Design and Implementation of a Microliter-Scale Batch Test Tube Pipetting Device Based on Mega2560 and RS485 Communication

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Abstract: To address the issues of low efficiency, large errors in traditional manual pipetting methods, and the high cost of existing automated pipetting equipment, a microliter-scale batch test tube pipetting device based on the Mega2560 microcontroller was designed. The device employs the RS485 differential communication protocol for precise control of the syringe pump, combined with a TB6600 driver for NEMA 17 stepper motors and a three-axis positioning system to achieve accurate liquid transfer from batch test tubes. The mechanical structure adopts an aluminum alloy profile modular framework, with collision sensors for positioning calibration and safety limit detection. The system is equipped with an industrial touch screen, supporting one-button parameter setting and real-time monitoring. Test results show that the device controls pipetting error within ±0.40 g (relative error ≤0.5%) in 50 mL and 100 mL fixed-volume pipetting tests, with stable performance during 8-hour continuous operation, and the cost is controlled within 10,000 CNY, providing an economical and practical automated pipetting solution for small and medium-sized laboratories.

Keywords: Microliter-Scale Pipetting; Mega2560 Microcontroller; RS485 Communication; Stepper Motor; Batch Test Tubes; Automated Device

1. Introduction

In modern medical, biological, and chemical laboratories, precise liquid transfer and dispensing are critical for experimental success. Traditional pipetting methods mainly rely on manual operation, which not only suffers from low efficiency but is also susceptible to human errors and external contamination, thereby affecting the accuracy and reproducibility of experimental results. Research shows that manual pipetting operation deviation increases significantly with extended operation time, with coefficient of variation between different operators reaching 3%–5% [1]. Currently available automated pipetting equipment can achieve high-precision, high-throughput liquid dispensing, but such equipment is generally expensive, with imported pipetting workstations mostly priced above 100,000 CNY [2], making it difficult for resource-limited small and medium-sized laboratories to deploy such equipment on a large scale. Laboratory automation has become an inevitable development trend.

In recent years, open-source hardware platforms have provided new directions for low-cost laboratory automation equipment development. Boppana et al. developed low-cost automated pipetting systems using single-board computers, achieving precision of 98%–102%, demonstrating the feasibility of low-cost solutions in microliter-scale pipetting operations [3]. Building on these advances, this paper researches and develops an economical, practical, easy-to-operate, precise, and efficient automated pipetting device. Using the Mega2560 microcontroller as the control core, combined with RS485 communication for precise syringe pump control and a modular mechanical structure, this device aims to significantly improve laboratory work efficiency, reduce experimental risks caused by human operational errors, and meet the needs of future laboratory automation and intelligence.

2. Overall System Design

2.1 Design Requirements

The design objective of this device is to achieve precise batch transfer of microliter-scale liquids. With the global liquid handling systems market continuing to expand rapidly [4], there is growing demand for affordable automated pipetting solutions. The main design requirements are: (1) use hardware module control positioning to achieve precise batch pipetting; (2) use collision sensors to improve positioning accuracy and ensure accurate operation of the test tube positioning system; (3) design a multi-functional chassis slot for conveniently fixing casters during equipment movement and mounting additional components; (4) adopt modular structure design to simplify assembly process and improve device flexibility and maintainability. The overall system structure is shown in Figure 1.

