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Design, Implementation, and Evaluation of an Automated Liquid Dispensing Machine

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Highlights

- This article discuss the design, implementation, and evaluation of a dispensing machine.
- A timing approach is used, which corresponds to the machine's desired dispense volume.
- The theoretical and experimental time to disperse the same volume on the machine is minimized.

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Microcontroller

Abstract

The metering of industrial manufacturing liquids is constantly being updated. Using an automated system, metered dispense can now be more accurate to its theoretical value. This system can help reduce the difference between theoretical and metered volumes in manufacturing applications. This paper describes an automated liquid dispensing machine that uses an AT Mega 328 microcontroller to control the metered volume to the programme set point. The machine's design and implementation include hardware systems assembled from various modules with various functions, such as a microcomputer, power supply, liquid level detection, liquid discharge, conveyor and container detection, and LCD modules. The data collected by the liquid level detection module is analyzed when the system is started to determine the liquid level in the tank. A user loads empty containers onto the conveyor, which are then transferred to the discharge point. The machine calculates the equivalent time in seconds to open the discharge solenoid valve via its control relay and dispenses the desired volume based on the user set point. The experiment performed on the machine with water as the test liquid revealed that the automated dispensing machine's maximum time permissible is 35 s, which corresponds to an equivalent volume of approximately 700 mL of water. Experiments were conducted to compare the theoretical time required to obtain a specified volume to the time required for the machine to dispense the same volume. The results showed that the machine's accuracy is approximately 97.87 %. Therefore, the machine can be used in beverage manufacturing companies, pharmaceutical industries, and laboratories to dispense and fill specified fluids that meet the machine's specifications.

1. INTRODUCTION

Manufacturing has advanced due to the use of information technology and control systems to reduce the direct use of human labor in the production of goods and services. According to [1], automation is a significant advancement in industrialization, and in their work, a microcontroller was used to control various system operations. The results were obtained for a 100 ml volume at a 97 % efficiency while the valve was left open for 10 seconds to fill 100 ml. Filling operations are typically performed manually in small-scale industries in Nigeria and many other sub-Saharan African countries. This operation has some drawbacks, including inequalities in product filling, product spilling, and bottlenecks caused by human activities, among others [2]. Many industries, including juice, syrup, beverage beverages, and pharmaceuticals, rely on filling machines that require speed and accuracy, and their success depends on it [3]. Furthermore, the manual method does not produce accurate and reliable results and requires a significant amount of time and human effort, resulting in low productivity.

Numerous liquid filling machines are available, each with its operating principles. Granular filling, powder filling, paste filling, and liquid filling machines are the most commonly used filling machines. The use of

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machines and automated production operations to discharge precise, accurate, and measurable quantities of products are known as an automated deposition. This research aims to create automated machines that are efficient, long-lasting, simple, easy to use, and understandable. The goal is to increase the productivity of small-scale industrial production. According to a market survey, Arduino-based microcontroller filling systems are less expensive due to less and easier programming [4]. Other filling machines on the market are expensive due to PLC (Programmable Logic Controller) and complex programming. [5] proposed an industrial-grade automatic liquid filling machine that uses a gear pump. A servo motor is connected inline between the encoder and the Gear pump in this configuration. The gear pump is synchronized with the encoder, and commands are sent to the main panel of the motor for a specified revolution, as well as feedback on the rotation. This ensures that the pump delivers the desired volume. The volume setting is changed from an HMI (Human Machine Interface) by changing the command to the gear pump.

In [6], alternate designs for broader applications and use were created, such as the ladder diagram design and the height-based PLC programming software. Capacitive sensors detect bottles held in place in a carton above a conveyor belt. The design of the bottle-filling machine is expected to demonstrate cooperation and integration with constraints such as improved performance, speed, accuracy, proficiency, and cost reduction. [7] conducted tests to ensure that the amount of insecticide solution dispensed by the machine into a bottle was within the specified tolerance of 200 ml to 240 ml. The experiment begins with empty 250 ml bottles being loaded onto the conveyor. The machine is then turned on, and after the last bottle has been successfully filled, the actual volume dispensed into the bottles using a beaker is measured and recorded. This method achieves volume correction while lowering manufacturer and customer costs by reducing filled liquid loss.

