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Commit: Digital pipette: open hardware for liquid transfer in self-driving laboratories

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Precise liquid handling is an essential operation for self-driving laboratories. In 2023, we introduced the digital pipette, a low-cost, 3D-printed device that enables accurate liquid transfer by robotic arms. However, the initial version lacked mechanisms to prevent cross-contamination when handling multiple liquids. In this commit paper, we present the digital pipette v2, an updated design that mitigates contamination risk by allowing robotic arms to exchange pipette tips. The new hardware achieves liquid handling accuracy within the permissible error range defined by ISO 8655-2, supporting a broader range of experiments involving multiple liquids.

1 Introduction

Self-driving laboratories (SDLs)[1] have been accelerating the pace of scientific discovery by integrating automated experiments with artificial intelligence (AI) for efficient decision-making. Given the central role of liquid handling in many experimental workflows, the precise automation of this process is a critical component of SDLs. Consequently, various automated liquid-handling devices have been developed and are now available commercially[2] or as open-source hardware. Popular liquid handling devices such as the OT-2 (Opentrons) and Science Jubilee[3] perform automated pipetting within confined spaces using gantry-based mechanisms. These systems are typically limited to vertical pipetting at fixed positions on standard well plates. While they are effective for many routine experiments, some workflows require more advanced pipetting capabilities. For example, 3D cell culture demands delicate motion to minimize mechanical stress during pipetting, as well as angled pipetting to reach the bottom edges of culture plates. Pipetting onto non-standard or dynamic targets, such as plants or small animals, necessitates real-time, computer vision-guided feedback to ensure accurate liquid placement.

To realize more flexible liquid handling, recent studies have explored the use of robotic arms equipped with manual pipettes.[4,5] These systems often employ customized end-effectors, which limit the robotic arm's versatility for other tasks, because manual pipettes are not suitable for standard two-fingered robot grippers, due to their shape and control mechanism. While electronic pipettes with digital control interfaces can serve as a potential alternative, most are ergonomically designed for human operation and do not integrate well with standard robot grippers. Moreover, their control APIs are often proprietary, which hinders the development of open-source control software. The high cost of commercial electronic pipettes further limits their adoption in budget-conscious laboratories. Although several open-source liquid handling tools have been developed for gantry-type robots,[6,7] integrating them with robotic arms remains challenging.

To address these problems, we introduced our digital pipette in 2023.[8] The device incorporates a low-cost commercial syringe and a linear actuator to control its plunger within a flat-sided enclosure, enabling precise liquid handling through electrical signals and eliminating the need for dexterous manipulations. Its simple design has facilitated adoption beyond the original development team, such as integration into the Science Jubilee platform.[9] A major limitation of the initial version was its inability to handle multiple liquids without risking cross-contamination. Although disposable pipette tips are commonly used to prevent contamination, the design of the commercial syringe was incompatible with these tips.

This commit paper presents the digital pipette v2, updated to handle multiple liquids without contamination by using disposable pipette tips (Fig. 1). We replaced the commercial syringe with a 3D-printed one compatible with commercial 10 mL pipette tips. This modification enables the robot to handle multiple liquids without contamination, broadening the range of possible experiments. Detailed descriptions of the

