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Design and fabrication of a low-cost 3D-printed pH sensor positioning robot for laboratory automation

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ABSTRACT

A fully open-source, 3D-printed robotic system is developed for automated pH measurements. The robot integrates a stepper motor-driven lead screw and an analog pH sensor to enable precise vertical positioning of the probe. A terminal-based control program allows automated motion and data acquisition, with safety features preventing overextension. Evaluation with standard buffer solutions (pH 4.0 and 7.0) demonstrates accurate and reproducible measurements. This modular, low-cost platform facilitates scalable and reproducible data generation for materials research.

1. Introduction

Materials informatics has dramatically transformed the way materials are designed and discovered. Traditionally, materials development relied heavily on researchers—hypotheses, intuition, and iterative trial-and-error experimentation[1–3]. The emergence of data-driven approaches, including machine learning and data mining, has enabled the extraction of meaningful patterns from large materials datasets, allowing the prediction of promising compositions and structures prior to experimental validation[4, 5]. This shift has significantly accelerated the materials discovery process. However, new challenges have also emerged. A major bottleneck lies in translating predicted materials into experimentally synthesized products. Predicted materials lack established synthesis routes, forcing researchers to rely once again on labor-intensive and skill-dependent trial-and-error strategies. In addition, materials informatics fundamentally depends on the availability of large, high-quality datasets, making systematic and reproducible data generation essential.

To address these challenges, combinatorial chemistry and high-throughput experimental platforms have been developed to automate parameter screening and accelerate data

acquisition[6–8]. While highly effective, such systems often require specialized expertise and substantial financial investment, limiting their accessibility to industrial facilities[9]. Recent advances in open-source electronics, open hardware ecosystems, and affordable 3D printing technologies provide an alternative pathway toward democratizing laboratory automation[10–12].

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By utilizing these technologies, researchers can design and fabricate customized robotic systems tailored to specific experimental needs at significantly reduced cost and increase reproducibility and throughputs[13]. In this work, a fully open-source, 3D-printed pH sensor positioning robot is presented that automatically moves a pH probe vertically to enable controlled and reproducible measurements. This system is intended as a modular component for integration into in-house automated materials synthesis platforms, demonstrating how accessible robotics can contribute to scalable and reproducible data generation in materials science.

2. Components and software

All parts used in the 3D-printed pH sensor positioning robot are listed in Table 1. The system combines mechanical, actuation, electronics, and sensor components to achieve precise vertical motion of the pH electrode. Mechanical components include aluminum frames, linear guide rods, lead screws, bearings, and 3D-printed parts that form the structural and moving elements of the robot. The actuation system consists of a NEMA 17 stepper motor controlled via an A4988 driver, which drives the lead screw to achieve controlled vertical translation. Electronics and control components are centered around an ELEGOO Uno R3 microcontroller and a standard breadboard, powered by a 12 V DC supply. *Gravity Analog pH Sensor Kit V2 (SKU SEN0161-V2)* manufactured by DFROBOT is implemented for pH measurement system. Blender is used to design models. A *Bambu Lab X1 Carbon* 3D printer is used for 3D printing, and polylactic acid (PLA) filament is used as the printing material.

2.1. Design

The basic design architecture of the pH meter robot is based on vertical motion control of the pH electrode for automated pH measurements. The system consists of aluminum frames, a pH meter, a stepper motor, and standard mechanical components such as screws and nuts. A stepper motor drives a lead screw through a shaft coupling, which converts rotational motion into linear displacement. This mechanism enables the stage, to which the pH meter is attached, to move up and down in a controlled manner as illustrated in Figure 1. The vertical translation of the stage allows the electrode to be positioned reproducibly for pH measurements.