Other designs use the pneumatic system with an ultrasonic sensor and incorporate the AT89C51 microcontroller [7-9]. A liquid filling machine controlled by a relay type PLC (XEC-DN32H (LSIS) (Large Scale Integrated Systems)) has been designed [10]. Various controller methods and algorithms that can be used to develop automated filling machines were reviewed [1]. Microcontroller Controlled Systems, Peripheral Interface Controller PIC Controlled Systems, Acorn RISC Machine ARM 7 Controlled Systems, Supervisory Control, and Data Acquisition Systems are among the methods examined. SCADA Software Controlled Systems: These are systems that are used to monitor and control plants or equipment. Others include a ladder logic-based PLC (SIEMENS LOGO PLC OBA6) [11]. To build the database management system, a programmable logic controller (S-7300IFM) uses the MS Visual Basic 6.0 programming language [3]. SCADA and PLC [12]. [13] describes a data-driven methodology for developing a mathematical model that can be used to optimize UAV-based autonomous predatory mite dispensing. [14] describes an automated homogeneous liquid-liquid microextraction procedure for caffeine separation in beverages. [15] describes a novel application of machine learning to identify the two-phase flow pressure drop in a proton exchange membrane (PEM) fuel cell flow channel. [16] seek to identify the factors influencing liquid aerosol flammability and to address data gaps by developing quantitative structure-property relationship (QSPR) models. A micro-liquid dispensing system based on a syringe pump is designed to study the influence of system factors on the liquid dispensing process, and a Fluent simulation model is established to simulate the dispensing process [17]. Other notable authors include [18] and [19]. Where these methods have performed well, limited work has been done to compare the theoretical volume with the metered volume. In this study, an automated dispensing machine is proposed and its performance is evaluated by comparing the theoretical volume with the dispensed volume.

2. MATERIAL METHOD

2.1. Design Considerations

The ATmega328P-based Arduino Uno is a microcontroller board (datasheet). It has 14 digital input/output pins, 6 analog inputs, a 16 MHz ceramic resonator (CSTCE16M0V53-R0), a USB connection, a power jack, an ICSP header, and a reset button. This is the microcontroller chosen because of its ease of use and compact size, which allows it to be easily attached to any system. Its operation is also simple.

Design Analysis of Components and Systems of the Machine

The Design of the Conveyor Belt of the machine

Required data

Length of the conveyor belt L_b = 124 cm
Width of the conveyor belt W_b = 13 cm
The conveyor belt is a banner flex
Number of rollers for the conveyor belt N_{roll} = 4
Diameter of the drive roller D_{roll} = 1.6 cm
Diameter of the driven roller D_0 = 1.4 cm
Distance between centres d_{cen} = 58.5 cm

Technical specification for motor

Rated voltage (DC): $V = 12V$
Gear reduction ratio: $GR = 19:1$
Stall torque: $\tau_s = 0.3422\,Nm$
Rated torque: $\tau = 0.0981\,Nm$
Motor speed $N = 480\,rpm$
Shaft diameter = 4 mm

Determination of mass on the conveyor belt

The maximum volume of liquid that can be filled $v = 700\,ml = 0.0007\,m^3$
The density of water $\rho = 1000\,kg/m^3$
Mass on the conveyor belt $M_c = \rho \times v$
Maximum mass $M_x = 1000 \times 0.0007 = 0.7Kg$

Determination of Required power

The Coefficient of friction of the belt is taken as $\mu = 0.5$ [20]
Required power: $P_r = \text{Belt pull} \times \text{Belt Speed}$ (1)
Required belt pull: $P_{bp} = \text{Total load} \times \mu$ (2)
Total load: $P_T = \mathrm{M}_x \times \mathrm{g}$
Therefore, $P_{bp} = \mathrm{M}_x \times \mathrm{g} \times \mu = 0.7 \times 9.81 \times 0.5 = 3.4335\,N$ (neglecting the weight of the belt).