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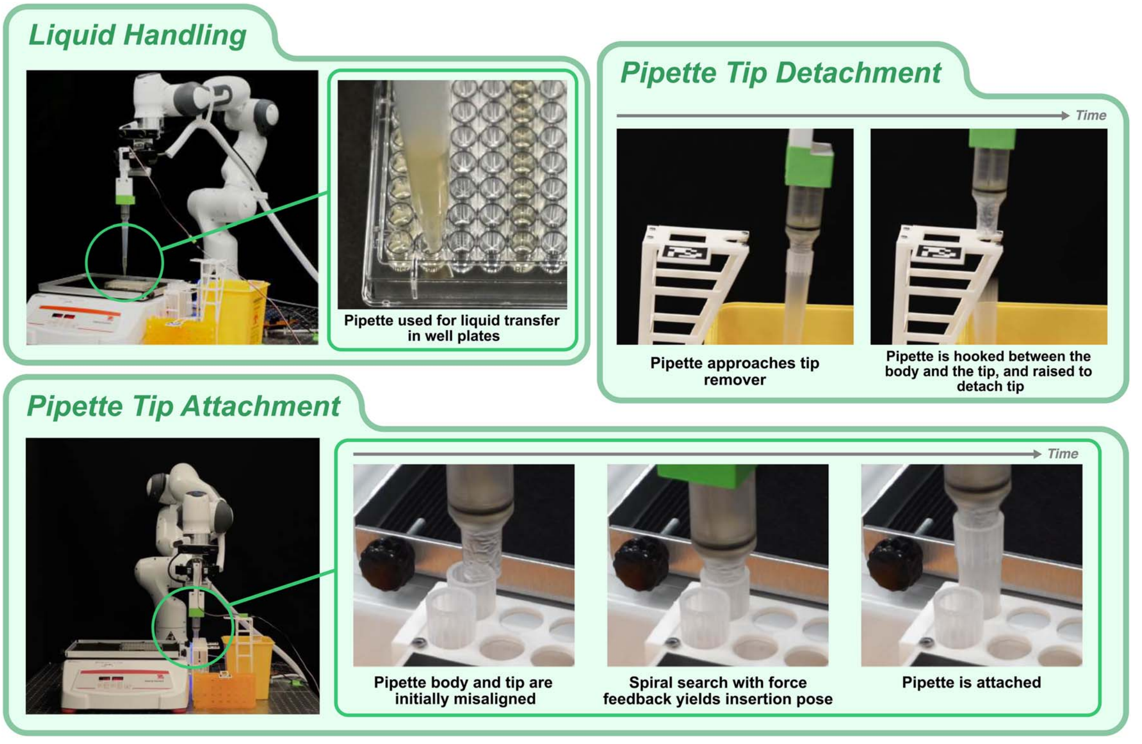

Fig. 1 Functionalities of the digital pipette v2. It enables liquid handling without cross-contamination using disposable pipette tips. Tips can be attached from a tip rack and detached using an external tip remover.

updated design and its experimental evaluation are provided in the following sections. The data in this paper are also shown in our other work introducing the application of this hardware.[10]

2 Design

2.1 Pipette design

The digital pipette v2 consists of four 3D-printed components: the platform, syringe, cover, and plunger. A photo of the assembled pipette alongside the CAD models is shown in Fig. 2. The most significant difference from the original version is the use of a 3D-printed syringe designed to accommodate a pipette tip. As a result of this change, the new version falls into the category of an air displacement (Type A) pipette,[11] whereas the original version was a positive (direct) displacement (Type D) pipette.

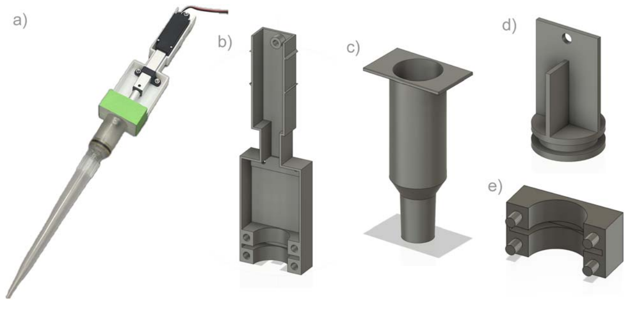

Fig. 2 (a) Photo of the assembled digital pipette v2. (b–e) 3D CAD models of the digital pipette v2 components: (b) platform, (c) syringe barrel, (d) plunger, and (e) cover.

