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Development and implementation of a programmable logic controller and human machine interface for control and monitoring of bottling operations.

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Abstract
This study presents control and monitoring tool for bottle filling, closing, and labelling machine using Programmable Logic Controller (PLC) and Human-Machine Interface (HMI). This tool was designed to optimize the production process in the bottled beverage industry, with dimensions of 200 cm × 70 cm × 100 cm. The conveyor transported bottles through the filling, capping, and labeling units. Sensors were installed to detect the presence of bottles. The liquid volume was determined through time settings inputted through the HMI, and the water pump did the filling. After filling, bottles were capped and tightened mechanically using an air impact system. Two DC motors handled the labeling by unrolling the label and rotating the bottle, ensuring the label adheres evenly to all sides of the bottle. The number of bottles produced was calculated using a capacitive proximity sensor and displayed on the HMI. Testing results show that the system effectively controls and monitors the bottle filling, capping, and labeling process via PLC and HMI. The system were able to fill water into the bottle with a maximum percentage error of 0.5% for a 1000 ml volume. The success rate for capping unit was 70%, while bottle labeling unit it was 80%.

Keywords:
Filling, capping, labelling, PLC, HMI.

1 Introduction

The manufacturing business is undergoing significant transformations due to technological advancements and growing consumer demand. The intensification of competition in the worldwide market necessitates organizations to enhance operational efficiency, minimize expenses, and uphold product quality. Implementing automation in the production process is a highly effective way to address these difficulties.

Automation aims to substitute manual systems with completely autonomous processes requiring minimal human involvement [1]. Various businesses, including those in the beverage and pharmaceutical sectors, require filling bottles with a specific volume of liquid. Utilizing relay logic control in implementing a system can result in a lack of adaptability. A Programmable Logic Controller (PLC) is an electronic system that operates digitally. It stores internal instructions to perform specific tasks such as logic, sequencing, timing, counting, and arithmetic operations, which are used to control machines or processes through digital or analog input/output modules [2][3]. PLC offers greater flexibility in automating diverse processes since it allows for modifications in system behavior without altering the electrical connection. Additionally, PLCs can monitor the system while it operates [4]. [5] Designing an automatic water-filling machine for bottles controlled by Arduino. Arduino programming language is more complex compared to PLC ladder logic. Research findings [6] indicate that employing PLC for automatic liquid filling in bottles reduced operational expenses and decreased energy usage compared to conventional control methods. Furthermore, this method offers increased flexibility and efficiency in time management.

The bottle-filling machine utilizes PLC as its controller. A conveyor belt transports the bottles. Upon detection of the bottle by the infrared sensor, the conveyor halts and activates the pump to fill the bottle. The pump operates for 15 seconds to fill a bottle with a capacity of 800 milliliters. The time setting in the program [7-12] determines the volume of the bottle's contents. The Human-Machine Interface (HMI) [13][14] enables monitoring of the bottle-filling machine's process. Machines [15][16] specialize in the automated closure of bottles using the electromechanical integration of pneumatic control systems. A study conducted by researchers [17-21] developed an automated system for filling and capping bottles, which operates on a conveyor belt. They used PLC to control the system.

The objective of this study is to create an automated system for the manufacturing process of bottled beverages. In addition to the bottle filling and closing operation, the system also carries out bottle labeling and counting procedures. The system uses PLC as the primary control mechanism and HMI device to oversee the process, calculate the quantity of liquid in each bottle, and present the total count of created bottles.

2 Research Methods

The block diagram of the bottle filling, capping, and labelling machine is shown in Fig. 1. Input**:**

a. HMI. The HMI NB7W TW00B is used as operational control as well as for real-time monitoring of the processes of filling, capping, labelling and counting bottles.
b. Push-button start. The push button start is used to start or activate the system.
c. Push-button stop. The push button stop is used to turn off the system
d. Emergency stop push-button. The emergency stop is used to shut down the system in case of an emergency or for maintenance.
e. Infrared proximity sensor. The infrared proximity sensor is used to detect bottles in the bottle-filling unit.
f. Capacitive proximity sensor 1. Capacitive proximity sensor 1 is used to detect bottles in the bottle capping unit.
g. Capacitive proximity sensor 2. Capacitive proximity sensor 2 is used to detect bottles in the bottle labelling unit.
h. Capacitive proximity sensor 3. Capacitive proximity sensor 3 is used to detect bottles and count the number of bottles processed.

