

# **Construction of a Low-cost Liquid Handling Device with 3D Printing for Polymerase Chain Reaction**

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## **I. Abstract**

Although a field still in its infancy, robots, and automated devices have been adopted in an increasing number of laboratories to make the workflow more efficient. However, the high cost of liquid handling devices exacerbates disparities between laboratories. To address this issue, this research developed an accurate and low-cost liquid handler, designed for easy replication through open-source software and 3D designs distributed online. The device was rigorously tested, achieving a systematic error of 2.54% at 5  $\mu\text{L}$  and a random error of 1.82%, yielding an overall accuracy of 97.46% and precision of 98.18%. Polymerase Chain Reaction (PCR) tests and gel electrophoresis analysis confirmed the machine's capability to accurately perform PCR. With a material cost of approximately \$206, this device offers a highly economical alternative to commercial liquid handlers, which typically range from \$9,000 to \$60,000. This innovation has the potential to significantly benefit underfunded laboratories, providing a cost-effective solution for repetitive PCR processes. For more details, visit the GitHub link: <https://github.com/Jeffrey-Moon/Liquid-Handler>.

## **II. Keywords**

Engineering Mechanics; Mechanical Engineering; Liquid Handling; PCR; 3D Printing;

## **III. Introduction**

The discovery of Polymerase Chain Reaction (PCR) brought enormous benefits and scientific developments such as genome sequencing and the study of molecular genetic analyses, including the rapid determination of paternity and the diagnosis of infectious disease. PCR enables the *in vitro* synthesis of nucleic acids through which a DNA segment can be specifically replicated in a semi-conservative way.<sup>1</sup> With the expansion of the molecular biology field, the demand for PCR increased dramatically and the need to ensure quality in a laboratory process has become increasingly important.<sup>1</sup> Indeed, successful PCR results rely heavily on the accuracy and reproducibility of pipetting, requiring considerable skill and practice. Even small errors in the dispense accuracy of sample DNA or RNA can translate into huge differences after amplification.<sup>2</sup> Furthermore, large sample numbers in screening assays make manual setup time-consuming, error-prone, and tedious.

Although a field still in its infancy, robots, and automated laboratory devices have been adopted in an increasing number of research laboratories in the pharmaceutical industry<sup>3</sup> and genomics laboratories to make the sequencing workflow more efficient and cost-effective.<sup>4</sup> These robots offer the reproducibility

<sup>1</sup> Fowler, E. Analytical technologies for real-time monitoring of biopharmaceutical manufacturing processes. *Am. Lab.* February 2006, 30–34.

<sup>2</sup> Gaisford, Wendy. “Robotic Liquid Handling and Automation in Epigenetics.” *Journal of Laboratory Automation*, vol. 17, no. 5, 1 Oct. 2012, pp. 327–329, [https://journals.sagepub.com/doi/10.1177/2211068212457160?url\\_ver=Z39.88-2003&rfr\\_id=ori:rid:crossref.org&rfr\\_da=t=cr\\_pub%20%200pubmed](https://journals.sagepub.com/doi/10.1177/2211068212457160?url_ver=Z39.88-2003&rfr_id=ori:rid:crossref.org&rfr_da=t=cr_pub%20%200pubmed), 10.1177/2211068212457160.

<sup>3</sup> Gaisford

<sup>4</sup> Tegally, Houriiyah, et al. “Unlocking the Efficiency of Genomics Laboratories with Robotic Liquid-Handling.” *BMC Genomics*, vol. 21, no. 1, 20 Oct. 2020, 10.1186/s12864-020-07137-1. Accessed 19 Mar. 2022.

and accuracy of low-volume dispensing, which is difficult to achieve using manual dispensing methods. The ability of these instruments to accurately, rapidly, and reproducibly pipette volumes under the 100-nL volume range minimizes the amount of wasted reagents, saving valuable samples and decreases repetitive labor, ensuring low-cost assays.<sup>5</sup>

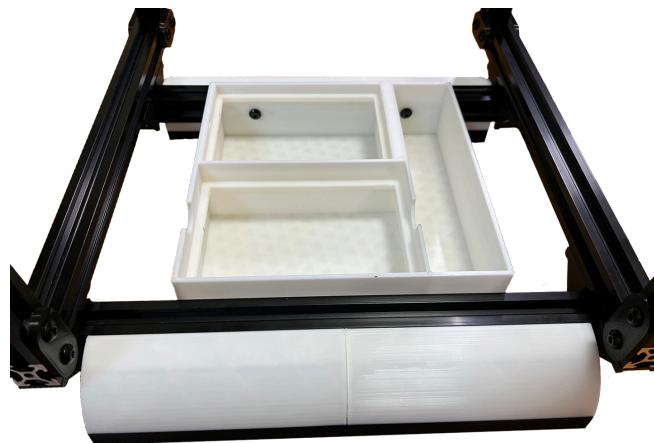
However, it's expensive. Pharmaceutical companies and large DNA sequencing service laboratories with a high cash flow are easily able to invest in state-of-the-art equipment. For smaller academic or clinical laboratories with much lower budgets, the reality is unlikely to be similar.<sup>6</sup> Furthermore, automated liquid handling devices can be extremely big, almost the size of a standard lab workbench,<sup>7</sup> which makes them extremely difficult to install. This disparity in accessibility creates an advantage to well-funded groups – it frees up time to allow valuable experts to focus on intellectual work while under-resourced/smaller labs need to spend more time on repetitive tasks which exacerbates the gap between the well-funded and under-funded laboratories.