2.2. Frame construction

Based on the predetermined dimensions, aluminum frames are cut to the required lengths and assembled. Corner brackets are used to join the frames and enhance structural rigidity. Two types of aluminum frames are employed, both with a cross-sectional area of 2cm×2cm and lengths of 50cm and 20cm, respectively. Before fixing the vertical and horizontal frames together, two square nuts are inserted into both the front and rear internal channels of each horizontal frame. The front square nuts are used to secure the upper and lower stages, whereas the rear square nuts are used to attach a storage box designed to house the breadboard and wiring.

2.3. 3D-printed components

Structural components are fabricated using a 3D printer. Three-dimensional models are generated in Blender, with iterative adjustments to ensure proper integration with the overall assembly. Printed components include the bottom, middle, and top stages; rod clamp collars for vertical fixation; and a rear enclosure for wiring and electronics as shown in Figure 2.

2.4. Stepper motor control circuit

The stepper motor and pH sensor are controlled using an ELEGOO UNO R3 microcontroller. The wiring configuration is constructed on a breadboard, integrating connections for stepper motor operation as well as the analog pH sensor input. The circuit design and code implementation follow established Arduino-compatible protocols, ensuring reliable operation and reproducibility. Figure 3 illustrates the control setup: panel (a) shows a photograph of the assembled system, including the ELEGOO UNO R3, pH sensor board, and breadboard, while panel (b) presents a schematic flow diagram of the electrical connections and signal flow. This configuration allows simultaneous control of the stepper motor and real-time acquisition of pH measurements, enabling automated positioning and monitoring in the robot system.

3. Result and discussion

3.1. Assembly procedure

Once all necessary parts are acquired and the aluminum frame is constructed, the robot is assembled. Figure 4 shows the final assembled pH meter robot from multiple perspectives, highlighting the completed frame, vertical stages, pH meter positioning, and stepper motor integration. All screws used in the robot frame assembly have a diameter of 5mm and a length of 8mm. Standardizing fasteners simplifies component management and reduces cost. To ensure proper fit, the radius of the screw holes in the 3D-printed components is designed to be 0.03mm larger than the screw radius, providing smooth insertion while maintaining mechanical stability. The assembly procedure is divided into four main steps as described below.

(1) Installation of stages, pH meter, and motor

The upper and lower stages are positioned on the horizontal aluminum frames with precise alignment to ensure symmetrical alignment. Screws are inserted into the pre-installed square nuts to secure the stages. The pH meter is inserted through the middle stage and fixed vertically using rod clamp collars to prevent displacement during operation. The motor responsible for driving the pH meter is mounted on the upper stage.

(2) Insertion of support rods and stage alignment

The middle stage is positioned between the upper and lower stages. Vertical support rods are inserted through all three stages, and rod clamp collars are used to secure the vertical alignment so that the stages are arranged coaxially. Due to dimensional constraints, the lead screw is inserted into the middle stage at this stage of assembly.

(3) Integration of the motor–lead screw mechanism

A coupling is attached to the motor shaft extending downward from the upper stage. The lead screw is inserted into the coupling and secured with set screws. This configuration converts the rotational motion of the motor into rotational motion of the lead screw, which produces vertical translational motion of the middle stage and the attached pH meter.

(4) Installation of rear enclosure

The rear enclosure is attached to the back of the robot using screws inserted into the previously installed square nuts within the horizontal frames. This enclosure houses wiring and electronic components, improving cable management and overall system organization.