Output:

a. Relay. The relay controls the power supplied to the actuators. When the PLC gives a control signal, the relay switches and connects or disconnects the power flow to the actuators.
b. DC motor 1. DC motor 1 is the main conveyor to move bottles from the starting point through the filling, capping, and labelling units.
c. DC motor 2. DC motor 2 is used as the label conveyor to attach labels to the sides of the bottles.
d. DC motor 3. DC motor 3 is used as the label motor to rotate the label, so it tears off and sticks to the bottle.
e. DC water pump. The DC water pump is used to pump water from a reservoir or container into the bottle.
f. Solenoid valve 5/2 1. Solenoid valve 5/2 1 controls pneumatic cylinder 1 to stop bottles in the bottle-filling unit.

g. Solenoid valve 5/2 2. Solenoid valve 5/2 2 controls pneumatic cylinder 2 to stop bottles in the bottle-filling unit.
h. Solenoid valve 5/2 3. Solenoid valve 5/2 3 controls pneumatic cylinder 3 to insert the nozzle into the bottle, allowing the DC water pump to fill the bottle with water.
i. Solenoid valve 5/2 4. Solenoid valve 5/2 4 controls pneumatic cylinder 4 to stop bottles in the bottle capping unit.
j. Solenoid valve 5/2 5. Solenoid valve 5/2 4 controls pneumatic cylinder 5 to stop bottles in the bottle capping unit.
k. Solenoid valve 5/2 6. Solenoid valve 5/2 6 controls pneumatic cylinders 6A and 6B to grip the bottles in the bottle capping unit. Solenoid valve 5/2 6 also controls pneumatic cylinder 6C to push the air impact screwdriver to close and tighten the bottle caps.
l. Solenoid valve 5/2 7. Solenoid valve 5/2 7 controls the air impact screwdriver, which uses compressed air from the compressor to close or tighten the bottle caps.

The wiring electronic installation design of the bottle filling, capping, and labeling machine is shown in Fig. 2.

