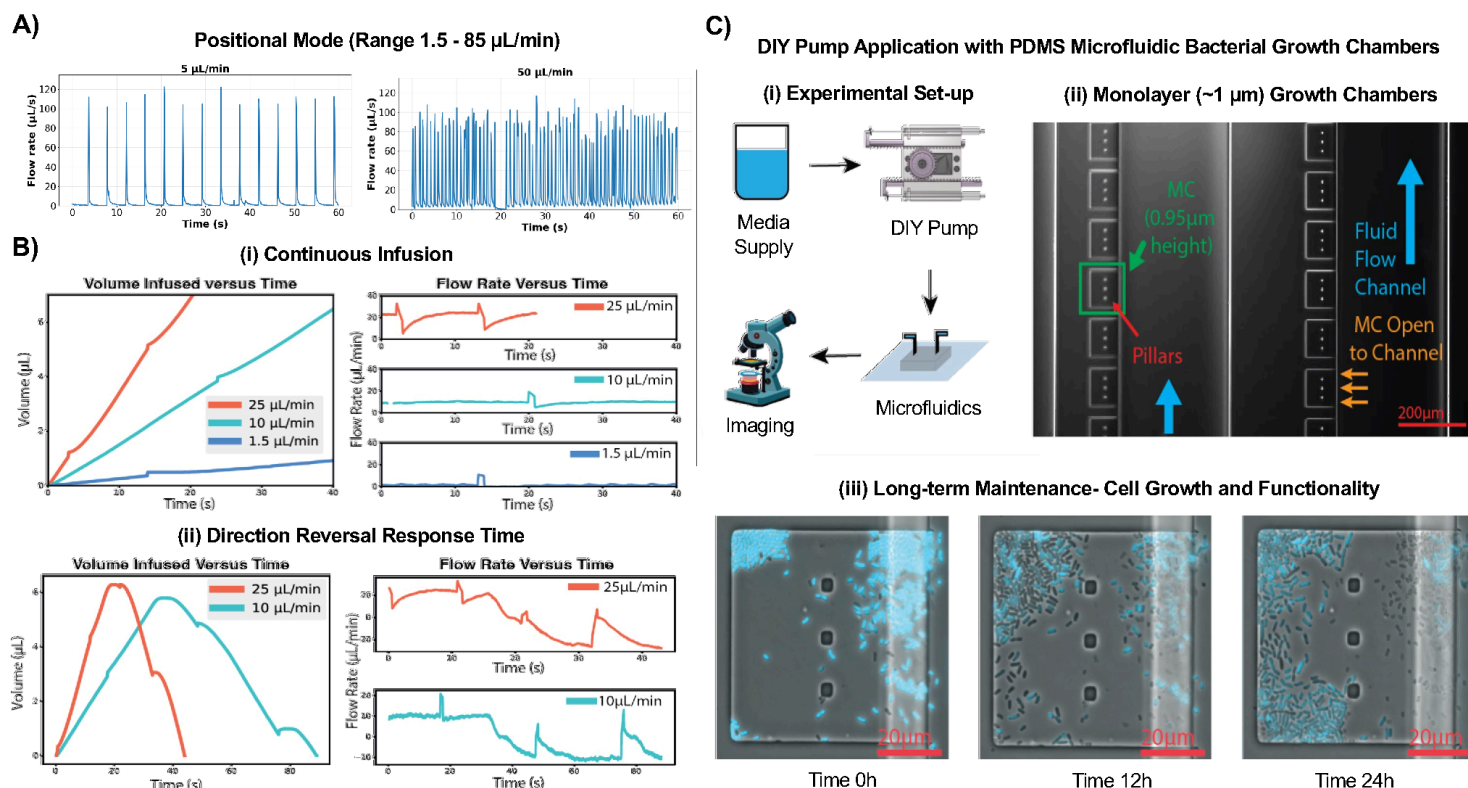


**Figure 6**

**Low-flow operation in positional actuation mode and experimental validation.** (A–B) Flow sensor measurements at 5 and 50  $\mu\text{L}/\text{min}$ , respectively. (C) Characterization of DIY pump flow in positional mode through image processing on movie (60fps) of fluid in micro-bore tubing. (i) Characterization of constant forward flow at 25, 10, and 1.5  $\mu\text{L}/\text{min}$ , enabling estimation of average flow despite discrete fluctuations. (ii) Characterization of flow reversal response time at 25 and 10  $\mu\text{L}/\text{min}$ , respectively. Results demonstrate that flow rates as low as 1.5  $\mu\text{L}/\text{min}$  can be achieved using a 10  $\mu\text{L}$  Hamilton syringe. (D) Experimental validation in microfluidic experiments demonstrating stable conditions for bacterial growth under continuous operation.

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [FlowSensorDataset.zip](#)
- [Oliveira2026SI.pdf](#)
- [EdgeDetectionSuppVideos.zip](#)
- [SupplementaryMovie3.mp4](#)
- [SupplementaryMovie6.mp4](#)
- [SupplementaryMovie4.mp4](#)
- [SupplementaryMovie7.mp4](#)

- [SupplementaryMovie5.mp4](#)
- [Oliveira2026SI.docx](#)
- [SupplementaryMovie2.mp4](#)
- [SupplementaryMovie1.mp4](#)