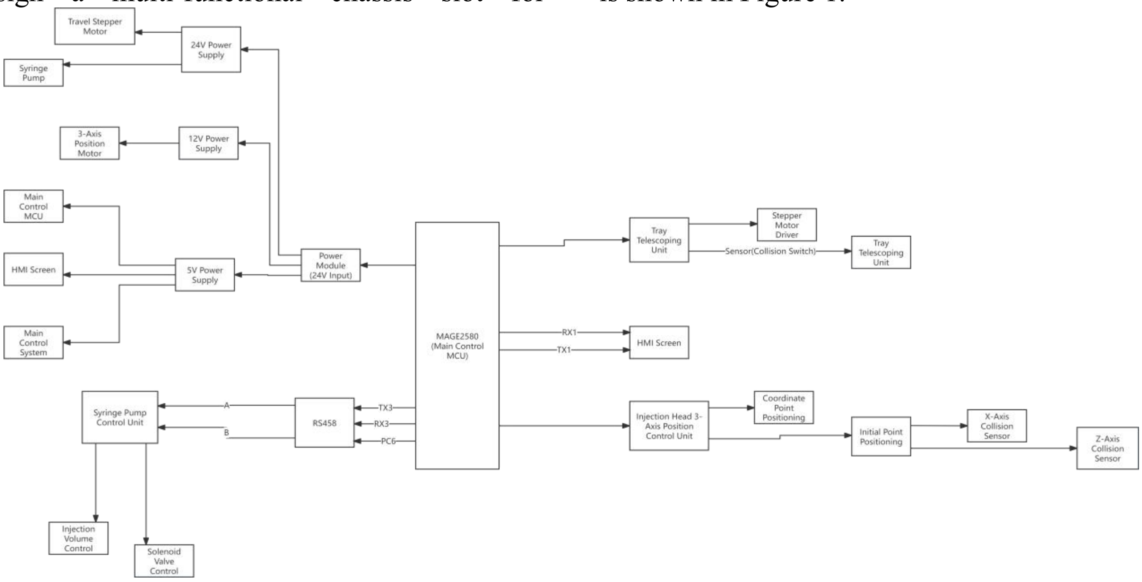


Figure 1. System Structure Block Diagram

2.2 Overall Hardware Architecture

This hardware system has six main modules. The core is the Mega2560 control module. Other modules include power supply, motor driver and DC-DC converter. They also contain relay, RS485 communication and industrial touch screen. The Mega2560 module controls all other modules. The power supply connects the NEMA 17 motor to the DC-DC converter. The converter outputs 12V and 5V power. It turns external power into usable power for the system. It supports mechanical movement and circuit work. The motor driver controls the tray and syringe pump. It manages the three-axis movement of the pump. The RS485 module is an innovative part. It uses differential signals for data conversion. It changes serial data into A/B signals for the pump [5]. The RS485 module uses 5V power. It adopts half-duplex communication. The PC6 serial port connects with the 485-to-serial module. They complete joint control work together. The controller drives the syringe pump to preset positions.

2.3 Overall Mechanical Scheme

The mechanical structure takes aluminum alloy profiles as its frame material. This material has a low overall weight. It provides high connection strength and stable mechanical performance. It also has excellent load-bearing capacity. It supports locking and positioning with T-slot nuts for structural adjustment [6]. Modular design is widely applied in laboratory equipment. Faina and other researchers developed a modular open-source liquid handling robot, named EvoBot. This robot supports flexible configuration for different experiments [7]. This design adopts a groove structure. Bolts and nuts can be mounted freely on the structure. Profiles do not need to be removed during assembly. The structure suits various experimental conditions efficiently. Collision sensors are installed on the device. They improve precision of the positioning system.

3. System Hardware Design

3.1 Hardware Design Block Diagram

This design uses the Mega2560 microcontroller as the core control unit. It matches multiple hardware modules to realize precise positioning control. The power supply module provides operating power for the entire system, the drive circuit module controls motor operation, the industrial touch screen module enables operation status monitoring, and the RS485 module achieves half-duplex communication. Serial port PC6 is used with the 485-to-serial module for coordinated control. The system hardware structure is shown in Figure 2.