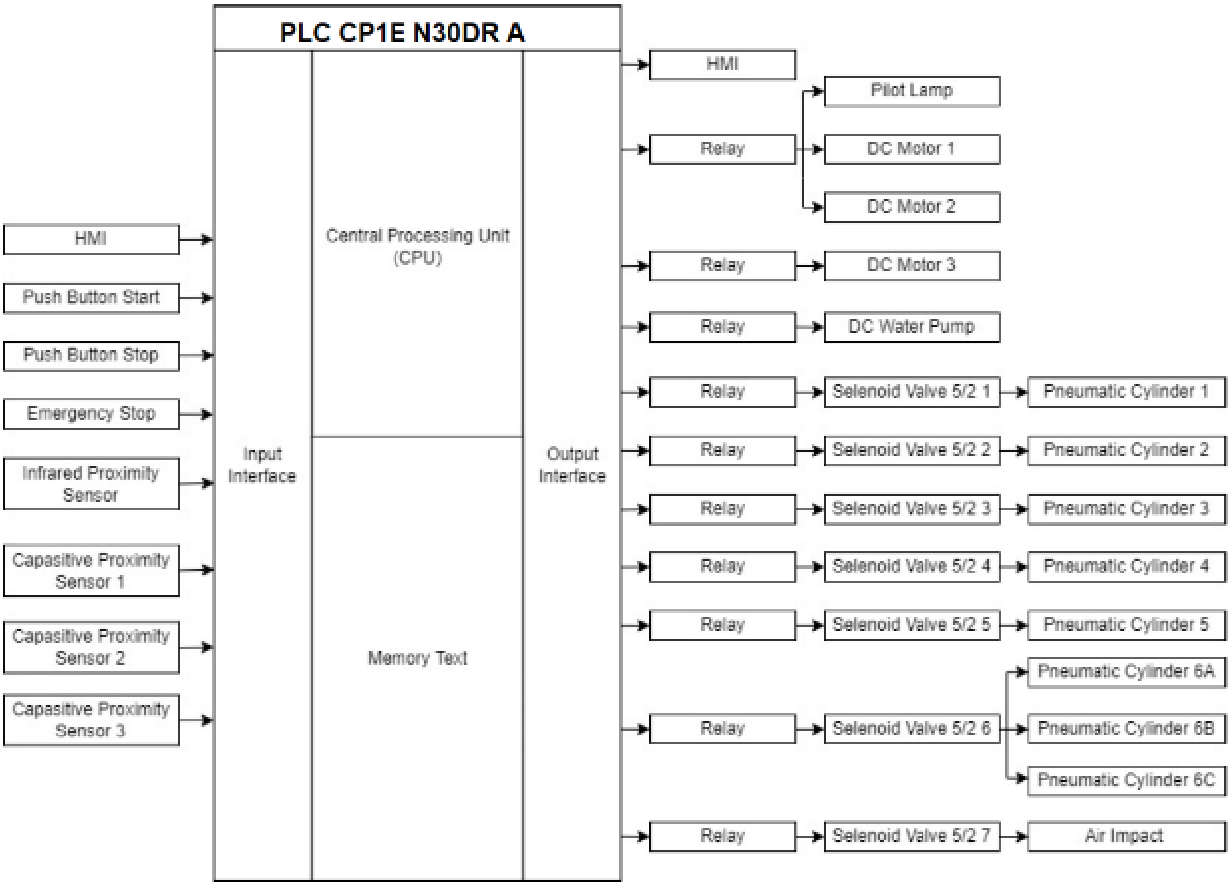

Fig. 1 The block diagram of the bottle filling, capping, and labelling machine.