Belt speed $S_b = \dfrac{2\pi r N}{60}$ (3)

where r is the radius of the shaft of the motor

Hence, $S_b = 0.1m/s$

Required power: $P_r = \text{Total load} \times \text{Belt Speed} = 0.343\mathrm{W}$

Determination of the load torque T

$$\text{Torque } T = \text{Total load} \times \text{Shaft radius} \quad (4)$$

$$T = 3.4335 \times 2E^{-3} = 6.867E^{-3}Nm$$

Determination of the rate of flow and the rate of discharge

The equations for estimating flow rate and discharge are [20]:

Required data

Working medium = water
Operation type = direct drive
State = Normally Close
Pipe diameter = 12.7 mm
DC Voltage $V = 12V$
Diameter of orifice = 1.3 cm
Head loss: $h = 12.5cm$
Pressure: $P = 1atm = 101325\, N/m^2$
The density of water: $\rho = 1000\, kg/m^3$
Acceleration due to gravity: $g = 9.81m/s^2$

Area of orifice: $A = \frac{\pi D^2}{4} = 1.327E^{-4}m^2$.

Applying Bernoulli's equation:

$$Z_1 + \frac{P_1}{\rho yg} + \frac{v^2{}_1}{2g} = Z_2 + \frac{P_2}{\rho yg} + \frac{v^2{}_2}{2g} \quad (5)$$

Let $P_1 = P$
$P_2 = 0, v_1 = 0, v_2 = v$

$$V = \sqrt{2g\left(\frac{P}{\rho g} + h\right)} \quad (6)$$

$$V = 14.32m/s.$$

If the area of the opening is A

$$Q = AV = A \times \sqrt{2g\left(\frac{P}{\rho g} + h\right)} \quad (7)$$

$$Q = 1.9E^{-3}m/s$$

The coefficient of discharge is C_d

The actual flow rate is: $Q_{Act} = C_d A \times \sqrt{2g\left(\frac{P}{\rho g} + h\right)}$. (8)

From the experimental test, the time to discharge 1 liter is 49 seconds

Hence, the rate of discharge $Q = 0.0204 l/s$
$Q = 20 ml/s$
$Q = 2.04E^{-5} m^3/s$
Assuming a 620 ml container,
Time T = 30 s to fill
Rate of discharge = 20.67 ml/s
$Q = 0.0206 l/s$
$Q = 2.06E^{-5} m^3/s$
Therefore, it is safe to assume that

The volume of flow: $V = \frac{Q}{A} = \frac{2E^{-5}}{1.327E^{-4}} = 0.15 m/s$ (9)

$$C_d = \frac{\text{Actual discharge}}{\text{Theoretical discharge}} = 0.011 \quad (10)$$

$$C_v = \frac{\text{Actual velocity}}{\text{Theoretical velocity}} = 0.0104 \quad (11)$$

Table 1 below presents the machine specification for the design.

Table 1. *Machine Specifications*

Specifications	Functionality/Value
Discharge capacity	50ml – 700ml
Tank capacity	2.5 liters
Power source	220ac +10 % 50hz
Operation mode	Automatic
Test liquid	Water
Led display	1 Led Display displays the status of the operation of the System in Real-Time
Function	Dispenses a certain volume of the product equivalent to the corresponding time selection

2.2. Description of the Machine

This study is based on the concept of gravity filling in time developed by [3]. The various sections include the filling section, the conveyor section, the detection section, and the control section. The Arduino Uno microcontroller is responsible for overall system control. The controller issues system instructions and all machine components communicate with the controller, sending necessary signals and data to various points. The flow of liquid is controlled by opening the valve for a specific amount of time, and the filling is controlled by a timer. To determine the duration of filling the liquid, the timer circuit employs the stable mode of operation of a 555 timer. Following that, the sensor sends an actuating signal to the solenoid valve, which fills the bottle with a volume of liquid equal to the timer value. After the product is discharged, the container moves away from the filling unit. A refill pump is installed to refill the level of the tank when the product falls below a certain level and to stop the pump when the product level reaches a certain level. The product tank is equipped with probes at various levels, and the product's electrical conductivity is used to determine the product's behavior.

2.3. Principle of Operation and Design

When the power button is pressed, the power supply circuit converts 220v AC to 12v DC. When the switch carrying the 5v is turned on, the 5v power is transferred to power the Arduino microcontroller and the other components on the circuit board. The Arduino board begins to execute the program that has already been installed on it. The block diagram showing the various components used in the design of the automated liquid dispensing machine is shown in Figure 1.