3.2. Control program

A control program is designed and developed to coordinate the vertical motion of the pH sensor and acquisition of pH measurements, enabling automated operation of the robot. Commands are executed via a terminal interface, enabling operation without specialized software. It is written using Arduino C++. Specific character inputs trigger predefined actions: “U” raises the pH sensor, “D” lowers it, “W” and “X” provide fine upward and downward adjustments, “S” stops motion, and “V” triggers pH measurement. pH values are displayed in the serial monitor. The commands “enterph” and “calph” perform pH sensor calibration. After immersing the sensor in a solution, “enterph” is entered, and after a 1-minute stabilization period, “calph” completes calibration. The procedure is first performed with a pH 7.0 standard buffer, then repeated with a pH 4.0 or 10.0 buffer. The movement distances for “U” and “D” are calibrated for the dimensions and mechanics of this robot. Safety features include the emergency stop command “S” and prevention of repeated consecutive “U” or “D” inputs, which avoids accidental overextension or mechanical damage. In the Z-axis adjustment system of this robot, no position-detection sensor is used to stop the movement. Instead, the displacement is controlled by the number of rotations of the stepper motor. Therefore, when the required movement distance of the pH meter changes depending on factors such as the sample volume, the adjustment must be performed manually by changing the number of motor rotations rather than automatically. Consequently, accurate adjustment is necessary.

3.3. Operation

Figure 5 illustrates the robot during operation, including the positioning of the pH probe and the control program interface. The system precisely controls vertical positioning of the pH probe, maintaining a consistent immersion depth and stabilization time prior to measurement. A stepper motor-driven lead screw provides smooth and reproducible probe insertion and withdrawal.

The pH measurement robot is evaluated using standard buffer solutions with nominal pH values of 4.0 and 7.0, corresponding to actual pH values of 4.01 and 6.86, respectively, and separately prepared solutions with pH values of 1.0, 2.0, 10.0, 11.0, and 12.0. First, the pH values were measured using a benchtop pH meter (LAQUA PH-SE, HORIBA Advanced Techno Co., Ltd., Japan), followed by measurements using the pH measuring robot. Each measurement was performed three times, and the average value was used as the final measured value. The measured pH values obtained using the benchtop pH meter and the pH measuring robot are summarized in Table 2.

Figure 6 presents the results obtained using the robot, plotted with error bars. Measured pH values matched the reference values for both buffers with a percentage error of 1.5 %, confirming the accuracy of the sensing and positioning system. Repeated measurements exhibit minimal variation, demonstrating high reproducibility. By eliminating errors associated with manual handling, such as variable immersion depth, angular misalignment, and vibration, the robot delivers reliable and repeatable pH measurements.

3.4. Modularity and future applications

The pH-measurement robot is designed with modularity in mind. First, it can behave independently as an assistant for researchers wanting to test pH of liquid samples. Its reusability helps reduce the need for specialty pH-measuring strips and also offers itself as a less costly alternative to commercially-available electronic pH meters. Additionally, though presented as an independently-functional robot, this robot is designed with the intention of becoming an

integrated part of a larger overall robotics system. Given that its program is written in Arduino C++, it is possible for it to communicate with other programs and systems that are a part of an Arduino-based system. One such application is to combine its use with a synthesis robot like the FLUID robot, where chemicals are added to a beaker or other similar-style container, and beakers are transported between robots using tools such as a conveyor belt or a robotic arm. [14] Once pH readings are taken, the meter is cleaned through the introduction of deionized water via a beaker transported by a separate arm and the pH is retaken to ensure previous product is rinsed properly. Once confirmed to be cleaned, then it is ready to take the next reading. While this is a basic example of its application, the lightweight design and utilization of open-source and easily-accessible systems helps reduce the barriers of entry when adopting and customizing the robot to introduce to ones own laboratory set-up.

4. Conclusion

In summary, a 3D-printed, open-source robotic system enables automated, reproducible pH measurements with precise vertical positioning of the probe. The stepper motor-lead screw mechanism and terminal-based control program provide reliable operation and minimal measurement variation. The measurement robot developed in this study is designed for easy installation through its use of a lightweight frame and offers higher customization while remaining low-cost through its use of 3D printing and adoption of open-source tools. Additionally, its program is easy to use and able to easily communicate with other Arduino-based systems, enabling modular capabilities where it can function independently or be incorporated into a larger system. Furthermore, additional functions can be integrated depending on the application. For example, a conveyor system can be installed at the base of the robot to automatically transport samples, while a beaker for electrode cleaning can be placed within the operating area to enable automated cleaning procedures. Since the design and construction methods of the robot are openly available, users can modify and expand the system according to their specific requirements, including the desired functionality and scale. This low-cost, modular platform thus offers a scalable solution for integrating automated measurements into laboratory workflows.