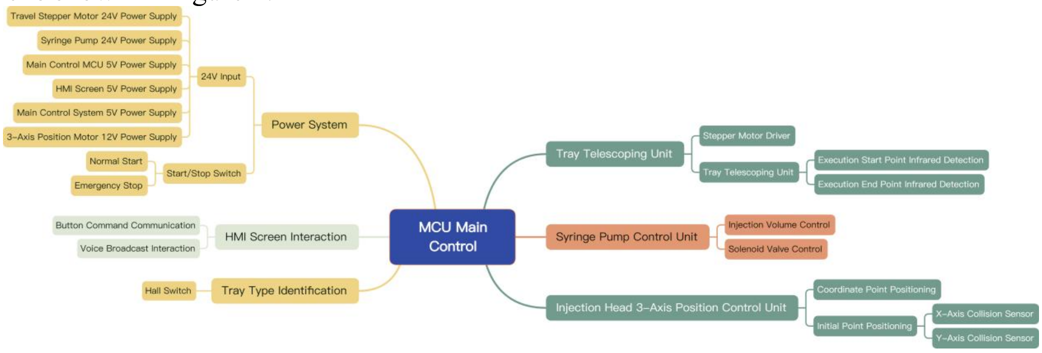


Figure 2. System Hardware Structure Diagram

3.2 Main Control Module

The main control module adopts the Arduino Mega2560 microcontroller. This microcontroller is built on the ATmega2560 chip. It integrates 54 digital I/O channels, 16 analog input pins, 256 KB flash memory and four hardware serial ports [8]. It is suitable for control systems requiring multiple I/O interfaces. The microcontroller supports three switchable power supply modes to ensure stable system power supply. It provides 15 channels of 8-bit PWM output and supports TWI and I2C bus communication. These sufficient hardware resources enable the coordinated control of multiple device modules. Open-source hardware has wide applicability in laboratory automation. Dettinger et al. developed the open-source pipetting robot PHIL, which realizes automatic operation for live cell culture experiments [9]. Wu developed an Arduino-based programmable multichannel syringe pump. It serves fluid delivery in microfluidics and flow chemistry [10].It proves Arduino platforms are versatile in liquid handling. Related research shows that image sensor-based feedback control can effectively improve the precision of micro liquid dispensing systems, providing theoretical basis for this device's closed-loop control strategy using microcontroller combined with sensors [11].

3.3 Syringe Pump RS485 Communication Module

The main function of the RS485 module is to achieve communication protocol conversion, converting signal data input from the microcontroller serial port into A/B format signal data that can drive the syringe pump. RS485 communication uses differential signal transmission, whose main advantage is common-mode interference suppression [5]. Especially in complex electromagnetic environments with severe interference in industrial settings, differential transmission significantly improves communication reliability. RS485 uses two communication lines (A line and B line), with logical 1 indicating a voltage difference of +(0.2–6)V between A and B, and logical 0 indicating a voltage difference of -(0.2–6)V. Maximum transmission rate can reach 10Mbps, supporting multi-point connections. Wijnen et al. developed an open-source syringe pump library using 3D-printing technology, providing customizable syringe pump designs at low cost [12], which offers reference for the syringe pump control scheme in this design.

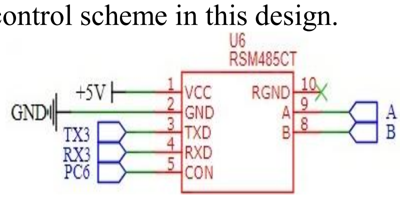


Figure 3. RS485 Working Principle Diagram

In this system, 485 communication uses half-duplex mode, with serial port PC6 used with the 485-to-serial module. When sending signals, PC6 is at high level input, and TX3 signal data can be output normally. When receiving signals, PC6 is at low level input, and A/B format signals are converted to RX3 serial signals for output, thereby achieving precise control of the syringe pump. The RS485 working principle is shown in Figure 3.

3.4 Driver Module

To achieve mechanical movement functions, the device uses NEMA 17 stepper motor power as the total power supply for the drive circuit, with the TB6600 model stepper motor driver controlling the NEMA 17 stepper motors. The TB6600 driver supports two-phase motor step control, with maximum subdivision of 32 subdivisions, adjustable output current of 0.5–4.0A, and maximum power consumption of 160W [13]. Seven subdivision modes can be selected through 3-bit code switches, and 8 current levels can be selected, enabling the motor to operate stably under conditions of low vibration, low noise, and high speed.