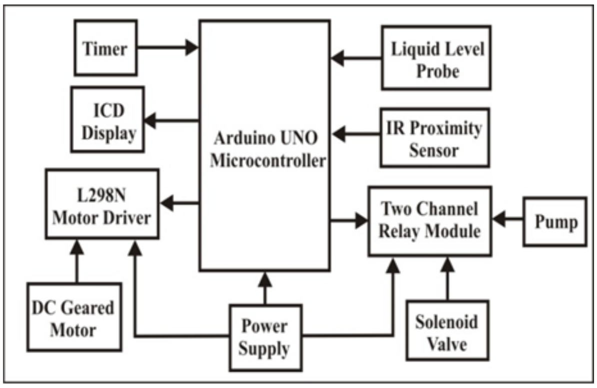

Figure 1. *Block diagram of the System*

The welcome dialogue and other owner credentials are displayed on the LCD during startup. The system enters the run mode after starting up. A signal is sent to the motor driver in run mode to start the DC-geared motor connected to the conveyor drive roller. The variable speed is already specified in the programme. The conveyor motor begins to drive the roller, which then drives the conveyor belt. Following that, the system scans the product tank level. The product tank is outfitted with probes placed at strategic points to indicate the tank's low and high levels. The product's conductivity is used to determine the various levels of the product. A reference voltage is connected to the tank, and when the product moves to the low level, the reference voltage is sent to the low-level probe, which is linked to the Arduino microcontroller, and the process is repeated when the product touches the high-level probe. If the tank level falls below a certain threshold, the microcontroller sends a low signal to the relay to which the pump is connected. The relay is activated and power is transferred to the pump, causing it to begin working and filling the tank. The system status is displayed on the LCD so that the user can monitor the system's operations. When the product reaches half of the tank's capacity, the status is also displayed on the LCD. When the product reaches full level, the status is displayed and a high signal is sent to the relay, which cuts off the supply to the pump and stops the product from filling the tank. If an empty container is placed on the conveyor belt while the system is running a scan on the product level, the container moves on the conveyor until a proximity sensor detects the presence of the container, and a status update is displayed on the LCD. To stop the conveyor motor, the proximity sensor sends an output signal to the microcontroller. When the conveyor comes to a halt, the system performs a scan on the timer circuit to determine the desired volume, which is represented by the user-specified equivalent time in seconds. A signal is then sent to the relay to which the solenoid valve is connected, and the valve opens for the time specified in seconds, which is equivalent to the current volume in ml. When the product has finished discharging, the controller sends a signal to the relay to cut the power to the solenoid valve, causing the valve to close. The controller sends another signal to the conveyor, this time to move the container away from the filling point. Figures 2 and 3 show the system flow chart and engineering drawing.