In order to address this issue, 3D printed materials were considered to construct an automated liquid handling machine specific to the PCR liquid handling process. 3D printing was selected for its accessible price, durability of its materials, and wide adaptability through the distribution of design on the internet. The prototype was further tested to assess accuracy. This research suggests that this 3D printed prototype is accurate enough to perform the PCR handling process and opens up the possibility for increased accessibility of automated liquid handling devices by open-source design sharing.

## IV. Methods

### ***Frame Construction***

The base of the device had to include a holder for the tips of the pipette, the microtubes for PCR, and the used tips. Because the components of the PCR mix had to maintain a low temperature while pipetting, a customized base was printed to include an empty space below the microtube section to place ice. The base was stabilized with 2020 V Type Aluminum Profile 300mm and corner brackets were used to construct the base. The base is shown in the figure below (Figure 1).



**Figure 1.** Base constructed from 3D printed base, aluminum profiles and corner brackets.

<sup>5</sup> Gaisford

<sup>6</sup> Tegally

<sup>7</sup> AG, Tecan Trading. "Fluent - the Effective Way to Increase Productivity - Tecan." *Lifesciences.tecan.com*, 2021, [lifesciences.tecan.com/fluent-laboratory-automation-workstation](http://lifesciences.tecan.com/fluent-laboratory-automation-workstation). Accessed 7 Oct. 2022.

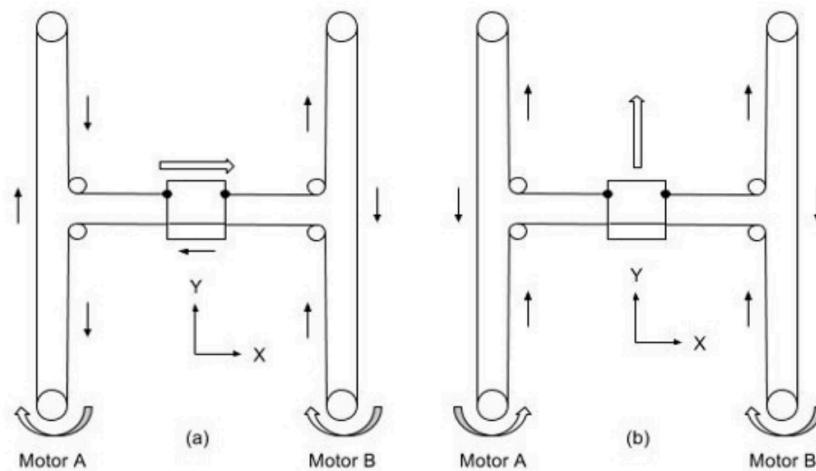
With the base of the device complete, 4 pieces of 2020 V Type Aluminum Profile 300mm is set vertically to create a topless box structure. On top of this, the H-bot structure will be recreated to enable the XY-plane movement for the pipette, and a lead screw design to enable Z-axis movement. Additional pieces were all 3D printed with a Flying Bear Ghost 5 printer, using PLA filament. The .stl files and the corresponding print settings can be found in the github link.

### **XYZ Axis Movement**

To achieve precise and flexible XY movements, we implemented the H-bot design, as illustrated in Figure 2, for several key reasons. Although the CoreXY design is often favored for its ability to reduce stress on the frame, we found its two-layer structure too complex and costly for easy online distribution. In contrast, the H-bot design, while generally less effective in large-scale models and at high speeds, proved to be better suited to our specific model requirements, where these factors are not significant.

One of the primary advantages of the H-bot design is its high space-to-movement ratio, which is crucial for creating a compact-sized machine. Additionally, the use of belts instead of lead screws and linear guides significantly reduces costs, making the design more economical. The load in the H-bot system is shared equally across the two identical stepper motors, ensuring balance and stability in the design. Furthermore, the stepper motors are positioned vertically outside the working space, which maximizes the available movement area within the machine.

