



An Arduino-based constant pressure fluid pump

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Abstract Constant pressure pumps are an invaluable yet underutilized resource for microfluidic flow systems. In particular, constant pressure pumps are able to stabilize the fluid pressure in systems where the viscosity may change due to chemical reactions or the flow rate may vary due to deformations of the channels. The constant pressure pump presented here is designed on the premise of creating and maintaining a pressure differential between the laboratory and a pressure reservoir. This pressure reservoir is then used to drive the input fluid at the specified gauge pressure. The pump design presented here is perfect for primarily undergraduate institutions and other laboratories with modest research budgets as it can be built for under US\$100 and construction is within the scope of an advanced undergraduate. The pump consists of an Arduino-compatible microcontroller, Adafruit electronic components, low-voltage air pump, Nalgene water bottle, and various fluid components. A complete parts list is included in the appendix. Comparable commercial pumps have a retail price in excess of US\$5000. Multiple pump designs were constructed and tested with the ability to hold a constant pressure of up to 14 psig (97 kPa-gauge) with a maximum flow rate of 65 $\mu\text{L}/\text{s}$ for water.

1 Introduction

Microfluidics has become a significant experimental platform across multiple scientific disciplines as it drastically reduces the volume of reagents, length of time required to perform experiments, and the expense of biological and chemical research. Due to the small volumes required, laboratories utilizing microfluidics are able to study systems where the cost or availability of reagents would otherwise be prohibitive. However, equipping a laboratory with microfluidics can itself be cost prohibitive due in large part to expensive specialized equipment. One such equipment barrier is a constant pressure pump. A common commercially available constant pressure pump, the Mitos P-Pump by Dolomite, starts at over US\$5000 for the Basic model. Even less expensive syringe pumps, such as the Fusion 100 by Chemyx, start at over US\$1000. Many smaller laboratories may struggle to overcome this financial barrier to entry. However, by building a pump in the laboratory using the design presented here, a constant pressure pump can be obtained for under US\$100 with minimal construction time or specialized expertise.

As funding for scientific research becomes scarce, laboratories are faced with increasing challenges and decisions regarding expensive equipment. An option becoming increasingly popular is to construct specialized equipment in-house, an option driven largely by the

ability to modify equipment and swap electronic parts as required by the current experimental constraints. A quick survey of the literature yields designs for in-house construction of humidity regulators [1], syringe pumps [2,3], flow rate regulators [4], and multichannel peristaltic pumps [5]. Behind all of these devices is an electronic microcontroller, such as an Arduino compatible board. The Arduino is a powerful resource for low-cost and open-source alternatives to the specialized tools which are commercially available. These commercially available options are often priced at ten to a hundred times the cost of the “DIY” alternative. Inexpensive microcontrollers with a variety of sensors and instruments, combined with a large open source community, make it increasingly practical to construct your own specialized equipment on demand. Here, we present the design for a constant pressure fluid pump utilizing an Adafruit ItsyBitsy microcontroller, Adafruit MPR1S pressure sensors, and small low-voltage air pumps. With these basic parts, it is possible to reduce the cost of specialized equipment by over an order of magnitude while having the flexibility to choose from several different designs and modify as the experimental needs change. In this report, we present three different single-pump designs ranging from under US\$100 to roughly US\$150. These pumps are all an order of magnitude less expensive than comparable commercially available pumps.

Fluid flow rate-controlled syringe pumps are ubiquitous in microfluidic laboratories due to their utility and regular usage in medicine. However, in some research applications, such as those where fluid viscosity is not

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constant or chemical reactions may create precipitates, flow rate-regulated pumps can cause complications due to the changing pressure within the channels. Even within constant pressure systems, there are distinct differences in the characteristics of the resulting fluid flow due to the forcing mechanism [6–8]. Thus, it is becoming apparent that the fluid pump design needs to be an experimental consideration and that syringe pumps may not be suitable for all applications.