3.5 Power Supply Circuit Design

The power supply system adopts a three-level power architecture:

(1) External power supply: Uses a 120W AC-DC power adapter, inputting 110–240V/50–60Hz AC and outputting 24V/5A DC as the primary power supply for the device.

(2) DC-DC 12V module: Uses the GOD50-24S12 power module to regulate 24V to 12V with 60W power. Due to the risk of damage during voltage conversion, a typical application circuit is connected in the middle of the module, using single-path connection with branch circuits providing protection.

(3) DC-DC 5V module: Uses the URB2405YMD-10WR3 power module to regulate 24V to 5V, with input voltage of 9–36V and input current of 2000mA, providing working power for control circuits and the RS485 module.

3.6 Relay Module

The function of the relay module is to control the on/off state of the solenoid valve. The microcontroller outputs high/low level signals through I/O port PA7 to control the relay. When PA7 outputs high level, the relay drives the syringe pump solenoid valve to open, the syringe pump starts working, and the water inlet channel closes. When PA7 outputs low level, the syringe pump closes and stops working, the water inlet channel opens, and the syringe pump starts to draw liquid for storage. The relay connects to two microcontroller I/O ports, PC6 and PC7, receiving high/low level signals to control the liquid pump and solenoid valve. The solenoid valve connects the liquid pump and water inlet pipe. Through precise time control, the solenoid valve switch controls the liquid pump to complete pipetting operations. Since the liquid pump has fixed pipetting volume, controlling the solenoid valve switch time can precisely determine the pipetting volume.

4. System Mechanical Design

4.1 Design Requirements

Aluminum alloy profiles form the mechanical framework. This material is light with good mechanical performance, high connection strength and strong load capacity for modular structures. Collision sensors improve design accuracy. The positioning system guarantees accurate pipetting. The frame uses a multi-functional groove design. It allows installation of casters and easy assembly of components. It also supports connection with droppers after startup.

4.2 Structural Design

The device is composed of an aluminum alloy frame, acrylic panels, push trays, foam pads, test tubes and motors. The three-axis linear motion system realizes precise positioning of the syringe pump. Florian et al. realized low-cost automatic micropipetting positioning via linear motion design [14].Their research provides references for the track and three-axis positioning design. The main dimensional parameters are as follows:

(1) Main dimensions: Five test tubes form one test group. Each operation contains twelve groups in total. The device main body dimensions are calculated as length 430 mm, width 300 mm, height 185 mm (plus 15 mm for feet).

(2) Push tray: 430 mm in length, 254 mm in width, 28.5 mm in height. It holds test tube holders and foam pads accurately.

(3) Test tube holder: 380 mm long, 254 mm wide and 3 mm high. It has 12 slots arranged in 4 rows of 3. Its pentagonal base ensures stable placement. Holes on both sides are for handles.

(4) Foam pad: It shares the same size as the test tube holder. Hollow openings fix test tubes and prevent liquid leakage.

(5) Motors: Two motors are adopted. One is mounted under the push tray for stable support. The other is fitted on the upper wheel track of the syringe pump.

(6) Acrylic panels: Uses fully transparent acrylic material as equipment baffles, facilitating observation of experimental conditions, precise operation, and reducing external factors. Side panel: length 402 mm, width 182 mm, thickness 5 mm; rear panel: length 312 mm, width 178 mm, thickness 5 mm; bottom side panel: length 402 mm, width 72.5 mm, thickness 5 mm.

(7) Display screen: Embedded in the upper right corner of one acrylic side panel, length 135 mm, width 83 mm, thickness 5 mm, used for displaying values and temperature inside the test tube holder.

(8) Test tube holder: Overall cylindrical body with length 156.5 mm, large diameter 60 mm,

small diameter 48 mm. Five test tubes constitute one group, arranged in a regular pentagon pattern.