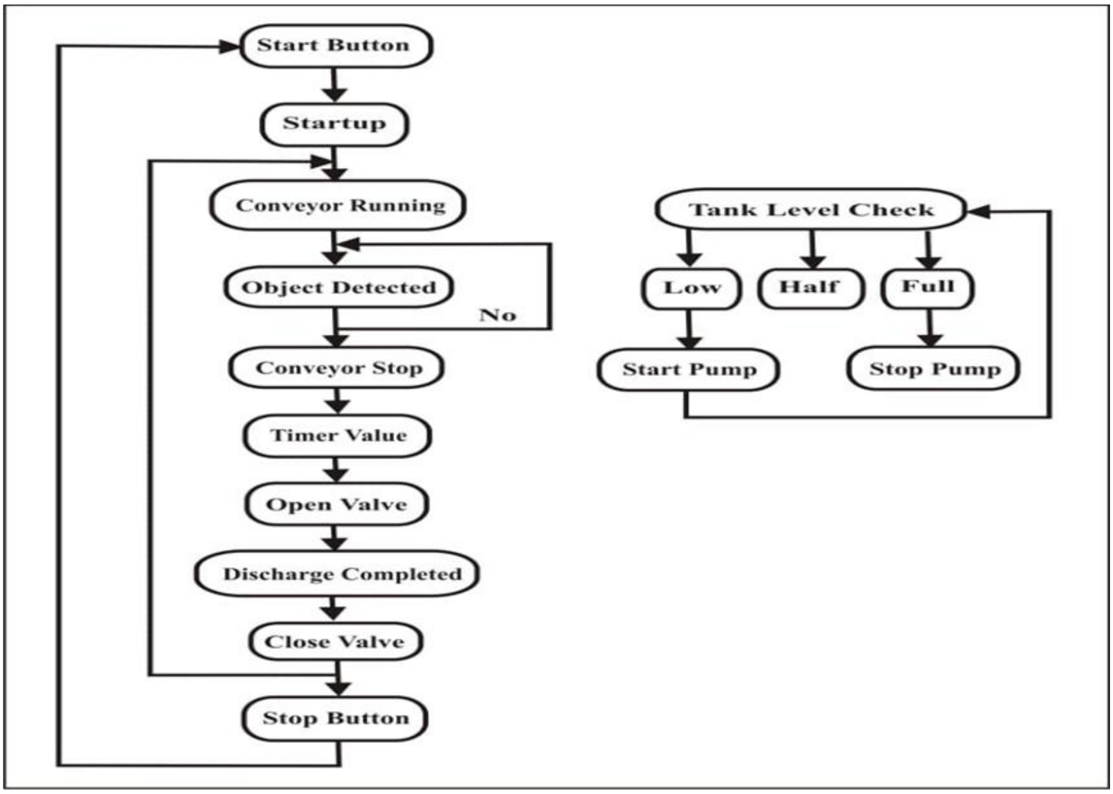

Figure 2. *Flow chart of the system*

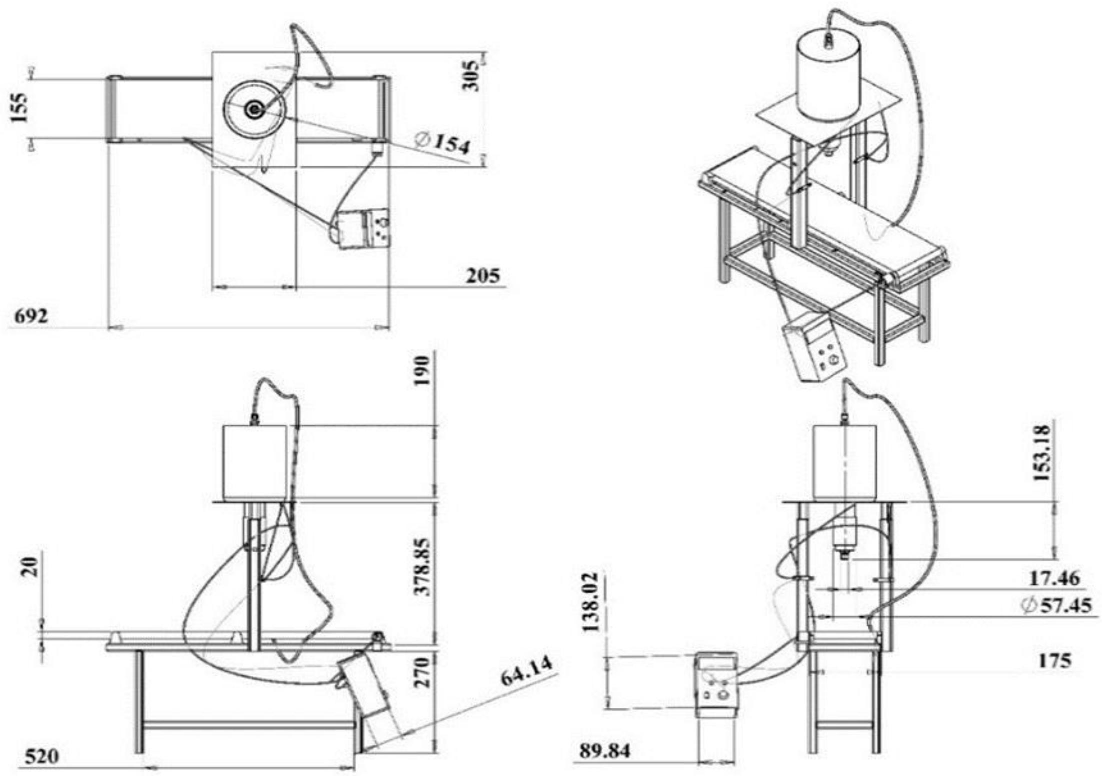

Figure 3. *Engineering drawing*

2.4. Construction

To carry out this research, the various components and modules used were first tested to ensure that they functioned properly. The frame was created by machining, cutting, welding, smoothing, and painting were used to create the frame. The sensors were installed in their intended locations on the frame. The gravitational filling method was used, so the fitting pipe was connected to the product tank and the solenoid valve's outlet was connected to a nozzle. The conveyor was then attached to the mechanical frame. The conveyor was built with a variety of rollers and conveyor belt materials. The bearings supported the belt rollers, and the driving roller was connected to a geared motor. There was also a mechanism for adjusting and tensioning the belt. In addition, fitting pipes were used to connect the product tank to the solenoid valve, and the outlet of the solenoid valve was connected to a nozzle during the filling section. The control panel houses all of the electrical components, and the circuit was wired according to the design. For ease of use, the control panel was supported by a rigid platform.