Recently, there has been increased interest in the design and construction of inexpensive constant pressure fluid pumps. Pumps have been demonstrated using feedback-controlled syringes [2, 9], laboratory-pressurized air supplies with pressure manifolds [10], and standalone air compressors [11]. However, in all of these examples the final design is significantly more expensive than the pump presented here. Further, these designs either cannot operate continuously, require a central pressurized air supply, or require substantial machining. By contrast, the design presented here can operate continuously, uses only inexpensive standalone parts, and requires no machining. Here, a small air pump is used to pressurize a pressure reservoir which drives flow from a comparably small fluid reservoir. Two designs with comparable costs are presented: one design is simpler and slightly less expensive, while the other is more extensible and can be inexpensively scaled to a large number of pumps.

2 Pump construction

The operating principle for the constant pressure fluid pump presented here is to use a small vacuum pump to maintain a pressure difference between the pressure reservoir and the laboratory. For positive pressure, the exhaust port of the pump is connected to the pressure reservoir. The pressure reservoir is connected to a smaller fluid reservoir such that the air pressure above the fluid, and thus the fluid pressure, is maintained at the reservoir pressure. The volume difference between the fluid reservoir and pressure reservoir is large enough such that the desired pressure is maintained even during fluid flow. Thus, the fluid flowing from the fluid reservoir maintains a constant pressure as regulated by the pressure reservoir. A solenoid valve connected to the pressure reservoir opens and releases air if the reservoir pressure exceeds the set pressure. A manual stopcock valve between the pressure reservoir and the fluid reservoir prevents the flow of fluid until the system is at the set pressure. Two pressure sensors, one inside the pressure reservoir and one outside, are used by the Adafruit ItsyBitsy microcontroller to measure the pressure differential. Two pressure sensors are used in order to hold a constant pressure differential, or gauge pressure, as ambient pressure can change over time.

The volume of the pressure reservoir and the pressure reservoir/fluid reservoir ratio are not critical so long as the vacuum pump rate exceeds the average flow rate. Based on the ideal gas law, $PV = nRT$, it can be

shown that $\Delta P = \Delta nRT/V$ such that the larger the pressure reservoir V the smaller the change in pressure ΔP for any outward gas flow Δn . However, an average fluid flow rate in excess of the pump rate will lead to an eventual drop in pressure. For typical microfluidic applications, this is highly unlikely to be a problem as even the modest 6V and 12V vacuum pumps used here are capable of liters per minute, vastly in excess of any realistic microfluidic fluid flow rate.

Two similar designs of constant pressure fluid pump, both utilizing the same basic operating principle, were tested. First, the Direct Motor Design (Fig. 1a) uses a water bottle as the pressure reservoir directly connected to the vacuum pump, solenoid valve, and smaller fluid reservoir vial. This design is the simpler of the two and uses the least components while still supplying the features needed to operate as a constant pressure fluid pump. Second, the Master Reservoir Design (Fig. 1b) uses a second water bottle as a “Master” pressure reservoir and a second solenoid valve to control pressure from the master reservoir to the pressure reservoir. This second design has the advantage of being more easily scaled to accommodate multiple pumps, needing only one vacuum pump for all of the fluid pumps. Both of the designs took low cost into consideration, and the complete parts list can be found in the Appendix A.2. The Direct Motor Design is less expensive at US\$119.97 as compared to the Master Reservoir Design at US\$153.90. Although the Master Reservoir Design is more expensive for a single fluid pump, this design becomes cost effective as additional fluid pumps are added. The Master Reservoir Design is less expensive than the Direct Motor Design when four or more fluid pumps are required. Additionally, an even more inexpensive pump was constructed using a less powerful 6V vacuum pump and different pressure sensors at US\$87.04. Due to the smaller motor, the under US\$100 fluid pump was only able to maintain a pressure differential of roughly 6 psig (41.4 kPa). The 12V vacuum pump used for both the Direct Motor Design and Master Reservoir Design was able to maintain a pressure differential of up to 14 psig (97 kPa).