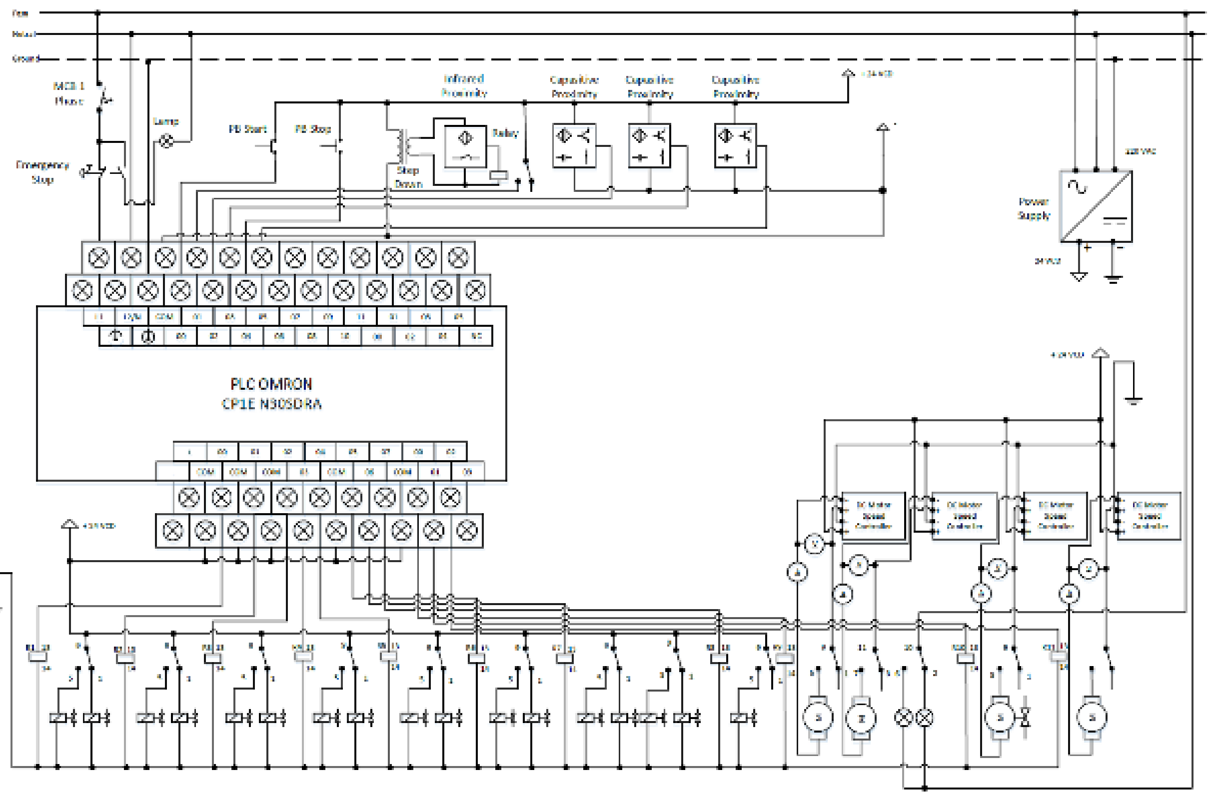

Fig. 2 Electronic wiring installation design.

2.1 Prototype Design

A bottle filling, capping, and labelling control and monitoring system is a tool for industrial workers to fill, cap, and label bottles in bottled beverage production using a programmable logic controller and a human-machine interface (Fig. 3).

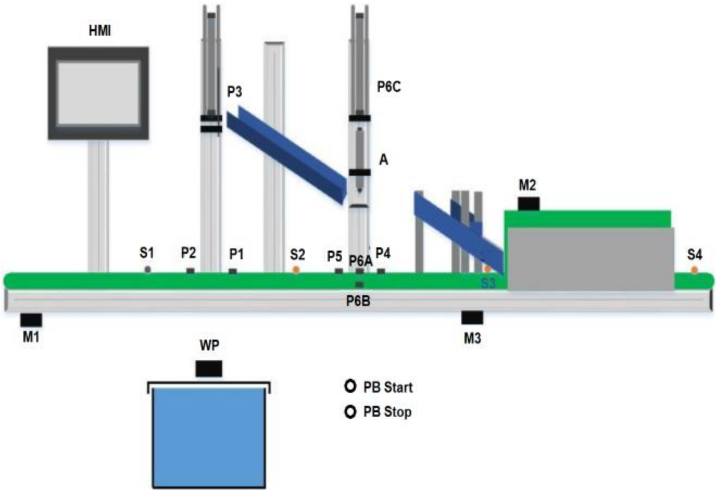

Fig. 3. Sketch of bottle filling, capping and labeling machine (Table 1).

Table 1. List of components in the bottle filling, capping, and labelling machine

Symbol	Component name
S1	Infrared proximity sensor
S2	Capacitive proximity sensor 1
S3	Capacitive proximity sensor
S4	Capacitive proximity sensor
P1	Pneumatic cylinder 1
P2	Pneumatic cylinder 2
P3	Pneumatic cylinder 3
P4	Pneumatic cylinder 4
P5	Pneumatic cylinder 5
P6A	Pneumatic cylinder 6
P6B	Pneumatic cylinder 6B
P6C	Pneumatic cylinder 6C
M1	DC motor 1/main conveyor
M2	DC motor 2/labeling conveyor
M3	DC motor 3/labeling motor
A	Air impact screwdriver
WP	DC water pump

2.1.1 Bottle Filling Unit

This unit fills liquid into bottles. When the push button start is pressed, the main conveyor runs, carrying the bottle. If the bottle is detected by the filling unit sensor (S1), the thruster, in the form of a pneumatic cylinder (P1), moves forward to stop the bottle, and P2 pinches the bottle. Then, the pneumatic cylinder (P3), as a nozzle booster, moves down, and the water pump turns on according to the timer setting to fill water into the bottle (Fig. 4).

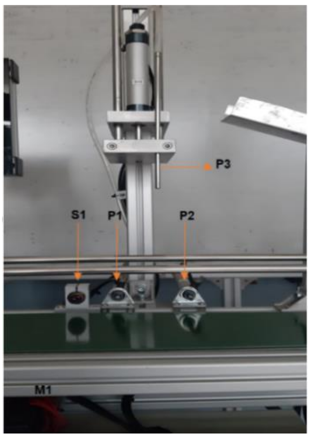

Fig. 4. Bottle-filling unit.

2.1.2 Bottle Capping Unit

This unit caps bottles after filling them with liquid. If the bottle is detected by the capping unit sensor (S2), the thruster in the form of a pneumatic cylinder (P4) moves forward to stop the bottle, and P5, P6A, and P6B pinch the bottle. Then, the pneumatic cylinder as a booster for the air impact screwdriver on (P6C) moves down, and the air impact screwdriver (A) turns on according to the timer setting to rotate the bottle cap (Fig. 5).