5. Supporting information

The Supporting Information contains further details regarding the following: hardware and software tools; chassis parts; static hardware parts; 3D-printed plastic parts; moving parts; power supply, cables, and wires; microcontroller boards; circuit diagrams; and parts and costs.

All source codes and design files for the pH sensor positioning robot are openly available at the following GitHub repository: <https://github.com/Materials-Informatics-Group/pH-measurement-Robot>

The Supporting Information includes:

- **3D-Printable Parts:** STL files for all custom-designed 3D-printed components used in the pH robot assembly.

<https://github.com/Materials-Informatics-Group/pH-measurement-Robot/tree/main/3D-Parts>

- **Firmware Code:** Basic commands for controlling the pH robot written in C++.

https://github.com/Materials-Informatics-Group/pH-measurement-Robot/blob/main/DFRobot_PH_Test.ino

6. Acknowledgment

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Table 1. Components used in the 3D-Printed pH-Measuring-Robot

Component	Category	Specification (Example)	Qty.
Aluminum frame	Mechanical structure	20 mm × 20 mm × 200 mm / 500 mm	2 at a time
3D-Printed frame parts	Mechanical structure	PLA, custom CAD design	13
Linear guide rod	Mechanical structure	Φ 5 × 300 mm stainless steel	2
Corner brackets	Mechanical structure	20 mm × 20 mm	8
End Cap	Mechanical structure	20 mm × 20 mm	6
Lead Screw / Threaded Rod	Mechanical structure	T10 × 500 mm lead screw	1
Lead screw nut	Mechanical structure	Brass	1
Shaft coupling	Mechanical structure	5 mm to 8 mm flexible	1
Bolts and screws	Mechanical structure	M3 20 mm	8
Bolts and screws	Mechanical structure	M3 12 mm SSR	4
Bolts and screws	Mechanical structure	M4 25 mm	2
Bolts and screws	Mechanical structure	M5 8 mm	20
Bolts and screws	Mechanical structure	M5 10 mm	4
Nuts and washers	Mechanical structure	M3	8
Nuts and washers	Mechanical structure	M4	2
Nuts and washers	Mechanical structure	M5 square	24
Stepper motor	Actuation	NEMA 17, 1.8°	1
Stepper driver	Actuation	A4988	1
Microcontroller	Electronics &	ELEGOO Uno R3	1

	Control		
Breadboard	Electronics & Control	Standard solderless	1
Power supply	Electronics & Control	12 V DC (5 A)	1
USB cable	Electronics & Control	Type-A to Type-B	1
DC barrel jack	Electronics & Control	5.5 mm × 2.1 mm, with screw terminals	1
DC barrel plug cable	Electronics & Control	5.5 mm × 2.1 mm	1
Aluminum electrolytic capacitor	Electronics & Control	100 μ F, 16 V	1
PH sensor module	Sensor system	Analog interface board	1
PH electrode	Sensor system	Laboratory probe	1

Table 2. Measured pH values obtained using the benchtop pH meter and the automated pH measurement robot

	Measured pH							
	pH meter				pH-Measuring-Robot			
pH	1st	2nd	3rd	Avg.	1st	2nd	3rd	Avg.
1	1.17	1.17	1.17	1.17	0.88	0.85	0.62	0.78
2	2.12	2.14	2.13	2.13	1.62	1.85	1.68	1.72
4	4.02	4.03	4.03	4.03	3.47	3.53	3.74	3.58
7	6.89	6.89	6.89	6.89	6.62	6.50	6.53	6.55
10	10.09	10.08	10.06	10.08	10.15	9.91	9.82	9.96
11	11.02	11.02	11.01	11.02	10.41	10.47	10.47	10.45
12	12.06	12.09	12.09	12.08	11.71	11.68	11.65	11.68

Figure 1. Mechanical design of the pH meter robot.