Constructing the pumps requires modifying the bottle lids, wiring the electronics, and connecting the tubing to the pressure sources. For most of the tubing connectors, a small hole was drilled in the lid of the reservoir bottle and the female end of a male-to-female barbed luer lock connector was epoxied in place. This was used on the lids of the water bottle and the small vial as can be seen in Fig. 2b. For the exit tubing on the small vial, a hole was drilled in the lid, and the tubing was inserted to the bottom of the vial and then epoxied into place.

The wiring diagram of the Direct Motor Design can be seen in Fig. 2a. Magnet wire was soldered onto the headers of the pressure sensor which was then placed inside the water bottle. A small hole was drilled into the water bottle lid for the magnet wire to pass through which was then sealed with epoxy. Wires were soldered onto the leads of the motor with the other ends connected to a solderless breadboard. The other connec-

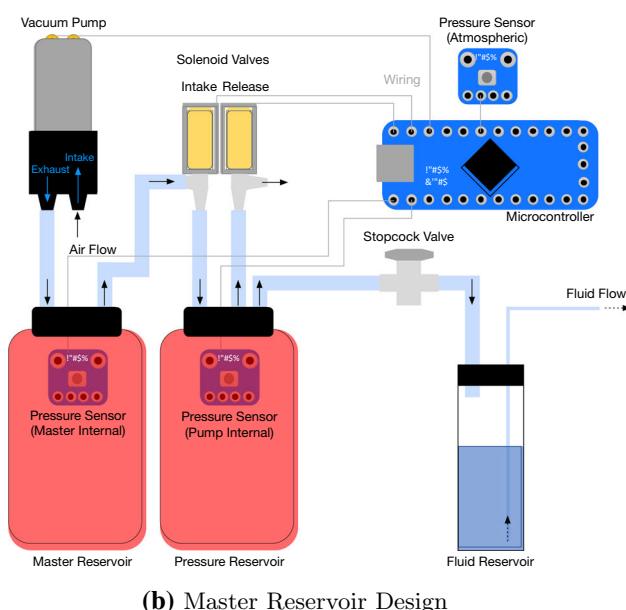
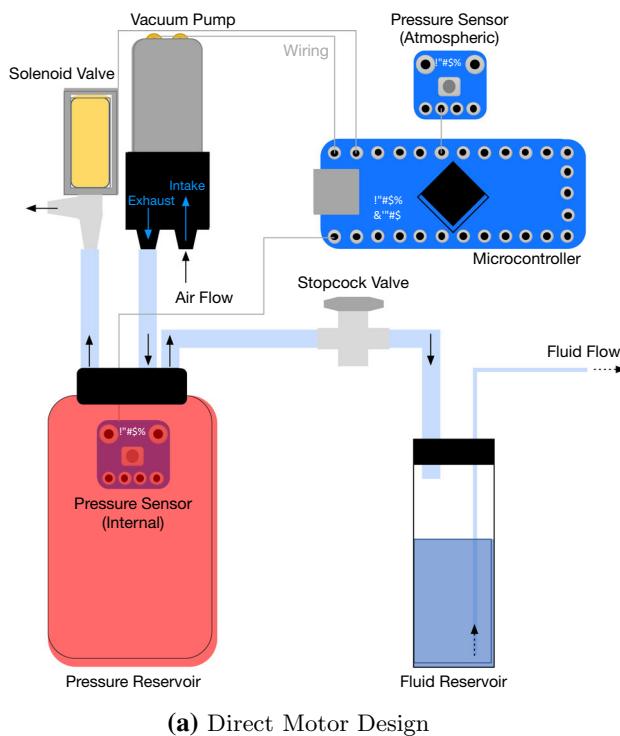