To keep the syringe airtight, we used a stereolithography apparatus (SLA) printer, which enables more precise printing than low-cost fused deposition modeling (FDM) printers. The head of the syringe barrel (Fig. 2(c)) is designed to accommodate a pipette tip (BRAND pipette tips, volume 1–10 mL, Sigma-Aldrich). To keep the overall length of the device short, the radius of the barrel is designed to cover the nominal volume (10 mL) within 5 cm to enable the use of a smaller linear actuator than the one used in the original version. The plunger (Fig. 2(d)) has a groove to attach an O-ring to ensure an airtight seal within the syringe piece. Grease (MOLYKOTE High-Vacuum Grease, DuPont) is used to maintain an airtight connection between the pipette tip and the syringe body, as well as the O-ring and syringe barrel. A linear actuator with a stroke of 5 cm (L16-50-63-6-R, Actuonix), secured to the platform (Fig. 2(b)) using screws and a mounting bracket, pulls on the plunger to generate suction inside the pipette tip. An Arduino microcontroller interfaces with the robot workstation *via* USB-serial communication to control the linear actuator, enabling operation of the pipette using a standard robot gripper without extensive hardware modifications. The cover (Fig. 2(e)) holds the syringe to the platform and is fixed with tape to ensure stability. The 3D models were designed with Fusion 360 (Autodesk Inc.). The platform and the cover were printed with white ANYCUBIC PLA using a KP3S printer (KINGROON Tech Co., Ltd), and the syringe and plunger pieces were printed with Clear Resin V4 (Formlabs Inc.) using a Form 3L printer (Formlabs Inc.). The

Table 1 Cost analysis of our proposed digital pipette v2

Parts	Price (USD)
Linear actuator (Actuonix L16-50-63-6-R)	70
Est. 3D printing cost for PLA parts (platform, cover)	35
Est. 3D printing cost for resin parts (syringe, plunger)	125
Electronic parts (Arduino, cables, connectors)	40

pipette can be assembled in under 10 minutes, excluding the printing time, with detailed assembly instructions and CAD models available in our GitHub repository (**https://github.com/ac-rad/digital-pipette-v2**).

The electrical circuit is unchanged from the initial version. We use an Uno 328 AVR Dev Board (Creatron Inc., Canada), which is compatible with the Arduino Uno Rev3, to control the linear actuator. The actuator is powered by a 6 V DC supply and communicates with the controller PC through USB serial. It receives a 5 V pulse signal from the Arduino that determines its extension length.

2.2 Cost analysis

The approximate prices for the components used to build the digital pipette v2 are shown in Table 1. The 3D printing prices were estimated using online printing services (Xometry, Shapeways), which are likely to be higher than the actual cost of the raw materials. Our pipette can be built for under 300 USD, which falls within the typical price range of laboratory micropipettes, which generally cost between 50 and 350 USD.

2.3 Attachment and detachment of pipette tips

We used a pipette tip rack for attaching tips and a pipette tip remover for detaching them (Fig. 3). Both are printed using a Form 3L printer with Formlabs Rigid 10 K Resin. Their designs are also available in the same GitHub repository.

Attaching pipette tips requires highly accurate alignment, which necessitates careful calibration in many existing pipetting systems. To reduce the calibration effort and improve positioning flexibility, we developed a force-feedback-based positioning system in which the robot moves the pipette along a spiral trajectory while monitoring the force at the end effector to locate the correct insertion point. For pipette tip removal, the robot moves to a fixed position to hook the pipette tip onto the remover and then pulls the pipette upward to extract the tip. Further details are provided in our other work.[10]

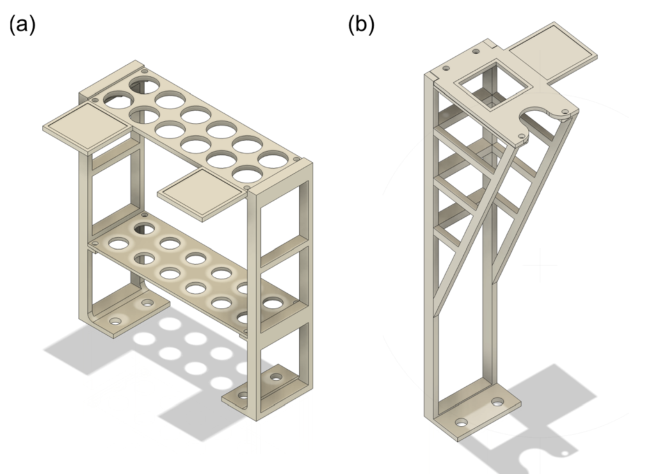

Fig. 3 CAD models of (a) the pipette tip rack, and (b) the pipette tip remover.

