Size-Shift Fill-Cap System

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Abstract: - Modern manufacturing in industries such as beverages and pharmaceuticals relies heavily on automated filling and capping machines to ensure high throughput and consistency. This paper presents a PLC-controlled bottle filling and capping system, Size-Shift Fill-Cap, which adapts to multiple bottle sizes without manual changeovers. The system uses integrated sensors to detect bottle dimensions and automatically adjusts the filling nozzle height and volume, as well as the capping mechanism, for three bottle sizes. A Programmable Logic Controller (PLC) coordinates the sequence in real time, while an HMI (Human-Machine Interface) allows operators to calibrate fill volumes and timings for each size. The prototype achieved precise filling and secure capping across all supported bottle formats. Testing demonstrated improved efficiency, with reduced cycle time per bottle compared to manual operations. The machine's flexibility, ease of use, and safety features highlight its potential to streamline bottling processes and reduce downtime during product changeovers.

Key-Words: - Automated Bottle Filling, Capping Machine, Programmable Logic Controller, Multi-Size Adaptability, Industrial Automation, Human-Machine Interface.

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1 Introduction

Automated bottle filling and capping systems have significant importance in industrial packaging operations. The systems ensure increased speed, hygiene, and accuracy in the process compared to manual methods. The proposed system has been successfully implemented in different applications, such as small-scale beverage manufacturing and laboratory applications. In traditional methods, bottle filling and capping systems have been implemented for specific bottle sizes by modifying the machines and changing parts for different types of bottles. With the requirement of different product sizes in the packaging process, there is a requirement for flexible filling and capping systems that can support different types of bottles. Recently, research and development activities have been carried out to fulfill the growing requirement of flexible filling and capping systems. A filling and capping system with a PLC for specific types of bottles was proposed to ensure uniformity in the process and increase speed and accuracy, [1]. Other researchers have developed various filling systems with flexible capabilities for various bottle sizes using simulations, [2], [3]. A simulation for filling various bottle sizes was developed by developing a single PLC program for various bottle sizes by using sensors and gates for separating various bottle sizes according to their types, [3], [4]. Similarly, an automated filling/capping system with user-defined volume selection for flexible volume changes was developed by using a program, [5]. Recently, an adjustable filling and capping machine was developed by using a PLC and HMI, which enables fast switching between various bottle sizes with minimal downtime, [5]. These works show the significance of multi-size adaptive bottling machines in industry.

This paper is an extension of the aforementioned papers and proposes a new system referred to as the "Size Shift Fill Cap system," which is a small machine that can be easily controlled by a PLC and can work with any size bottle seamlessly. The uniqueness of the proposed system is that it can easily change according to the sensors, which can detect the size of the bottle and adjust the fill level and cap position according to that. The system does not have to be recalibrated or have any parts replaced during the process. The next section will discuss the approach used for the system (Section 2), followed by the results obtained from the system (Section 3), and finally, conclusions and future work will be discussed in Section 4.

2 Methodology

2.1 System Architecture

The Size Shift Fill Cap system uses a Delta Programmable Logic Controller (PLC), which controls all sensing and actuation. The system receives input from various sensors placed at different points along the bottling line and controls the filling pump, conveyor motors, and capping actuators. Figure 1 shows the block diagram of the Size Shift Fill Cap system. The block diagram shows how the system receives the start signal and processes it with signals from various sensors and actuators. The system uses three different types of sensors. The first type of sensor is an inductive sensor at the infeed point of the system. This sensor detects the presence of a bottle and determines its size by detecting the diameter of the bottle. The second type of sensor is a proximity sensor. This sensor determines whether a bottle is properly aligned under the filling nozzle. The third type of sensor is a capacitive sensor at the output point of the system. This sensor determines whether a bottle has been capped and is moving out of the system. The signals from each of these sensors are connected to the digital inputs of the PLC.

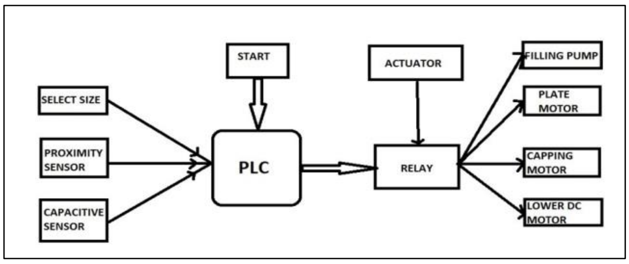

Fig. 1: PLC-based control block diagram of the Size-Shift Fill-Cap system.
Source: Created by the Authors

2.2 Mechanical Design

The machine's mechanical setup is configured in two stages: a filling station and a capping station connected by a conveyor system. At the filling station, a linear actuator is used to adjust the height of the filling nozzle assembly. This adjustment is crucial to accommodate different bottle heights: before dispensing, the PLC commands the linear actuator to move the nozzle down to a pre-calibrated position appropriate for the detected bottle size.

The vertical positioning of the filling nozzle is controlled by the PLC via a linear relationship between the actuator's stroke and the PWM (Pulse Width Modulation) or timed drive signal. The nozzle height H is determined by Equation (1):

$$H = H_{max} - (v \cdot t_{act}) \quad (1)$$

where H_{max} is the home position, v is the constant velocity of the 24V DC actuator, and t_{act} is the energizing duration set via the HMI. This linear control ensures repeatable alignment for the 0.25L, 0.5L, and 1L formats.