Fig. 1 A diagram of both constant pressure fluid pump designs. **a** Direct Motor Design where the pressure reservoir is connected directly to the air compressor. **b** Master Reservoir Design where the pressure reservoir is connected to a secondary “Master” pressure reservoir which is connected to the air compressor. In both figures the electronic components have been simplified for clarity.

tions consist of jumper wires inserted into the solderless breadboard. Additional electronics were added to create a basic user interface which for the sake of clarity are not shown in Fig. 2a. These additional components

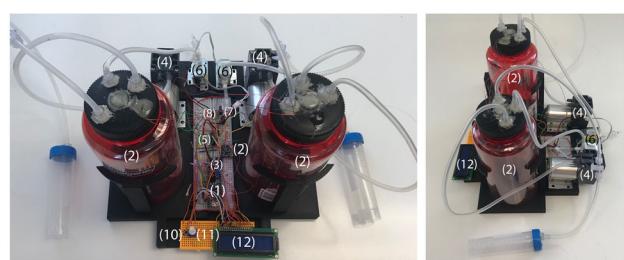
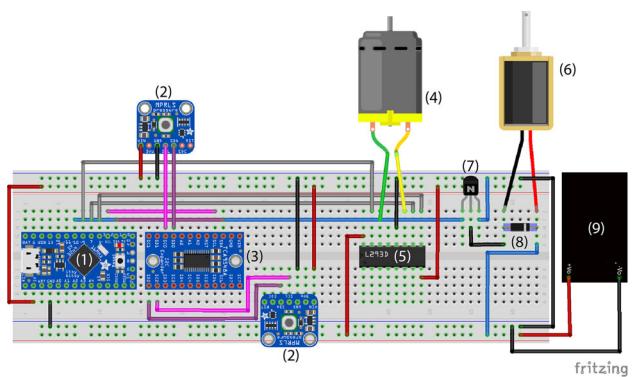


Fig. 2 The Direct Motor Design pump. **a** Minimal wiring diagram of the required electrical components for a single Direct Motor Design constant pressure fluid pump. **b** Top view and side view images of an assembled Direct Motor Design double pump with additional control interface components and a 3D printed base. The complete wiring diagram is shown in Fig. 5 of the Appendix. The labeled components are (1) ItsyBitsy microcontroller, (2) MPRLS pressure sensor, (3) multiplexer, (4) DC vacuum pump motor, (5) L293D motor driver, (6) solenoid valve, (7) NPN transistor, (8) resistor, (9) 12 V DC power supply, (10) button, (11) potentiometer, and (12) LCD screen.

are an LCD screen to display the pressure readout, and a potentiometer and push button to set the pressure differential. These additional components allow the pump to operate as a standalone system. Without these components, the pressure differential is set directly by the computer. A complete wiring diagram for a Direct Motor Design double pump with these additional components is shown in Fig. 5 of the Appendix.

The pump control code that was used to run the Itsy-Bitsy microcontroller was created in the Arduino IDE and is understandable for anyone with minimal programming experience. Sample code is available online at the Arduino Project Hub.¹ The control method for both pump designs was a slight variation of the standard bang-bang control method. For the Direct Motor Design, the pressure differential is constantly being checked and the microcontroller dictates what each component should do. If the pressure is too high in

¹ Sample code available from the Arduino Project Hub, <https://create.arduino.cc/projecthub/tomkinn/constant-pressure-pump-1a085a>.