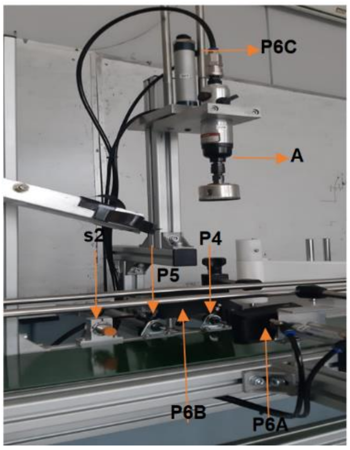

Fig. 5. Bottle capping unit.

2.1.3 Bottle Labelling Unit

This unit labels bottles after capping them. If the labeling unit sensor (S3) detects the bottle, the label on rotary motor (M3) turns on according to the timer setting to attach the label to the side of the bottle. Then, the bottle moves through the label conveyor (M2) to glue the label on all sides (Fig. 6).

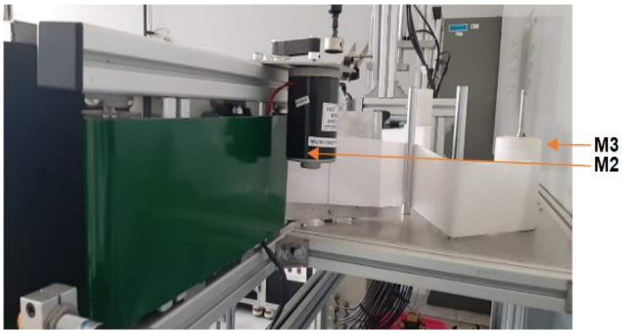

Fig. 6. Bottle labelling unit.

If a bottle is detected by the bottle counting sensor (S4), it will be on ('1'), signaling the increment instruction to add a value (+1) to the storage data (Fig. 7).

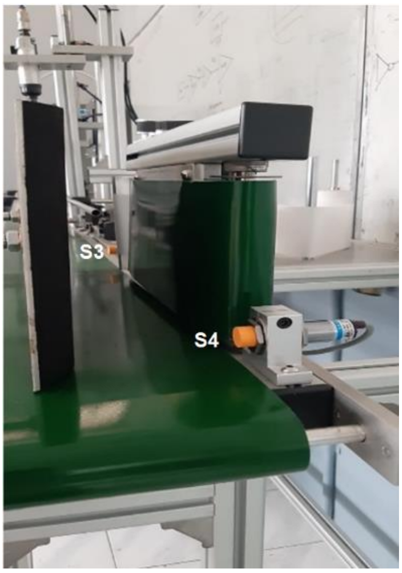

Fig. 7. Bottle counting sensor.

2.2 Program Design of HMI

The HMI has four designs: the home screen, the filling screen, the capping screen, and labeling screen. The design of the home screen is shown in Fig. 8. The home screen serves for on-off control, monitoring system conditions, running timer settings, and bottle counting results.

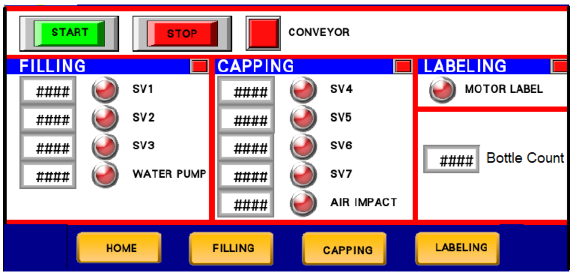

Fig. 8. Program design of home screen.

Fig. 9 shows the design of the filling screen. The screen is a facility for setting time settings on several components in stage filling and displaying the course of timer settings when the system is working.

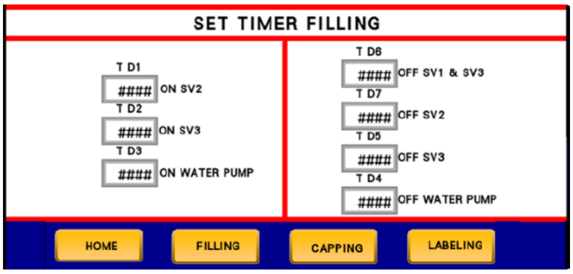

Fig. 9. Program design of filling screen.