In this design, the two stepper motors are aligned at the same height, driving the timing belt as shown in Figure 2. In the figure, the carriage, represented by a square, is attached to the timing belt on both sides. The carriage moves horizontally (left and right) along a linear guide, which itself has the pipette and components that account for the Z-axis movement. Figure 2a demonstrates that moving in the +X direction is achieved by rotating both motors clockwise at the same speed and by the same amount. Figure 2b shows that movement in the +Y direction occurs by rotating the A and B motors in opposite directions but still at equal speeds and amounts. When motion is required in a non-orthogonal direction, both motors must contribute, combining these basic movements. This configuration enables precise and coordinated movement in the XY plane, ensuring the accuracy necessary for our application.



### **H-Bot**

**Figure 2.** Design of the H-Bot system and representation of how XY movement is achieved. a) H-bot X-axis movement mechanics b) H-bot Y-axis movement mechanics.

The Z axis movement was achieved by the use of a shaft coupler attached to a stepping motor as seen in Figure 3. The shaft coupler was connected to a lead screw, which enabled Z-axis movement through the stepping motor's preset motion.



**Figure 3.** Stepper motor with shaft coupler and lead screw mechanism, providing smooth and precise movement for the attached pipette.

### ***Electronics and Wiring***

The setup utilized three Nema 17 stepper motors, each rated for 1.7A per phase with a recommended voltage of 12V, and a TowerPro servo motor with a rated current of approximately 850 mA and an operating voltage range of 4.8V to 6.6V. For controlling the stepper motors, a CNC Shield V3 was used in conjunction with A4988 driver modules equipped with heatsinks. The A4988 drivers are capable of handling a voltage range of 8V to 35V.

In stepper motors, both voltage and current are crucial parameters, but current is particularly important. The torque output of a stepper motor, which is essential for moving loads effectively, is directly proportional to the current flowing through the motor's windings. Higher current levels increase torque. However, running stepper motors at higher voltages can lead to overheating, particularly if the current is not appropriately managed. The effective voltage across the motor coils is also limited by back electromotive force (EMF), which increases with motor speed and reduces the net voltage applied to the windings. This makes current regulation more critical than voltage adjustments for maintaining optimal motor performance and avoiding overheating. Once the supply voltage exceeds the motor's rated voltage, its role becomes secondary to the current regulation. The rated voltage of each stepper motor winding is typically in the range of 2.8V to 3.6V, corresponding to an operating voltage for the whole motor of 8.4V to 10.8V.

Considering the total minimum current and voltage requirement for the stepper motors, a 12V, 120W AC to DC Switched-Mode Power Supply (SMPS) was selected to power the CNC Shield for several reasons. First, SMPS is highly efficient in converting AC power to DC with minimal energy loss, thereby reducing overall power consumption, especially when powering multiple motors simultaneously. Also, SMPS provides stable and regulated DC output, ensuring consistent and reliable performance of the stepper motors, which is crucial for precise applications. Additionally, SMPS is compact and lightweight, making it space-efficient and easy to integrate into systems with limited space. Finally, SMPS can handle a wide range of input voltages, accommodating variations in the input power supply (in this case, 110V to 220V). Ultimately, utilizing an SMPS AC to DC power supply ensures efficient, reliable, and space-saving power delivery to multiple stepper motors, enhancing their performance and system stability.

The wiring was kept simple. A three-prong rocker switch was attached before connecting the 220V AC cable to the SMPS AC to DC power supply. The output of the power supply, 12V and 10A, was

then connected to the CNC Shield which was connected to the Arduino. On the CNC shield, all the motors were connected as well as the A4988 Driver Modules.

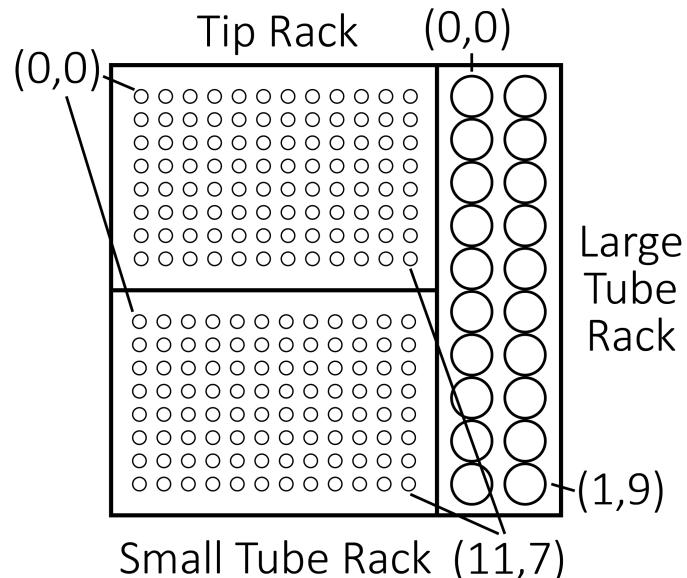
## Programming

To program the liquid handler, we utilized a combination of Arduino and Python with PySerial, creating a more flexible and user-friendly control system. The Arduino IDE was used to develop the core functionality, controlling all stepper motors to enable XYZ-Axis movement and managing pipette actions such as pressing and releasing.