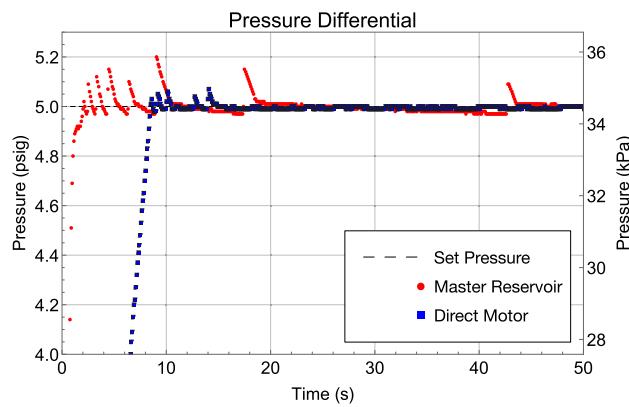
the pressure reservoir, then the outlet valve will open to vent excess pressure. If the pressure is too low, the microcontroller will deliver a signal to the air pump using pulse width modulation to control for the magnitude of the pressure change required. For the Master Reservoir Design, the master reservoir is kept at a higher pressure than the controlled reservoir and thus when the controlled reservoir needs to increase pressure the solenoid valve connecting it to the master reservoir is opened. Similar to the other design, when the pressure needs to be lowered, the outlet solenoid valve opens to vent excess pressure. A syringe tip was added to the end of the solenoid valve to reduce the rate of air being released from the pressure reservoir as otherwise the pressure dropped very quickly and could overshoot the set value. The necessary code can be written, and construction of both the Direct Motor Design and the Master Reservoir Design can be successfully completed, by an advanced undergraduate without significant experience.

3 Discussion and analysis

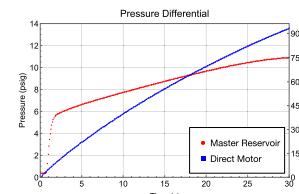
Both pump designs shown here were built with the same materials and were tested with the same methodology. As seen in Fig. 3, there are distinct differences in the abilities of these two pump designs. While set to hold a constant pressure, the Direct Motor Design is able to keep a more consistent level of pressure, leveling off after roughly 15 seconds as in Fig. 3a. The Master Reservoir Design is able to reach pressure more quickly as the master reservoir is already pressurized, but throughout the test is subject to relatively large spikes in pressure as air rushes in from the master reservoir very quickly. These spikes could be tuned by limiting the pressure of the master reservoir or restricting the flow between the two bottles. For the trial shown in Fig. 3a, with the pump set to hold at a constant pressure of 5.00 psig (34.5 kPa), the average pressure of the Direct Motor design was 4.99 ± 0.03 psig (34.4 ± 0.2 kPa) and the Master Reservoir average pressure was 5.00 ± 0.06 psig (34.5 ± 0.4 kPa) (95% CI, Gaussian PDF). Based on these data, the Direct Motor Design maintains a more constant pressure while the Master Reservoir Design pressurizes more quickly.

To further investigate the rate of pressurization, both pumps were set to increase pressure indefinitely as shown in Fig. 3b. The Master Reservoir Design initially increases in pressure more quickly, up to the preset pressure of the master reservoir, before pressurizing more slowly due to the increased volume. The Direct Motor Design increases in pressure at a more uniform rate.

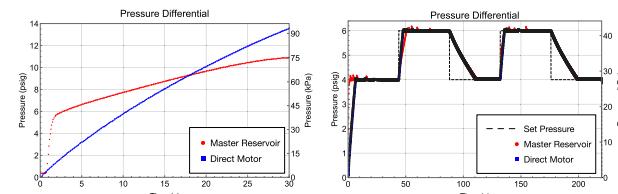
To investigate increasing and decreasing pressure, a stepped pressure set point was used for both pumps with the results shown in Fig. 3c. The Master Reservoir Design pressurizes slightly more quickly due to the preset master reservoir while both pumps decrease pressure comparatively slowly due to the syringe needle limiting



(a) Pressure Holding Test



(b) Rate of Pressurization



(c) Rate of Pressure Changes

Fig. 3 Comparison of the Direct Motor Design and the Master Reservoir Design. **a** Holding a constant pressure of 5.00 psig (34.5 kPa). **b** Pressurizing as rapidly as possible. **(c)** Stepping the pressure between 4.00 psig (27.6 kPa) and 6.00 psig (41.4 kPa).

exhaust flow. As can be seen, both pumps pressurize comparably in these tests.