List the time settings on the bottle-filling unit:

a. ON SV2. Setting the delay time of solenoid valve 2
b. ON SV3. Setting time delay solenoid valve 3
c. ON water pump. Setting the water pump delay time
d. OFF SV1 & SV3. Setting the working time of solenoid valves 1 and 3
e. OFF SV2. Setting the working time of solenoid valve 2
f. OFF SV3. Setting the working time of solenoid valve3
g. OFF water pump. Setting the working time of the water pump

Fig. 10 shows the design of the capping screen. The screen is a facility for setting time settings on several components in stage capping.

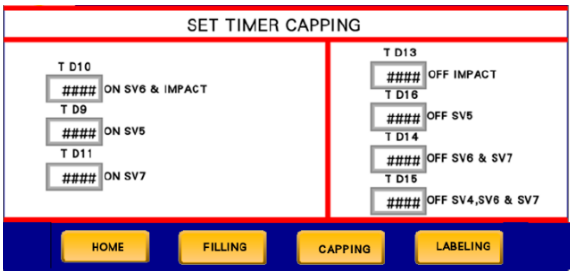

Fig. 10. Program design of capping screen.

List of time settings on the bottle closure unit:

a. On solenoid 6 & impact. Setting the delay time of solenoid valve 6 and air impact.
b. On solenoid valve 5. Setting the time delay of solenoid valve 5.
c. On solenoid valve 7. Setting the time delay of solenoid valve 7.
d. Off impact. Setting the working time of air impact.
e. Off solenoid valve 5. Setting the working time of solenoid valve 5.
f. Off solenoid valve 6 & 7. Setting the working time of solenoid valves 6 and 7.
g. Off solenoid valve 4. Setting the working time of the solenoid valve 4.

Fig. 11 shows the design of the labeling screen, which is a facility for setting time in stage labeling.

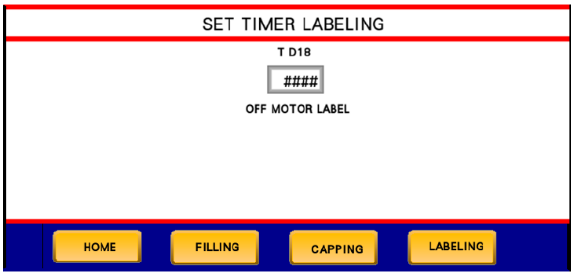

Fig. 11. Program design of a labeling screen.

OFF label motor for setting the working time of the label motor.

3 Results and Discussion

The results of the bottle filling, capping, and labelling machine are shown in Fig. 12.

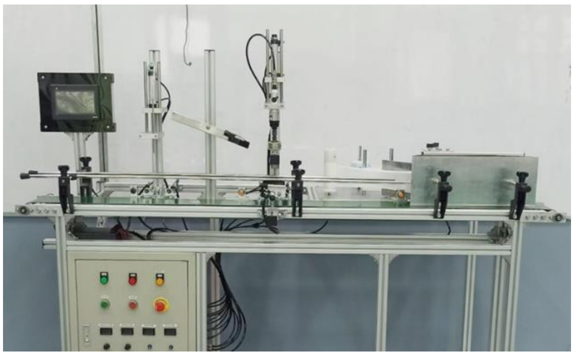

Fig. 12. The bottle filling, capping, and labelling machine.

3.1 Stage Filling Measurement

Measuring the volume of bottled drinking water involves calculating the precise amount of water filled into each bottle during the filling process. This process is essential to ensure that each bottle contains the appropriate volume of water as specified. The main purpose of this measurement is to ensure consistency in the filling volume between bottles so that consumers receive products that meet their expectations.

The measurement was performed 10 times to ensure the accurate value of the setting time, which is 17.5 seconds.

The error can be calculated using Eq. 1.

$$\text{Error} = \frac{\text{Result} - \text{Set Point}}{\text{Set Point}} \times 100 \qquad (1)$$

The results of stage-filling measurements show a maximum error value of 0.5% (Table 2).