A cartesian coordinate system was established in the program, designating the top left as the origin, and considering the right and bottom as the positive X and Y directions, respectively. The coordinate unit was defined using stepper motor steps, where a movement of 1 step towards the bottom right corresponds to the coordinate (1, 1). For more information on the XY-Axis movement and its functioning, please refer to the design and hardware details provided above.

Once the coordinate system was constructed, the program was designed to continuously mark the current coordinates of the pipette during execution, allowing easy pipette location tracking. Through trial and error, the coordinates for the first tip location, first tube location, tip ejection location, and the gaps of the tube/tip rack were manually determined and recorded as a constant in the code. We also determined the step counts for the Z-Axis separately for the tip rack, tube rack, and tip ejection, as each required different heights.

Based on these coordinates and information, we created several helper functions and three main functions: Tip(), B2TPipette(X, Y, x, y), T2TPipette(x1, y1, x2, y2), and reset(). The Tip() function automatically ejects the current tip and moves to the tip rack to attach a new tip. To ensure the correct tip is attached, the function keeps track of the number of tips. The B2TPipette(X, Y, x, y) function pipettes liquid from the big tube rack at (X, Y) to the small tube rack at (x, y). The T2TPipette(x1, y1, x2, y2) function pipettes liquid from coordinates (x1, y1) to (x2, y2) within the small tube rack. The reset() function returns the pipette back to the origin while releasing the servo if it is pressing on the pipette. These coordinates are specific to the tube rack coordinate system as seen in Figure 4. The small tube rack and tip rack has the top left tube as (0, 0) and the bottom right tube as (7, 11). The big tube rack has the top left tube as (0, 0) and the bottom right tube as (1, 9).



**Figure 4.** Coordinate systems for the tip rack, small tube rack, and large tube rack.

To enhance usability and allow for more complex sequences of operations, we implemented a Python script using PySerial to control the Arduino. This setup allows users to input sequences of operations through command-line arguments, which are then translated into commands sent to the Arduino.

The Python script uses argparse to accept command-line arguments for repetitions, from coordinates, to coordinates, and tube types. It then constructs a sequence of commands based on these inputs and sends them one by one to the Arduino using PySerial.

We implemented a robust communication protocol between Python and Arduino: The Python script waits for the Arduino to send an "Arduino ready" message before sending any commands. Each command sent from Python is acknowledged by the Arduino with a "Command completed" message. The Python script waits for this acknowledgment before sending the next command, ensuring that each operation is completed before the next begins.

This setup allows for much greater flexibility in programming sequences of operations. Users can now create complex sequences directly from the command line, without needing to modify and upload new Arduino code for each change in the sequence.

For example, a user can now run a sequence like this: {python pyserial\_control.py --repetitions 1 2 3 --from\_coords 0,0 1,1 2,2 --to\_coords 3,3 4,4 5,5 --tube\_types B T B}

This would execute a sequence of operations: First, attach a tip, then transfer from big tube (0,0) to small tube (3,3) once. Next, change the tip, then transfer from small tube (1,1) to small tube (4,4) twice. Finally, change the tip, then transfer from big tube (2,2) to small tube (5,5) three times.

This PySerial-based approach significantly increases the convenience and flexibility of the liquid handler, allowing for quick changes to operation sequences without needing to modify the Arduino code and upload a new code to the Arduino.

## **Assessing the Liquid Handler**

The accuracy and precision of the device were assessed by a test for their systematic and random error in the pipetting process. Liquid handling was performed with the machine and the resulting change in weight was measured with a microscale that could measure up to 0.0001 gram (g) of difference. The theoretical yield was set at 5  $\mu\text{L}$ , equivalent to 0.005 mg of distilled water, and both systematic and random errors were calculated to determine the device's accuracy and precision. For the measurement of the random error, the average mass was measured and all data was inserted to find the standard deviation. 1 standard deviation or sigma ( $\sigma$ ) away from the data average was defined as the random error of the pipette.<sup>8</sup> For the systematic error, the percent deviation of the data average from the theoretical yield was measured.

For comparison, the same pipetting process was performed manually using the same pipette to establish a benchmark for expected accuracy and precision. This step was crucial, as the device's performance is inherently linked to the accuracy of the pipette it uses. By understanding the inherent accuracy of the pipette through manual testing, we can accurately attribute any discrepancies in the automated system's performance to the device itself rather than the pipette. This ensures that when the difference between the manual testing and device testing is minimized, the transition from manual operations to automated operations did not cause a decrease in performance. By comparing the machine's results with manual pipetting, we ensured that the liquid handling performed by the device was able to achieve the same results as the manual process.