Figure 2. 3D-printed components of the robot: (a) top stage (Stepper-motor-Holder), (b) middle stage (PH-meter-Holder), (c) bottom stage (Lower stage), (d) pH-meter-clamp-collars for securing the pH meter and pH-meter-Holder, (e) rod-clamp-collars for securing each rods, holders and stages, (f) rear box (Control-boards-Holder) for organizing cables and wires.

Figure 3. (a) Photograph of the ELEGOO UNO R3 microcontroller, pH sensor board, and breadboard used for stepper motor control. (b) Schematic flow diagram of the electrical connections and signal flow drawn using KiCad. (c) Schematic flow diagram of the electrical connections and signal flow drawn using Blender.

Figure 4. Photographs of the assembled pH meter robot: (a) front view, (b) back view, (c) left side view, and (d) right side view. The images illustrate the final assembled frame, stages, pH meter, and mounted stepper motor.

Figure 5. Photographs of the pH meter robot during operation: (a) before measurement, (b) during measurement, (c) after measurement, and (d) terminal interface showing the control program in use.

Figure 6. Measured pH values obtained using the automated pH measurement robot for solutions with nominal pH values of 1.00, 2.00, 4.01, 6.86, 10.00, 11.00, and 12.00. Error bars represent the standard deviation of three measurements

Figure 7.*

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This work presents an open-source, low-cost 3D-printed robotic system that enables precise and reproducible automated pH measurements through stepper motor-controlled probe positioning and integrated data acquisition.

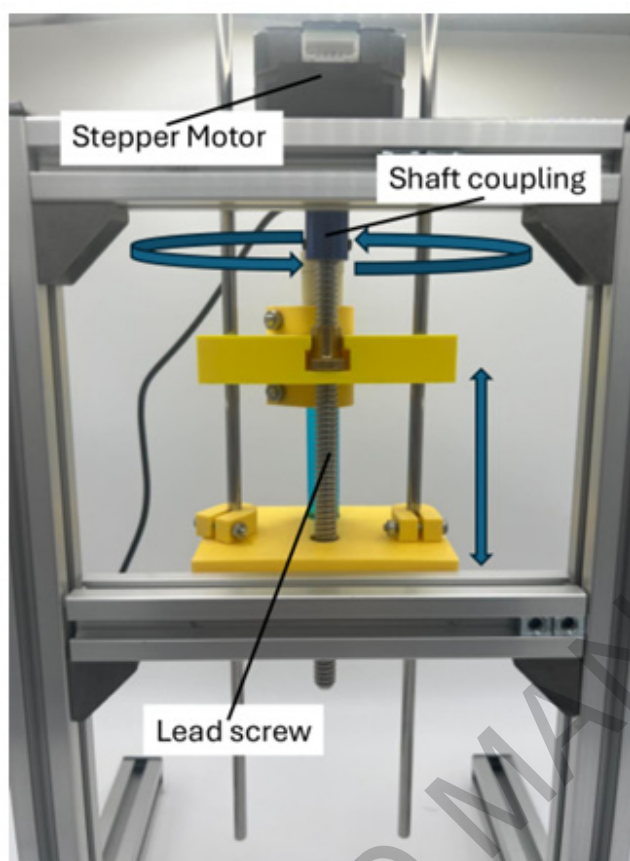


Figure 1. Mechanical design of the pH meter robot.