After the machine was built, a continuity test was performed on all of the various components, and they were all found to be well connected. The entire system was tested in operation mode to ensure that all of the various sections were functional and communicating with the microcontroller. Each section was tested with the program written on the microcontroller and the flow of the system's process. Figure 4 shows a picture of the machine.

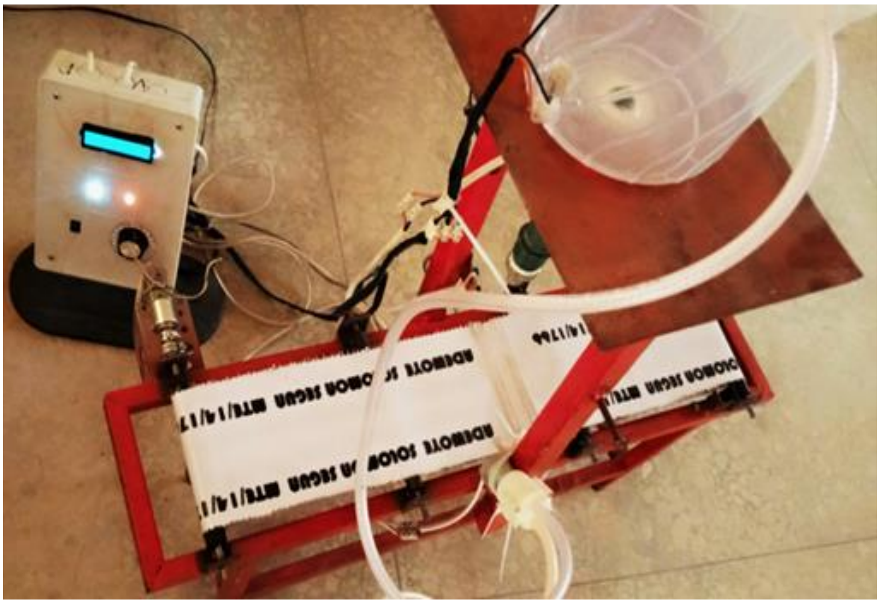

Figure 4. *Automated liquid dispensing machine final setup*

2.5. Performance Evaluation

The experiment in this study aims to determine how close the time required to deliver a set volume from the implemented machine is to the theoretical time required for the same volume at each iteration. Because time is a continuous variable, the criteria used were the sum of squared errors, mean squared errors and accuracy.

The sum of squared error (SSE)

The SSE is the sum of the squared differences between the experimental time and the theoretical time. The lower the SSE value, the more efficient the machine as presented in [21]

$$SSE = \sum_{i=1}^{n} \left(x_i - o_i\right)^2 \tag{12}$$

where x_i experimental time at iteration i , o_i is the theoretical time at iteration i and n is the number of iterations available for analysis.

Mean squared error (MSE)

The Mean Squared Error (MSE): This metric indicates how close an experimental time to dispense the same volume is to a theoretical time required for the same volume. This is accomplished by squaring the differences between the experimental time and the theoretical time ("errors"). Squaring is required to remove any negative signs. Larger differences also give more weight. The lower the MSE value, the more efficient the machine as presented in [21]

MSE formula: $$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(x_i - o_i\right)^2 \quad (13)$$

where x_i experimental time at iteration i , o_i is the theoretical time at iteration i and n is the number of iterations available for analysis.