The prototype was taken to a laboratory and performed the liquid handling process of PCR. Subsequently, the applicability of the real PCR process of the liquid handling device was tested. The liquid handler pipetted 6 different components to produce a PCR master mix. The components were: 14.25 $\mu\text{L}$  PCR H<sub>2</sub>O, 2.5  $\mu\text{L}$  10X PCR Buffer, 0.5 $\mu\text{L}$  dNTP, 5 $\mu\text{L}$  primer mix, 2 $\mu\text{L}$  unprocessed tubulin gene

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<sup>8</sup> Eppendorf. *Random Error and Systematic Error of the Eppendorf Reference®*. 2. 2013.

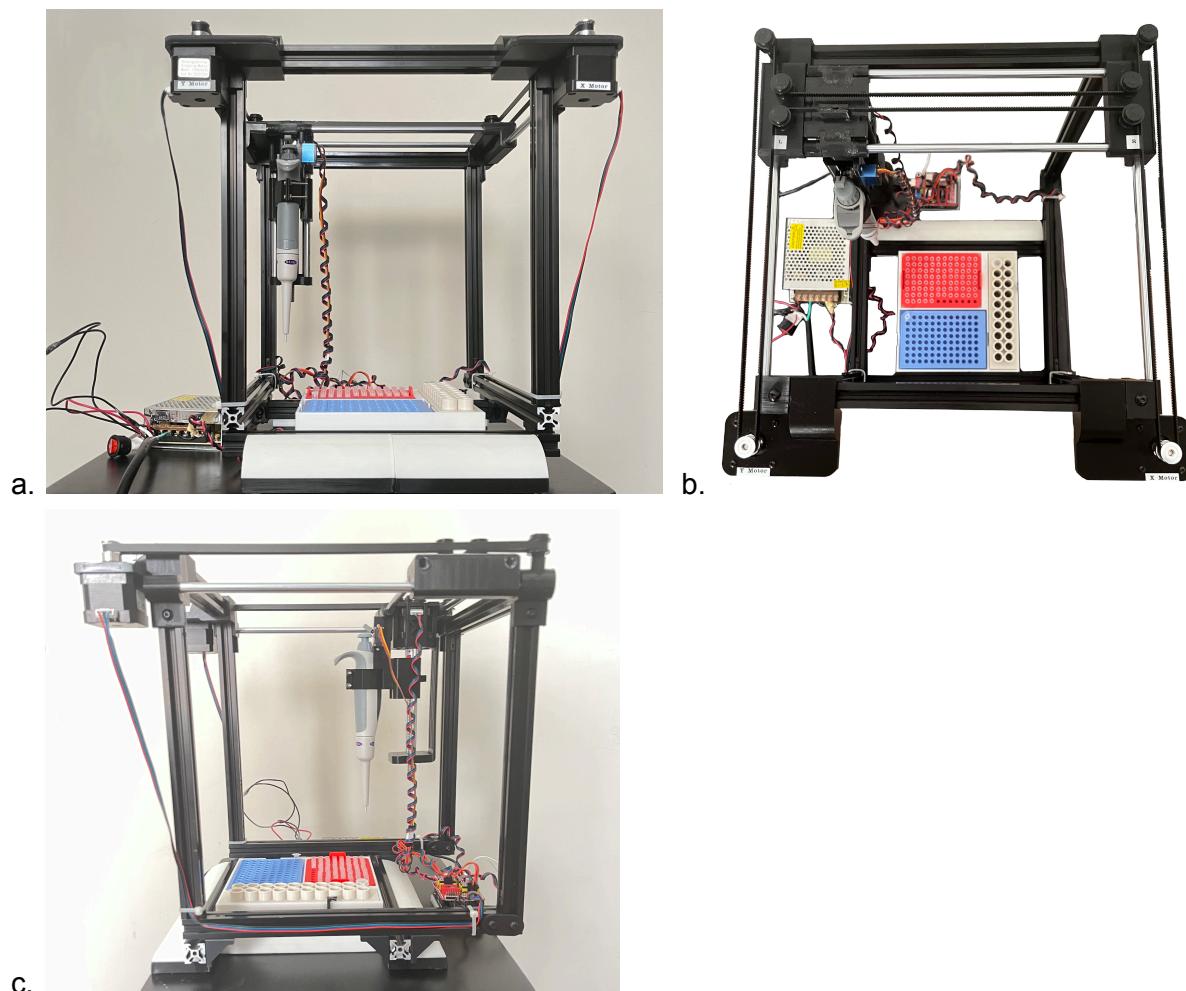
of plants, and  $0.75\mu\text{L}$  Taq polymerase. With a total volume of  $25\mu\text{L}$  in each PCR tube, a total of three tubes were prepared with the liquid handler. Another three PCR tubes were mixed by an experienced professional as a control group. The two groups of PCR tubes were then placed in the Bio-Rad T100 Thermal Cycler. Two randomly selected PCR tubes from each group were then analyzed with a standard western blot analysis.