Figure 1

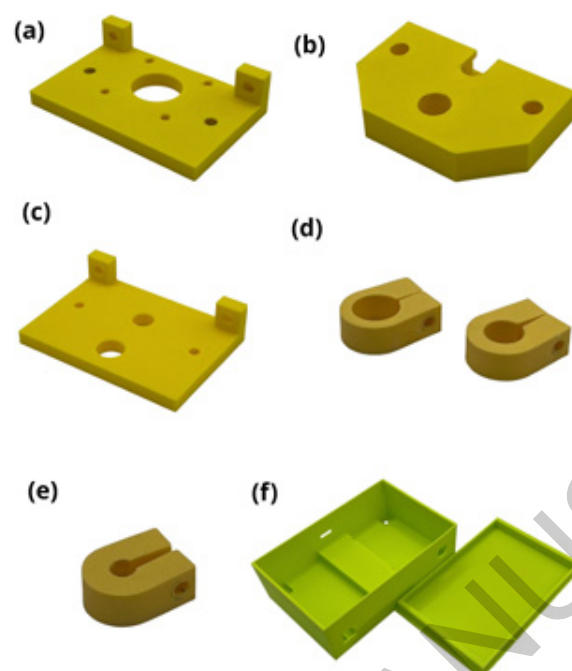


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Figure 2

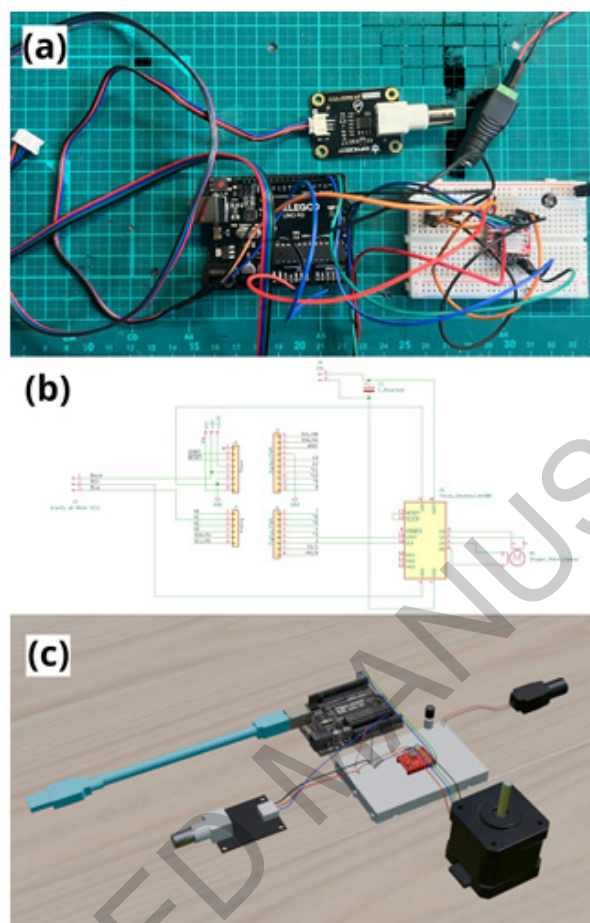


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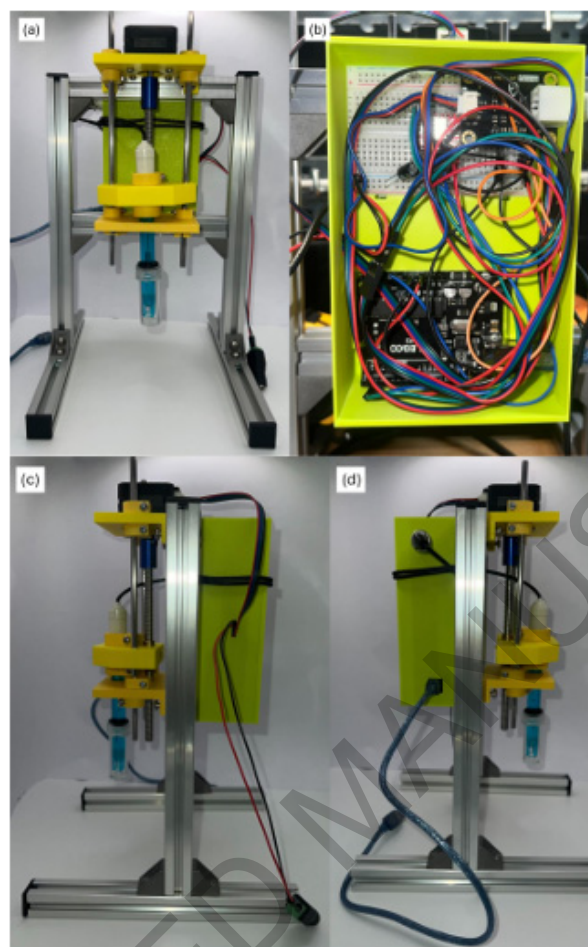