3 Evaluation

We evaluated the pipette's liquid dispensing accuracy using a gravimetric testing procedure described in the International Standard on Piston-Operated Volumetric Apparatus (ISO 8655-6).[12] In this procedure, the weight of dispensed volume was measured using a 0.1 mg precision balance (AUX220 Analytical Balance, Shimadzu), and the systematic and random errors were calculated from the mean delivered volume over multiple iterations at target volumes of 1 mL, 5 mL, and 10 mL. While a robotic arm operated the pipette in this evaluation, other details of the evaluation followed the original paper.[8] Based on the experimental conditions (temperature 23.4 °C and air pressure 100.4 kPa), a Z correction factor of 1.0036 was used for calculation.

Table 2 summarizes the results, reporting the mean delivered volume $\bar{V}$, the systematic error η_s, and the random error C_v. The observed errors were significantly below the maximum permissible limits defined by ISO 8655-2,[11] indicating high repeatability of the digital pipette v2.

In addition, four experienced human operators performed the same gravimetric testing procedure to compare the reliability of the digital pipette v2 with manual pipetting (Fig. 4). To evaluate the pipetting performance when handling small volumes, we tested dispensing at 0.2 mL, 1 mL, and 5 mL. Each operator performed five replicates at each volume. For the 0.2 mL and 1 mL volumes, a standard P1000 pipette was used as the human baseline, while a 5 mL serological pipette was used for the 5 mL volume. Operators were instructed to carefully aspirate the desired volume and dispense it fully, mirroring the procedure followed by the digital pipette v2. For

Table 2 Results of the gravimetric test. The systematic error η_s and the random error C_v obtained from the gravimetric test are shown with the values of the original version[8] and the maximum permissible errors defined by ISO 8655-2

Volume (mL)	Device/standard	$\bar{V}$ (mL)	η_s (%)	C_v (%)
10.0	Digital pipette v2	9.9909	−0.09	0.10
	Digital pipette v1	10.0083	0.08	0.07
	ISO 8655	—	0.6	0.3
5.0	Digital pipette v2	4.9949	−0.10	0.16
	Digital pipette v1	4.9922	−0.16	0.14
	ISO 8655	—	1.2	0.6
1.0	Digital pipette v2	0.9951	−0.49	0.58
	Digital pipette v1	0.9887	−1.1	0.76
	ISO 8655	—	6.0	3.0

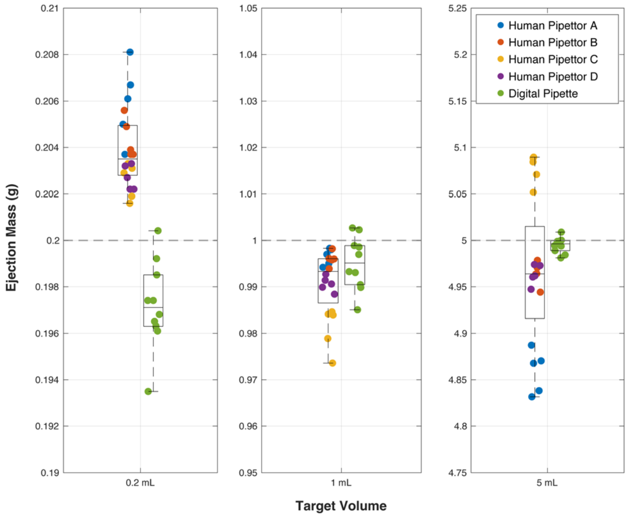

Fig. 4 Gravimetric comparison of the digital pipette v2 with human pipettors, for volumes of 0.2 mL, 1 mL, and 5 mL. A Levene's test was conducted to compare the variances between the two groups (digital pipette v2 *vs.* human).

the 0.2 mL and 1 mL tests, there were no significant differences in variance between the two groups ($p = 0.8754$ and $p = 0.6533$, respectively). However, for the 5 mL test, the digital pipette v2 demonstrated significantly lower variance ($p = 0.0046$).