Finally, the important metrics of the device were assessed. As a low-cost liquid handling device, the cost was considered most important. The accuracy and precision of a liquid handling device were recorded as important values to prove the device's effectiveness. The throughput of one cycle, including making master mixes for three PCR tubes, was measured to find its efficiency in the laboratory setting. Lastly, basic metrics such as dimensions and range of volume for the pipette were recorded in the table.

## V. Results and Discussion

### *Final Product*

The final product is presented in the front view, top view, and side view in the figure below (Figure 5).



**Figure 5.** Final product liquid handler a) front view b) top view c) side view from the left.

The front view provides a comprehensive look at the entire structure, showcasing all the components in their respective positions. The two stepper motors are prominently displayed at the top, each connected to a 20-tooth pulley wheel and a GT2 timing belt, which together facilitate precise XY-axis movement. These motors are properly interfaced with the CNC Shield V3, ensuring accurate control over their operations.

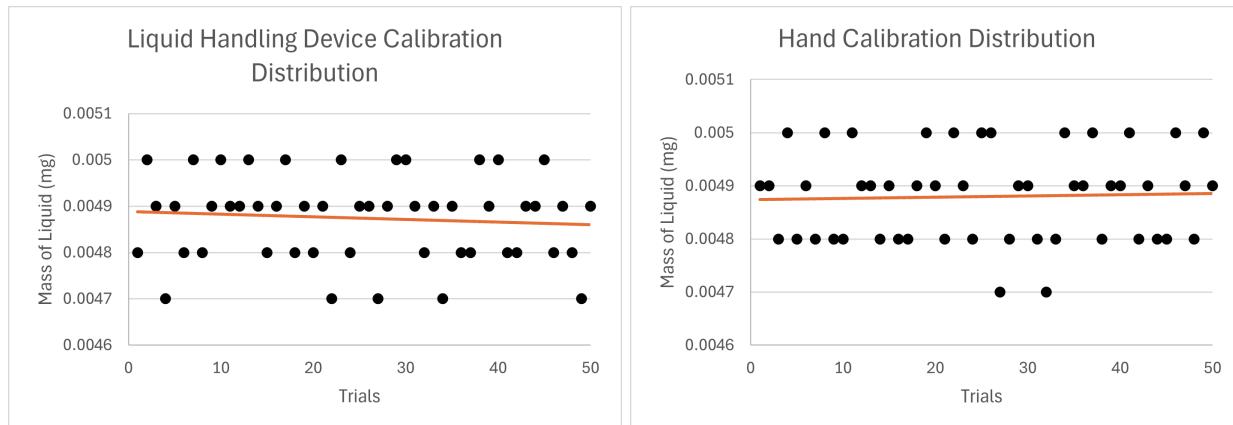
The top view emphasizes the H-bot structure, which is crucial for enabling coordinated XY-axis movement of the pipette. This design choice optimizes the available workspace, ensuring smooth and accurate pipetting across the designated area.

In the side view, the focus shifts to the stepper motor connected to a lead screw, which is directly attached to the pipette and servo motor. This arrangement is responsible for the Z-axis movement, as well as the precise piston pressing action required for accurate liquid handling.

The overall design of the product also allows for the flexible placement of key electronic components, such as the Arduino and the SMPS, facilitated by the use of long wire lengths. This flexibility ensures that the device can be easily adapted to different lab setups and workspaces, enhancing its usability and convenience.