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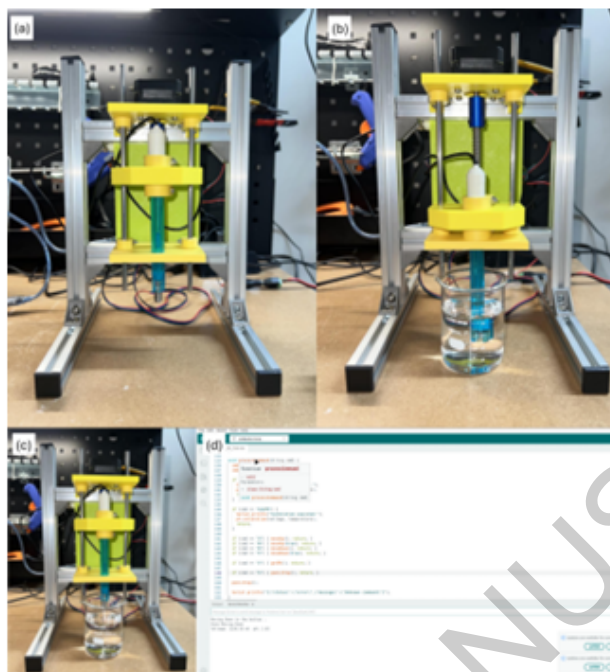


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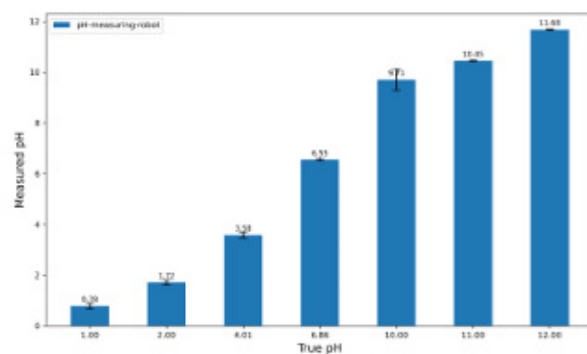


Figure 6. Measured pH values obtained using the automated pH measurement robot for solutions with nominal pH values of 1.00, 2.00, 4.01, 6.86, 10.00, 11.00, and 12.00. Error bars represent the standard deviation of three measurements

Figure 6

3D printed pH-Measuring-Robot

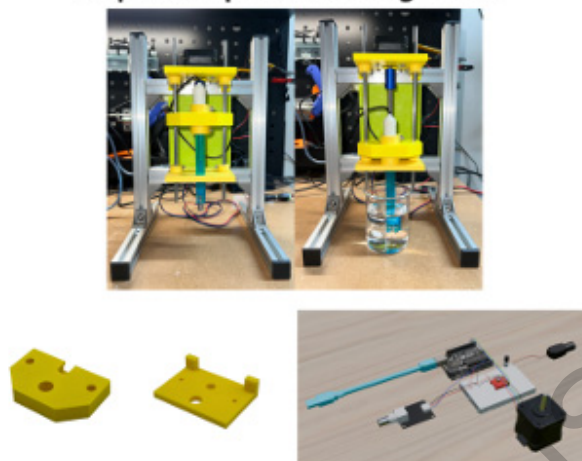


Figure 7. *
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Figure 7