3.1 Calibration

The linear actuator in the digital pipette v2 is operated by a 5 V signal, where the pulse length determines the actuator's extension. The relationship between pulse length (in µs) and delivered volume (in mL) was measured after assembling the pipette, and the optimal pulse length for the target volumes was determined from the resulting calibration plots before the evaluation. The calibration should be performed regularly to maintain high accuracy. Example calibration plots for the 10 mL target volume are shown in Fig. 5 and 6.

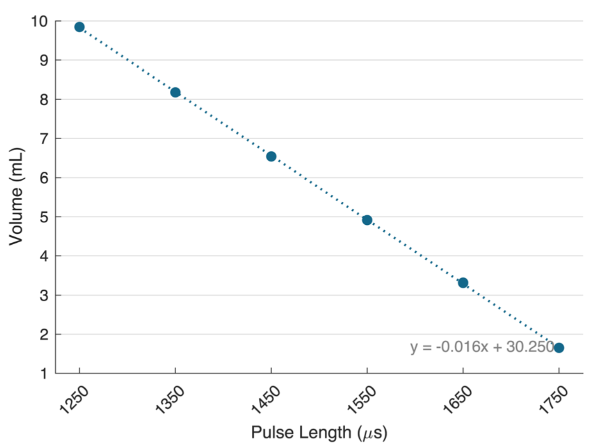

Fig. 5 Pipette calibration plot for six pulse lengths between 1250 and 1750 µs. Error bars are included but not visible.

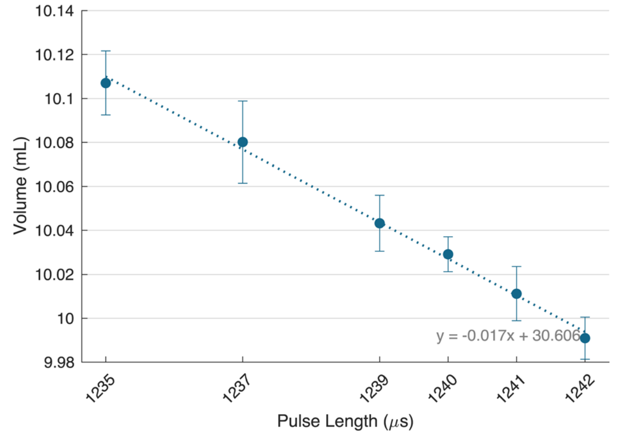

Fig. 6 Pipette calibration plot for six pulse lengths between 1235 and 1242 µs, used to calibrate the pipette for 10 mL expulsion.

4 Conclusions

In this commit paper, we presented the digital pipette v2, which supports the attachment and detachment of pipette tips by using a 3D-printed syringe. The new design enables robotic arms to handle multiple liquids without cross-contamination while maintaining the accuracy specified by international standards.

Although the new design broadens the scope of supported experiments, several limitations remain. First, the current syringe requires grease between the pipette tip and the syringe to maintain an airtight seal, unlike most commercial pipettes. This is due to surface roughness resulting from the limited precision of 3D printing. The need for greasing increases maintenance costs. In the future, alternative fabrication methods, such as CNC machining, may be adopted to obtain smoother surfaces, as demonstrated in the development of a tip holder for Open Lab Automata.[13] Second, biochemical experiments often involve handling very small liquid volumes around 1 µL. While the nominal volume of the digital pipette can be adjusted by modifying the syringe design, achieving µL-level accuracy may require higher-precision actuators. Finally, the current system relies on an external pipette tip remover, whereas most commercial micropipettes are equipped with a built-in tip ejection mechanism. Incorporating such a function would require a more complex mechanical design that can be actuated by an external signal. We will continue developing open hardware for precise, automated liquid handling with robotic arms.

Author contributions

N. Y: conceptualization, methodology, writing – original draft. K. A: investigation, visualization, writing – original draft. K. D.: project administration, writing – review & editing. S. O., D. B., I. Y.: investigation, writing – review & editing. M. R., A. A. G.: supervision, writing – review & editing, funding acquisition.

Conflicts of interest

There are no conflicts to declare.

Data availability

The design files and source code used in this paper can be found at **https://github.com/ac-rad/digital-pipette-v2** (DOI: **https://doi.org/10.5281/zenodo.17549134**).

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