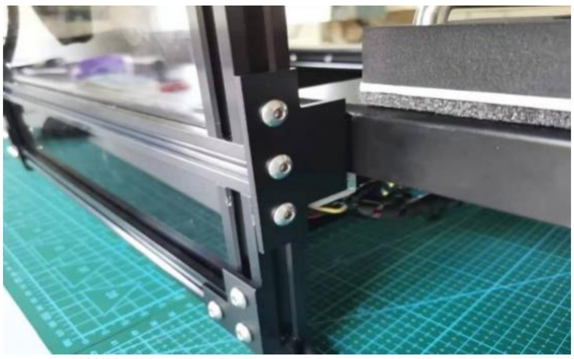
Mechanical structure design drawing is shown in Figure 4.

Figure 4. Mechanical Structure Design Drawing

4.3 Functional Component Design

4.3.1 Collision switches

The system is equipped with 4 collision switches, installed on the syringe pump motion axis unit and tray unit respectively. The microcontroller collects level signals from the 4 collision switches through 4 I/O ports. The tray corresponding to PA3 and PA4 interfaces are normally at high level. When PA4 becomes low level, the tray extends and the motor stops working. When PA3 becomes low level, the tray resets and the motor stops working. The collision switches on the syringe pump motion axis work on the same principle as the tray, ensuring system operation safety. Syringe pump motion axis unit and tray unit is shown in Figure 5.



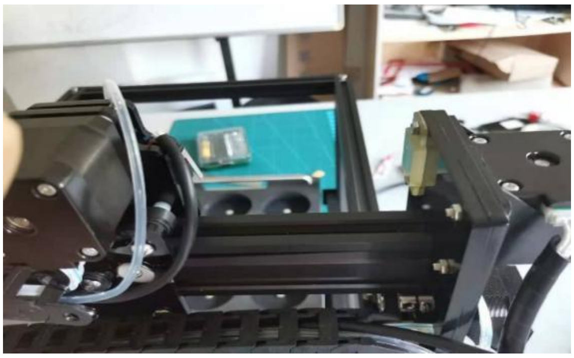


Figure 5. Tray Unit and Syringe Pump Motion Axis Unit

4.3.2 Industrial touch screen design

The industrial touch screen is embedded in the upper right corner of one acrylic side panel. The circuit RX1 and TX1 serial ports communicate with the microcontroller through instruction format, receiving instruction signals and displaying values and temperature information inside the test tube holder in real-time, providing intuitive operation status feedback for operators. Industrial Touch Screen is shown in Figure 6.

Figure 6. Industrial Touch Screen

5. System Debugging and Performance Analysis

5.1 System Debugging

5.1.1 Structural improvement

In the initial design, the foam tray holes were circular, which caused inconvenience in test tube rack installation and introduced significant installation errors. The improved solution changed both the test tube rack bottom surface and tray foam holes to regular pentagon shapes, facilitating installation positioning and effectively reducing installation errors. Tray foam pad is shown in Figure 7.

5.1.2 Syringe pump axis operation test

After confirming program and syringe pump module connections, specific coordinate values were set. The X-axis and Y-axis motion positions and directions were observed to confirm whether the syringe pump movement met program requirements. After the test passed, fixed-volume pipetting accuracy testing was conducted.

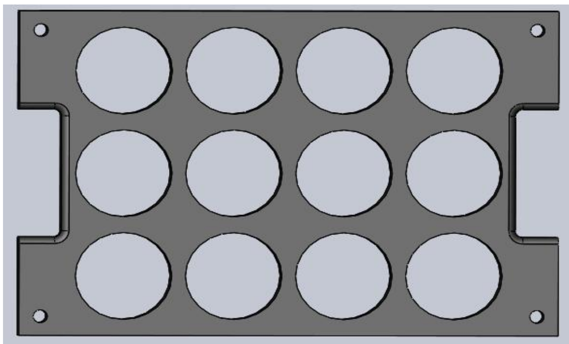


Figure 7. Tray Foam Pad

5.2 Fixed-Volume Pipetting Accuracy Test

Table 1. Data Table for 100 mL Fixed-Volume Pipetting

Beaker No.	1st (g)	2nd (g)	3rd (g)	4th (g)
Beaker 1 (178g)	278.001	278.005	278.002	278.009
Beaker 2 (181g)	281.003	281.009	281.001	281.010
Beaker 3 (179g)	279.001	279.005	279.002	279.008
Beaker 4 (180g)	280.004	280.010	280.000	280.007
Beaker 5 (181g)	281.008	281.002	281.006	281.001
Beaker 6 (182g)	282.001	282.002	282.005	282.009