### **Liquid Retention Rate Analysis**

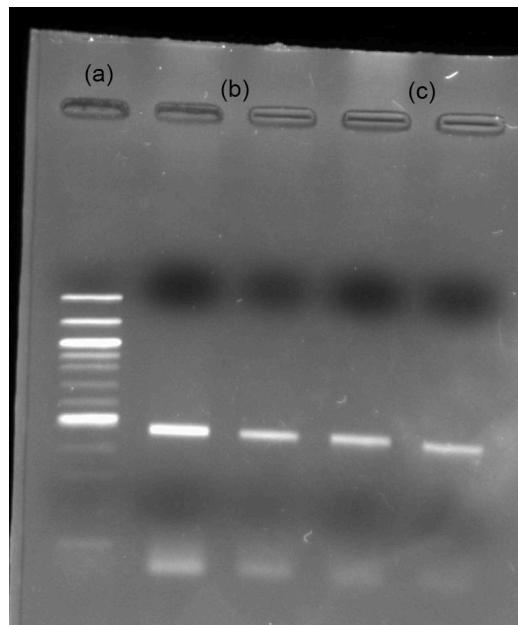
The systematic and random error in the pipetting process of the automated liquid handler was assessed. The data distribution of the results is presented in a graph below (Figure 6). The theoretical yield was 5  $\mu\text{L}$  or 0.005 mg of distilled water. With a sample size of 50, the mean value of the data was 0.004873 mg and the consequently calculated systematic error was 2.54% at 5  $\mu\text{L}$ . The standard deviation of the data was 9.124E-05 and the random error resulted in 1.82% at 5  $\mu\text{L}$ . This was not significantly different from the values obtained when performing the pipetting process by hand with the same pipette. When performed by hand, the mean value of the data was 0.004879 mg and the consequently calculated systematic error was 2.41% at 5  $\mu\text{L}$ . The standard deviation of the data was 8.485E-05 and the random error resulted in 1.70% at 5  $\mu\text{L}$ .



**Figure 6.** Data distribution of calibration done by the liquid handling device (left) and calibration done by hand (right) in milligrams with 50 trials.

### **Test PCR and Gel Electrophoresis Analysis**

Subsequently, the applicability of the liquid handling device in the real PCR process was tested. The liquid handler pipetted 6 different components to produce a PCR master mix that was distributed into three PCR strip tubes with 0.25  $\mu$ L in each tube. Another three PCR tubes were mixed by an experienced professional as a control. The PCR results are displayed below (Figure 7), proving that the liquid handler is applicable for PCR pipetting without influencing the result significantly.



**Figure 7.** PCR test results a) DNA ladder b) control group pipetted by experienced professional c) group pipetted by liquid handler; The white bands display that there is no significant difference between the control group and the group pipetted by the liquid handler.

### **Important Metrics**

After measurement, the important metrics of the liquid handling device was noted and organized in a chart below (Table 1). The accuracy was calculated as 97.46% and the precision was calculated based on the data excluding the outlier, resulting in 98.18%. The total cost of the device was \$205.99 at the time of purchase which was last updated on Aug 19th, 2024. The total dimension of the device is 35.4 cm x 44.7 cm x 38.2 cm. The time for a single B2T sequence, a sequence pipetting from the large tube to the small tube was 17.57 s and the time for a single T2T sequence, a sequence pipetting from the small tube to the small tube was 15.86 s. The additional steps, such as the duration of changing tip and the duration of resetting executed at the end was 18.18 s and 14.67 s, respectively. Additionally, the very first tip equipment when the program is ran took 6.33 s. Thus, a sequence of pipetting once from a large tube to a small tube and once from a small tube to another small tube would in total take 72.61 s or 1 minute and 12.61 seconds. Lastly the range of volume of the device was dependent on the pipette, ranging from 0.5  $\mu$ L to 10  $\mu$ L.

**Table 1.** Chart of the metrics regarding the automated liquid handling device.

<b>Accuracy</b>	97.46%
<b>Precision</b>	98.18%
<b>Cost</b>	\$205.99
<b>Dimensions (WDH)</b>	35.4 cm x 44.7 cm x 38.2 cm
<b>Duration of Changing Tip</b>	18.18 s
<b>Duration of Single B2T Sequence (0, 0) to (0, 0)</b>	17.57 s
<b>Duration of Single T2T Sequence from (0, 0) to (11, 7)</b>	15.86 s
<b>Duration of Reset</b>	14.67 s
<b>Range of Volume</b>	0.5 µL - 10 µL

## Discussion

The research was initiated to present an affordable and reliable replacement for the existing liquid handlers. Our focus was on reducing costs while achieving results comparable to manual pipetting, thereby alleviating the burden of repetitive labor in laboratories. Given budgetary and time constraints, we limited the device to a single range of motion, specifically designed for the PCR liquid handling process - a widely used and repetitive task in biological laboratories globally.

The liquid handler was tested for accuracy in two different ways. Its pipetting accuracy and precision was measured initially using a 0.0001g readability analytical balance. The accuracy was 97.46% and the precision was 98.18% which was not significantly different from the accuracy and precision of the manual process, 2.41% and 1.70% all at 5 µL. We plan to further test the device at 1µL and 10µL for more confirmation and availability to confirm with other devices. Opentrons stated that their OT-2 Robot has an accuracy of 15% error and precision of 5% error at 1µL, and an accuracy of 2% error and precision of 1% error at 10 µL.<sup>9</sup> Although direct comparison cannot be made, considering the accuracy and precision error increasing when the retention volume decreases, our device seems to show a reasonable performance compared to the OT-2 Robot by Opentrons.