Accuracy (ACC)

The accuracy formula calculates the accuracy as the difference between the error rate and 100 %. The error rate is calculated to determine accuracy. The error rate is calculated as the percentage of the difference between experimental time and theoretical time divided by theoretical time as presented in [21]

$$Error\_rate = \frac{abs(\exp erimental\_value - Theoretical\_value)}{Theoretical\_value} \times 100$$
$$ACC = 100\% - Error\_rate \quad . \quad (14)$$

3. THE RESEARCH FINDINGS AND DISCUSSION

The flow of the solenoid valve is 0.15m/s at a discharge rate is 2×10-5m3/s. The equation relating the time and rate of flow is described in Equation (15)

$$t = \frac{q}{\eta}(s) \quad (15)$$

where t = time (s), q = quantity (ml) and η = flow rate (ml/s) .

The maximum time of the automated dispensing machine is 35 s, implying that the maximum quantity of product volume that the automated dispensing machine can discharge is 700 ml. The experiment carried out in this work proves the feasibility of the design proposed in this article. SSE, MSE, and ACC are used to compare the performance of the design machine in terms of the time required to disperse the same volume as the theoretical volume to verify machine efficiency. Table 2 and Figures 5 and 6 show the findings.

Table 2. *Theoretical and Experimental Time, and the volume*

Volume (mL)	Theoretical Time (s)	Experimental Time (s)	Difference	Squared difference	Error rate
100	5.00	5.30	-0.30	0.09	6.00
150	7.50	7.90	-0.40	0.16	5.33
200	10.50	10.70	-0.20	0.04	1.90
250	12.50	12.30	0.20	0.04	1.60
300	15.00	14.90	0.10	0.01	0.67
330	16.50	16.20	0.30	0.09	1.82

350	17.50	17.60	-0.10	0.01	0.57
400	20.00	20.30	-0.30	0.09	1.50
450	25.00	25.50	-0.50	0.25	2.00
600	30.00	29.90	0.10	0.01	0.33
650	32.50	31.90	0.60	0.36	1.85
700	35.00	35.70	-0.70	0.49	2.00
				SSE	1.6400
				MSE	0.1367
				ACC	97.8688