As can also be seen in Fig. 3a, c the Direct Motor Design maintains a more stable pressure. The Master Reservoir Design is prone to overshoot while raising the pressure within the pressure reservoir due to the high pressure within the master reservoir itself. This overshooting combined with the limited exhaust flow reduces the stability of maintaining a set pressure.

Based on the results of these tests, it was determined that the primary advantages of the Direct Motor Design are the stability of a set pressure with very little overshoot and the lower cost for a single pump, while the primary advantages of the Master Reservoir Design are the rapid pressurization increases and the extensibility of the design to accommodate numerous pumps. However, for the common two pump configurations the Direct Motor Design is still a less expensive option. The assembled Direct Motor Design double pump is shown in Fig. 2 with the wiring shown in Fig. 5 of the Appendix.

For laboratories equipped with a compressed air line and/or a vacuum line, there are additional design options. These options include connecting the compressed air or vacuum line to the master reservoir in place of the vacuum pump or replacing the master reservoir with the compressed air or vacuum line directly. These designs would eliminate the need for the vacuum pump entirely. However, without proper flow rate limiting these designs may be prone to overshoot the set value. Additionally, pumps with a compressed air

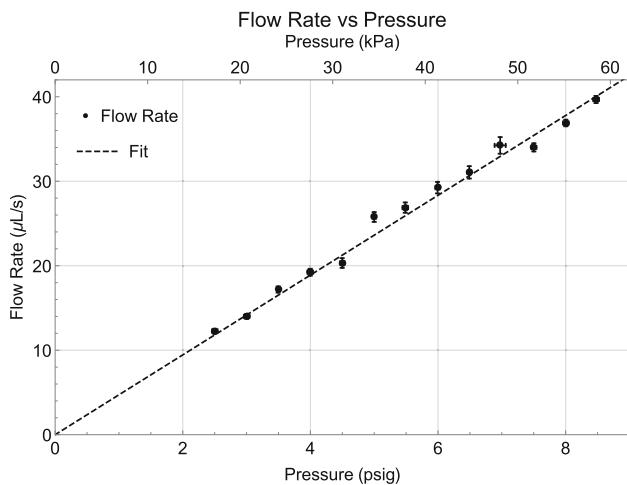


Fig. 4 Flow rate of water in $\mu\text{L}/\text{s}$ versus applied pressure differential for the Direct Motor Design pump. The flow rate is linear with pressure differential as would be expected for Poiseuille flow.

or vacuum line may be able to achieve higher pressure differentials than those with the 12V motor used here but will be less portable due to the required connections to the laboratory supply lines. Neither of these designs were tested as laboratory supply lines were not available.

To test the fluid flow capabilities of the Direct Motor Design pump, 0.012 in. (0.30 mm) ID tubing, 12 in (0.30 m) in length, was connected to the fluid reservoir filled with water and the flow rate was measured at various gauge pressures. Flow rate was measured by recording the time required to pump a predetermined volume. As can be seen in Fig. 4, the flow rate increased linearly with pressure up to 40 $\mu\text{L}/\text{s}$ at 8.50 psig (58.6 kPa) as would be expected for Poiseuille flow. For water flowing at 40 $\mu\text{L}/\text{s}$ through 0.012 in. (0.30 mm) ID tubing the Reynolds number is approximately 170, well within the laminar regime. Extrapolating to the observed saturation pressure for the pressure sensors, 14 psig (96.5 kPa), the pump can deliver a flowrate of at least $66.33 \pm 0.03 \mu\text{L}/\text{s}$. The extrapolation used a linear fit line through zero with a calculated slope of $4.738 \pm 0.002 \mu\text{L}/(\text{s psig})$ ($0.6872 \pm 0.0003 \mu\text{L}/(\text{s kPa})$). From the Poiseuille equation for laminar flow, $Q = \frac{\pi r^4 \Delta P}{8\eta L}$ where η is the dynamic viscosity, the expected slope ($Q/\Delta P$) for water is $4.6 \mu\text{L}/(\text{s psig})$ ($0.66 \mu\text{L}/(\text{s kPa})$). A longer fluid flow tube or more viscous fluid would decrease the flow rate linearly as described by the Poiseuille equation.