Subsequently, the device performed the PCR process while an experienced biologist performed the PCR with equal material and controlled variables. The result displayed no signs of significant difference, indicating its availability in real application in laboratories for the PCR liquid handling process.

In terms of market comparison, our liquid handler stands out not only for its low cost but also for its compact size. While most commercial liquid handlers occupy an entire or half of the lab bench, our 3D-printed device measures just 35.4 cm x 44.7 cm x 38.2 cm, making it a viable option for smaller laboratories or those with limited space. Moreover, the design's accessibility is further enhanced by the ability to distribute all 3D-printed CAD designs online, allowing easy reproduction worldwide. The simplicity of sourcing materials and the availability of a detailed manual contribute to its potential for widespread adoption, particularly in underfunded or resource-limited settings.

<sup>9</sup> Opentrons. "OT-2 Automated Lab Robot | Opentrons." *Insights.opentrons.com*, insights.opentrons.com/ot-2-lp. Accessed 7 Oct. 2022.

However, there are certain limitations to this device. First, the device needs to connect the computer to the device to send commands. Although the accessibility was significantly increased through the usage of PySerial, the user needs to have some understanding of the Python programming language. Also, this increases the space taken up by the device significantly with the computer laid to the side. To address this issue, further research aims to replace the Arduino UNO and CNC Shield with a custom-designed PCB and create a control panel on the liquid handler machine itself using a liquid crystal display. This way, users can operate the liquid handler without the need for a computer. Furthermore, the device requires the user to change the pipette volume manually. This presents an issue with the flexibility and adaptability of the machine. The device's incapability to change pipette volume deters its ability to be applied to different experiments beyond PCR. Currently, a bevel gear design controlled by a low torque stepper motor is planning to be implemented for accurate volume change. Finally, the accuracy and precision, although proven to be sufficient to perform PCR, can be improved upon. Several ways are proposed such as implementing the reverse pipetting method to increase accuracy.<sup>10</sup>

## VI. Conclusion

The development of a low-cost liquid handling device presented in this research demonstrates a significant advancement in making automated laboratory devices more accessible. Despite the device's economical construction, it achieved a relatively high accuracy and precision, almost equal to the hand retention results, for its low cost and was able to perform PCR without damaging the sample DNA template.

The development of this low-cost liquid handling device offers a critical advantage in labor efficiency, which is particularly important for underfunded laboratories. In research environments where resources are limited, the manual execution of repetitive tasks like PCR pipetting can consume a significant amount of time and energy, diverting attention from more complex and innovative work. By automating these routine processes, the device frees up valuable time for researchers, allowing them to focus on tasks that require higher cognitive skills and creativity.

For underfunded labs, where staff may be limited and the demand for productivity high, this automation reduces the burden on researchers, helping to prevent burnout and improve overall workflow efficiency. The time saved by using this automated system can be redirected toward tasks that drive scientific discovery, such as data analysis, experiment design, and problem-solving, thereby enhancing the lab's capacity to produce high-quality research despite limited resources.

Moreover, the reduction in manual labor also minimizes the potential for human error, leading to more consistent and reliable results. This reliability is crucial in ensuring that research findings are reproducible and credible, which is especially important in environments where resources to redo experiments are scarce.

Furthermore, the open-source nature of the design enhances its potential impact. By making the 3D-printed CAD designs and instructions freely available online, the device can be easily reproduced and adapted to meet the specific needs of laboratories around the world. This adaptability is particularly important in regions where access to specialized equipment is limited, enabling local innovation and customization that can drive scientific progress in context-specific ways.

However, there are limitations on accessibility and the need for frequent calibrations, demanding future development and research of the device. The necessity of a connected computer and basic programming knowledge for operation limits the device's usability in environments without these resources. Additionally, the current inability to automatically adjust pipette volumes restricts the device's versatility in handling a broader range of laboratory tasks.

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<sup>10</sup>Teye, Marian. *Application Note How to Pipette PCR Master Mix for Increased Accuracy in QPCR Results*. 2018.

Future research should focus on enhancing the device's user interface, possibly integrating a built-in control panel with a liquid crystal display and automated volume adjustment mechanisms such as a stepper motor with a bevel gear design to further improve its practicality and adaptability. Moreover, while the accuracy and precision are adequate for PCR, ongoing refinements, such as incorporating reverse pipetting techniques, could further enhance performance.

Overall, this research underscores the importance of developing cost-effective alternatives to high-end liquid handling devices which have costs ranging from \$9,000 to \$60,000, paving the way for broader adoption of automated tools in diverse laboratory settings. The open-source nature of the design ensures that this innovation can be widely distributed and adapted, contributing to the global effort to make scientific research more inclusive and efficient.

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