Table 2. Result of stage filling measurements

Sample	Set point (ml)	Setting time (second)	Result (ml)	Error (%)
1	1000	17.5	1000	0
2	1000	17.5	1000	0
3	1000	17.5	995	0.5
4	1000	17.5	1000	0
5	1000	17.5	1000	0
6	1000	17.5	1005	0.5
7	1000	17.5	1000	0
8	1000	17.5	996	0.4
9	1000	17.5	995	0.5
10	1000	17.5	1000	0

3.2 Stage Capping Measurement

Bottle capping stage testing aims to determine the system's success percentage in sealing bottles.

Based on the test results shown in Table 3, it was found that out of 10 attempts, seven bottles were successfully sealed. The percentage of success can be calculated using Eq. 2.

$$\text{The success rate} = \frac{\text{bottle successfully sealed}}{\text{Sample}} \times 100\% \quad (2)$$

According to Eq. 2, the success rate is determined as: The success rate $= \frac{7}{10} \times 100\% = 70\%$. The result of stage capping measurement shows a success rate of 70%.

Table 3. Result of stage capping measurement

Sample	Result
1	The bottle successfully sealed
2	The bottle failed to seal.
3	The bottle successfully sealed
4	The bottle successfully sealed
5	The bottle successfully sealed.
6	The bottle failed to seal
7	The bottle successfully sealed.
8	Bottle failed to seal
9	Bottle successfully sealed
10	Bottle successfully sealed

3.3 Stage Labelling Measurements

Bottle labelling stage testing aims to determine the success percentage of the system in attaching labels to bottles. Based on the results of the bottle labelling unit test shown in Table 4, eight out of ten attempts successfully labeled the bottles. The percentage of success can be calculated using Eq. 3.

$$\text{The success rate} = \frac{\text{bottle successfully labeled}}{\text{Sample}} \times 100\% \quad (3)$$

According to Eq. 3, the success rate is determined as: The success rate $= \frac{8}{10} \times 100\% = 80\%$. The result of stage labelling measurement shows a success rate of 80%.

Table 4. Result of stage labeling measurement

Sample	Result
1	Bottle successfully labeled
2	Bottle successfully labeled
3	Bottle failed to label
4	Bottle successfully labeled
5	Bottle successfully labeled
6	Bottle successfully labeled
7	Bottle failed to label
8	Bottle successfully labeled
9	Bottle successfully labeled
10	Bottle successfully labeled

3.4 . Processing Time Measurement

Processing time is the time interval required to complete the entire filling, capping, and labeling of bottles in one full iteration.

The processing time was measured by timing the completion of filling, capping, and labeling one full iteration of bottles. Table 5 shows the measurement performed 10 times. The process took 65.27 seconds, 65.18 seconds, 65.32 seconds, 65.36 seconds, 65.26 seconds, 65.30 seconds, 65.20 seconds, 65.54 seconds, 65.29 seconds, and 65.15 seconds. Eq. 4 provided the average process time value.

$$\text{Average} = \frac{\text{Sample total}}{\text{Sample}} \quad (4)$$

According to Eq. 4, the success rate is determined as: average $= 65.29$ seconds. The measurement results show that the system requires an average time of 65.29 seconds to complete the entire process in one full iteration.

Table 5. Result processing time measurement

Sample	Processing time (second)
1	65.27
2	65.18
3	65.32
4	65.36
5	65.26
6	65.30
7	65.20
8	65.54
9	65.29
10	65.15

4 Conclusion

The automatic bottle filling, capping, and labeling system, which uses a programmable logic controller and human-machine interface, has substantially improved production efficiency in the bottled beverage industry, with the results concluded as:

1. Results indicates that the system can fill water into bottles with a maximum error rate of 0.5% for 1000 ml bottles. The success rate of the bottle capping process was 70%, while for bottle labeling it was 80%.
2. This system was capable of monitoring and controlling the entire production process in real-time via the HMI, allowing operators to track the number of bottles produced and adjust the component time settings. The average time required to complete one cycle of filling, capping, and labeling is 65.29 seconds.
3. It is recommended that an IoT SCADA dashboard be integrated in the device, to control and monitor the operating system remotely.

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