Both pump designs presented here were intended for use as a constant pressure source, utilizing a manual stopcock valve to prevent fluid flow during pressurization. An additional solenoid valve regulating the fluid flow could introduce a fluid start/stop response rate measured in milliseconds after achieving the set pressure. Experiments requiring quickly or continuously changing flow rates introduce additional design challenges not considered here.

4 Conclusion

The Direct Motor Design and the Master Reservoir Design both provide significantly less expensive alternatives to the commercially available constant pressure fluid pumps. These pumps can handle a large range of pressure differentials and can be easily programmed to provide a time dependent pressure. The Master Reservoir Design can more quickly achieve a set pressure, while the Direct Motor Design maintains a more stable pressure set point with minimal overshooting. For a single Direct Motor Design pump, the cost is US\$119.97 depending on needs and materials. The price can easily be below US\$100 at US\$87.04 for the least expensive pump design presented here.

Both designs demonstrated here can be easily modified for specific laboratory requirements. For example, if both positive and negative pressure differentials are required a second air compressor can be attached to the pressure reservoir in the opposite orientation. Alternatively, a single peristaltic pump can provide both positive and negative pressure directly. Peristaltic pumps operate by rolling a rotor lobe across the flow tube, compressing the tube to move the contents. Due to this mechanism, peristaltic pumps can operate equally in forward and reverse, thus creating positive or negative pressure within the reservoir. However, as flow is conditional on a complete collapse of the flow tube most peristaltic pumps are designed for liquid flow. When used for air, the tube may not be compressed enough to sustain a significant pressure differential. Specifically, a peristaltic pump, the Adafruit 1150, was used in the early prototypes of the work presented here but yielded a significantly lower maximum pressure differential of only about 1 psig (7 kPa). Future designs could utilize a more powerful peristaltic pump, such as the Boxer 9QQ, for reversible operation with a single pump.

For most common applications of a constant pressure fluid pump, the two designs presented here provide a robust and inexpensive alternative to the commercially available options. In-house fabrication of laboratory equipment is becoming more common and accessible as open-source alternatives are becoming increasingly available. There is little doubt that as Arduino-based microcontrollers become more ubiquitous research groups will increasingly look to them as an inexpensive, customizable, and extensible option for their equipment needs.

Author contribution statement

ML, SF, and NT originated the idea; TL, ML, and NT designed the device; TL built the device and collected the data; TL and NT wrote the initial draft; and all authors read, edited, and approved the final paper.

A Appendix

A.1: Direct Motor Design double pump wiring

The complete wiring for the Direct Motor Design double pump shown in Fig. 2b of the main text with additional LCD display, potentiometer, and button is shown in Fig. 5.

A.2: Parts list

The complete parts list for the Direct Motor Design and Master Reservoir Design. All parts were sourced as indicated.

A.2.1: Direct Motor Design

Item	Number	Total price (USD)
Nalgene water bottle	1	\$9.99
12V DC vacuum pump	1	\$25.99
Electric solenoid valve	1	\$8.99
L293D H-bridge motor driver	1	\$2.95
Silicone tubing 3-meter	1	\$7.50
MPRLS pressure sensor	2	\$29.90
Adafruit ItsyBitsy microcontroller	1	\$9.95
TCA9548A I2C multiplexer	1	\$6.95
Male-to-female luer lock connector	8	\$8.00
Polycarbonate luer lock stopcock	1	\$1.76
Plastic test tubes - 10	1	\$7.99
Total cost		\$119.97