Fixed-volume pipetting accuracy tests were conducted on the automated pipetting device for 50 mL and 100 mL volumes. To avoid significant data errors, beakers were pre-weighed. Beakers 1–6 had masses of 178.00 g, 181.00 g, 179.00 g, 180.00 g, 181.00 g, and 182.00 g respectively, with weight precision of 0.01 g. Test data are shown in Tables 1 and 2.

Table 2. Data table for 50 mL Fixed-Volume Pipetting

Beaker No.	1st (g)	2nd (g)	3rd (g)	4th (g)
Beaker 1 (178g)	228.003	228.002	228.001	228.008
Beaker 2 (181g)	231.007	231.002	231.007	231.006
Beaker 3 (179g)	229.001	229.005	229.004	229.001
Beaker 4 (180g)	230.004	230.001	230.002	230.009
Beaker 5 (181g)	231.003	231.002	231.006	231.000
Beaker 6 (182g)	232.007	232.001	232.011	232.007

From the data in Tables 1 and 2, it can be seen that for both 100 mL and 50 mL fixed-volume pipetting, the absolute error of the data is within ±0.40 g, and the relative error is controlled within 0.5%, meeting the design accuracy requirements. Compared with the low-cost automated pipetting system accuracy (relative standard deviation <3%) reported by Boppana et al. [3], this device shows significant advantages in pipetting accuracy. Yoshikawa et al. designed an open-source digital pipette hardware for liquid transfer in self-driving laboratories [15], providing a reference for further miniaturization and intelligence of pipetting devices. The image sensor feedback-based micro liquid dispensing control method proposed by Qian et al. [11] provides an improvement direction for further enhancing the microliter-scale pipetting accuracy of this system.

5.3 Fault Analysis and Handling

During system debugging, three main types of faults were encountered:

(1)Sensor connection fault: During debugging, the motor continued to operate after the tray reached the specified position, and the sensor did not function for limit detection. Inspection found loose sensor wiring. Reconnection fixed the fault.

(2)Mechanical structure fault: Poor installation angles affected screw fastening. This led to abnormal servo motor operation. The fault was fixed after repositioning and tightening screws. Screw fastening was strictly checked in follow-up assembly.

(3)Insufficient power supply: The push tray responded slowly in tests. The aging battery caused low output voltage. The device worked normally after battery replacement.

6. Conclusion

This study develops an automatic batch pipetting device for microliter test tubes based on the Mega2560 microcontroller, RS485 communication and TB6600-driven NEMA 17 stepper motors. The three-axis positioning system achieves high-precision liquid transfer. In 50 mL and 100 mL pipetting tests, the error is within ±0.5%, and the actual deviation is about ±0.40 g. The device is equipped with an intelligent calibration algorithm, which can correct positioning deviation within 2 seconds to keep stable precision during long-time operation. The industrial touch panel simplifies operation with parameter setting, real-time monitoring and data feedback. Integrated AI algorithms detect liquid leakage and equipment faults and send alarms to guarantee experimental safety. SolidWorks, Proteus and Arduino are adopted for modeling, circuit simulation and programming. After repeated optimization, the system features simple structure and high efficiency.

An 8-hour continuous operation test proves its good performance in temperature control, positioning accuracy and stability. Compared with commercial high-end equipment costing over 100,000 CNY, this device costs less than 10,000 CNY. It lowers the application threshold of automation equipment for laboratories. Future research will focus on improving microliter-level pipetting accuracy, and develop intelligent remote monitoring and control functions with new technologies.

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