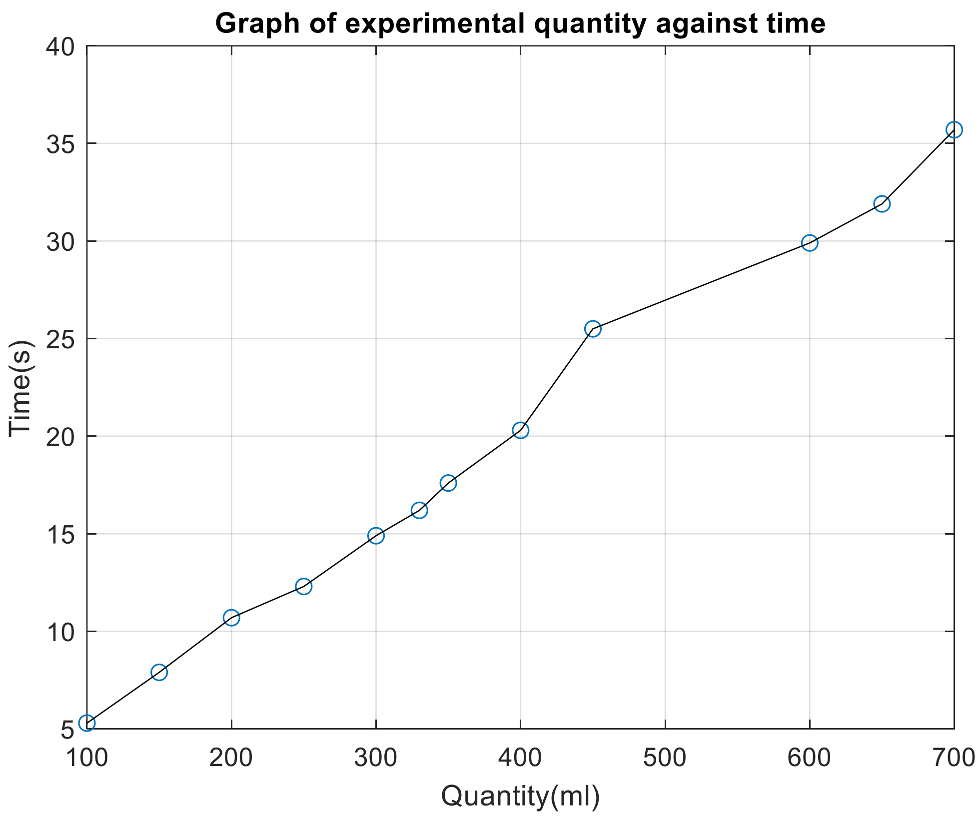

Figure 5. *Graph of the experimental quantity against time*

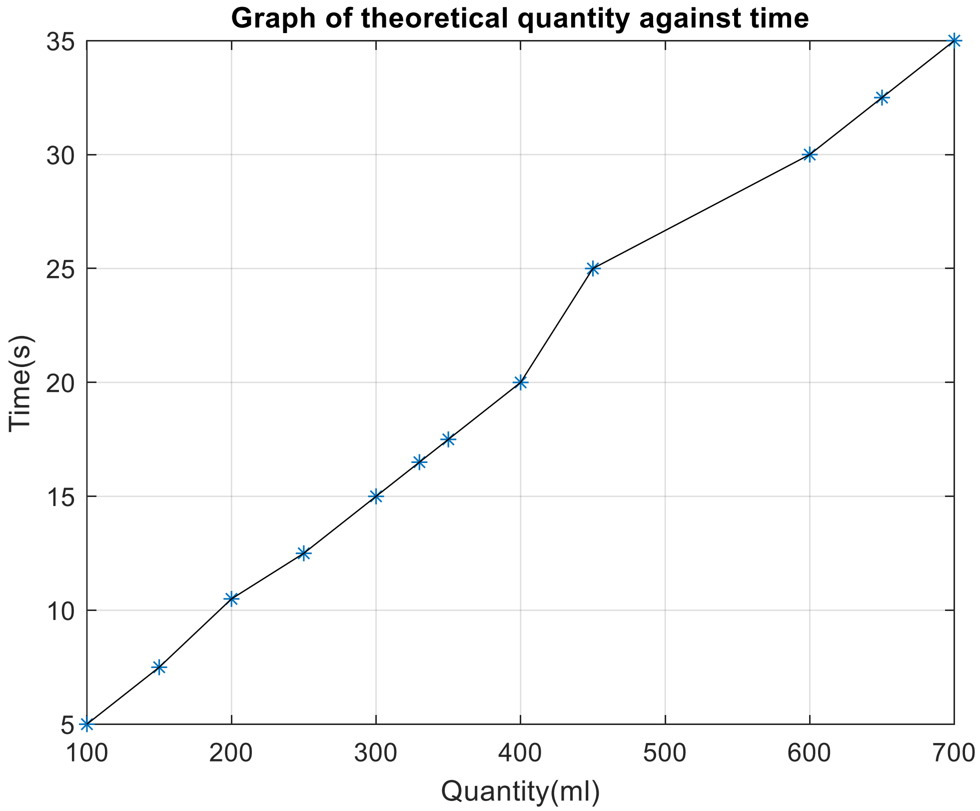

Figure 6. *Graph of theoretical quantity against time*

The results of the experiment show that the proposed design distributed the set volume in the shortest time possible compared to its theoretical time. This is demonstrated by the minimal SSE value of 1.64 and the MSE value of 0.1367 in Table 2. Furthermore, the machine's accuracy is approximately 97.87 %, indicating how close the theoretical time is to the machine dispense time in the experiment for the set volumes.

4. CONCLUSION

This article proposes a new design of an automated liquid dispensing machine for small and medium-scale industrial applications based on the time required to dispense the set volume. The microcontroller uses the timer circuit to perform a scan to determine the desired volume, which is represented by the user-specified equivalent time in seconds. The relay to which the solenoid valve is connected then receives a signal, and the specified valve opens for the time in seconds, which is equivalent to the current volume in ml. This article analyses the machine's performance in-depth and many experiments have been completed. The proposed design frequently presents a minimal time difference from the theoretical time to dispense the same volume, resulting in a minimal SSE value of 1.64, an MSE value of 0.1367, and an accuracy of approximately 97.87 %, demonstrating the feasibility and effectiveness of the design. However, the proposed design has a maximum dispensing time of 35 s, implying that the automated dispensing machine can discharge 700 mL of product in volume. Because increasing the time reduces the machine's accuracy significantly. As a result, in future research, the machine's capacity will be increased, and efforts will be made to improve efficiency even for large volumes by adding artificial intelligence techniques.

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CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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