A.2.2: Under \$100 direct motor design

Item	Number	Total price (USD)
Nalgene water bottle	1	\$9.99
6V DC vacuum pump	1	\$10.98
Electric solenoid valve	1	\$8.99
L293D H-bridge motor driver	1	\$2.95
Silicone Tubing 3-meter	1	\$7.50
BME280 pressure sensor	2	\$11.98
Adafruit ItsyBitsy microcontroller	1	\$9.95
TCA9548A I2C multiplexer	1	\$6.95
Male-to-female luer lock connector	8	\$8.00
Polycarbonate luer lock stopcock	1	\$1.76
Plastic test tubes - 10	1	\$7.99
Total cost		\$87.04

Item	Number	Total price (USD)
Nalgene water bottle	2	\$19.98
12V DC vacuum pump	1	\$25.99
Electric solenoid valve	2	\$17.98
L293D H-bridge motor driver	1	\$2.95
Silicone tubing 3-meter	1	\$7.50
MPRLS pressure sensor	3	\$44.85
Adafruit ItsyBitsy microcontroller	1	\$9.95
TCA9548A I2C multiplexer	1	\$6.95
Male-to-female luer lock connector	8	\$8.00
Polycarbonate luer lock stopcock	1	\$1.76
Plastic test tubes - 10	1	\$7.99
Total cost		\$153.90

A.2.3: Master Reservoir Design

A.2.4: Sources

Item	Link
Nalgene water bottle	https://amzn.to/33GqnjB
12V DC vacuum pump	https://amzn.to/2VSNh4L
6V DC vacuum pump	https://amzn.to/2Mmf6iF
Electric solenoid valve	https://amzn.to/2pqAkTB
L293D H-bridge motor driver	https://www.adafruit.com/product/807
Silicone tubing 3-meter	https://amzn.to/2oMOChq
MPRLS pressure sensor	https://www.adafruit.com/product/3965
BME280 pressure sensor	https://amzn.to/2ORh4Jx
Adafruit ItsyBitsy microcontroller	https://www.adafruit.com/product/3677
TCA9548A I2C multiplexer	https://www.adafruit.com/product/2717
Male-to-female luer lock connector	https://bit.ly/2IV6YDC
Polycarbonate luer lock stopcock	https://bit.ly/32ko59G
Plastic test tubes	https://amzn.to/33CRGeU

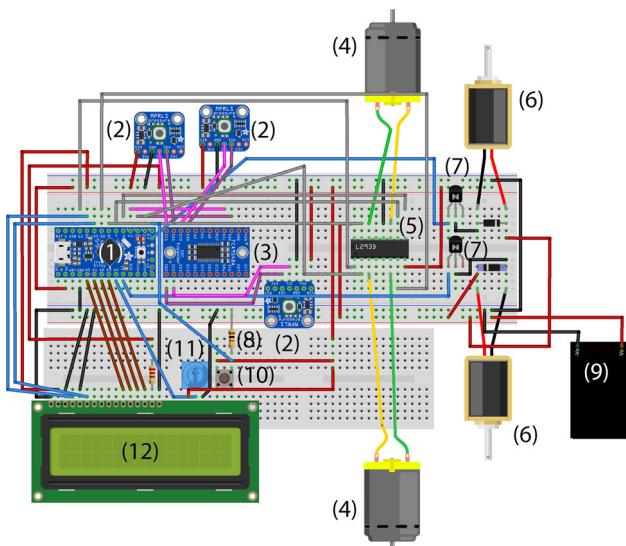


Fig. 5 The complete wiring for the Direct Motor Design double pump shown in Fig. 2b of the main text with additional LCD display, potentiometer, and button. The labeled components are (1) ItsyBitsy microcontroller, (2) MPR1S pressure sensor, (3) multiplexer, (4) DC vacuum pump motor, (5) L293D motor driver, (6) solenoid valve, (7) NPN transistor, (8) resistor, (9) 12 V DC power supply, (10) button, (11) potentiometer, and (12) LCD screen.

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