The fill operation is performed by an electric water pump that is activated for a preset duration (controllable via the HMI) to dispense the required volume. By timing the pump activation to match the bottle size, the system ensures accurate fills for each container (e.g., a longer pump-on interval for larger bottles).

The dispensing volume V is a function of the constant flow rate Q of the 12V brushless pump and the activation time. t_{fill} calibrated in the HMI. The model is expressed in Equation (2):

$$V = Q \cdot t_{fill} \quad (2)$$

Since Q is stabilized by the 12V/10A power supply, the PLC achieves volume precision by adjusting. t_{fill} in millisecond increments.

To prevent splashing and foaming, the nozzle inserts into the bottle to an appropriate depth, then retracts once filling is completed. Figure 2 shows a pair of guide rails (centering bars with a spring mechanism) on the conveyor centers each incoming bottle under the nozzle.

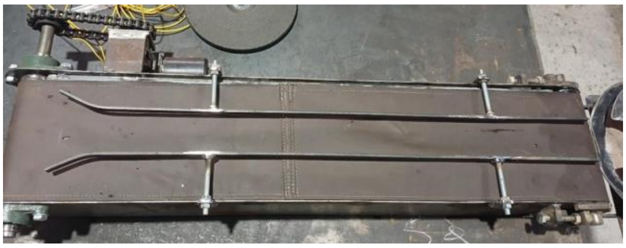

Fig. 2: Guide Rails
Source: Created by the Authors

After filling, the main conveyor belt transports the bottle to the capping station. A custom-designed star wheel indexing mechanism (or rotary plate) temporarily holds and positions each bottle for capping. As the filled bottle arrives, it contacts a sensor that triggers the indexing motor (a NEMA 17 stepper motor) to rotate the star wheel, moving the bottle into the capping position. At this point, a cap is dispensed onto the bottle neck from a cap feeder chute (a cap hopper and slide, referred to as the "cap holder" mechanism in the design). The capping itself is accomplished by a second linear actuator fitted with a capping head (or chuck). When the bottle is in place, the PLC energizes this actuator to press the cap down and twist-tighten it. The downward motion and duration are precisely timed in the PLC program to avoid over-tightening. An HMI-set parameter ensures the actuator applies sufficient force for a secure seal without damaging the cap or bottle threads. Once the cap is affixed, the actuator retracts and the star wheel indexes again, releasing the capped bottle onto a secondary outfeed conveyor. An output sensor confirms the bottle's departure, signaling the PLC that the cycle is complete and the system can reset for the next bottle.

Throughout the operation, a Human-Machine Interface (HMI) is available as an operator interface. The HMI offers a way to select or confirm the selected bottle size mode, view the status of sensor and actuator operation, and even adjust parameters such as filling time, pump speed, and capping force, as required, as they are critical factors in adjusting the machine's operation when introducing a new type of bottle into the process. However, bottle calibration by the HMI is only possible once parameters such as nozzle height position, fill time, etc., have been stored within the PLC memory and automatically implemented during operation on a given bottle size.

2.3 Key Components

The hardware component selection was based on the multi-size operating requirement. A Delta DVP-12SE PLC with an expansion module DVP-16SP was selected because it has adequate I/O points and high processing speed for handling simultaneous sensor inputs. Two stepper motors with a TB6600 stepper driver are utilized. One stepper motor precisely indexes the star wheel for the capping action. The NEMA 17 stepper motor has a step angle of 1.8° per step. To accomplish the required indexing for a 6-pocket star wheel, the PLC will calculate the required steps (N) as shown in Equation (3):

$$N = \frac{\theta_{target}}{\theta_{step}} \cdot \mu \quad (3)$$

where θ_{target} = 60° is the angle of rotation, θ_{step}=1.8° is the step angle, and μ is the micro-stepping factor set in the TB6600 driver. This mathematical accuracy ensures that the position error is less than 5 mm.

The TB6600 driver is set at 24 V and optimized for the best torque at the desired speed since it is best suited for maintaining stepper motor torque. The 24 V DC gear motor (200 RPM, High Torque 37GB520) is used for the conveyor belt and cap feeding. This motor can stall without damaging itself when indexing the bottles. The linear actuators are each a 24 V DC motor with a stroke length that can reach the height of the tallest bottle. Using electric actuators instead of pneumatics makes it easier to control the PLC since it does not require compressed air. All the actuators and motors are driven by relays or motor drivers connected to the PLC outputs. The entire system is driven by a DC power supply of 24 V/10A.

2.4 Design Constraints and SDG Alignment

The requirements for the Size Shift Fill Cap machine were driven by economic, technical, safety, and sustainability factors. From an economic point of view, the choice of stepper motors and DC actuators was made in consideration of reduced capital and operational costs without compromising on accuracy. From a technical point of view, the choice of modular components and a PLC/HMI system ensures reduced downtime and ease of integration into existing production systems. The safety requirements were met by the choice of low DC voltages and multiple sensors with an emergency stop system. Finally, from a sustainability point of view, the machine contributes to the United Nations' SDG 9 Industry, Innovation and Infrastructure by virtue of its on-the-fly size adjustment capability. It contributes to SDG 12 Responsible Consumption and Production by virtue of reduced product waste and SDG 7 Affordable and Clean Energy by virtue of DC power and replaceable components. The added value of this study is the provision of a cost-effective, user-friendly, and scalable multi-format bottling solution for SMEs without compromising on significant retraining and reconfiguration times.

2.5 Control Logic

The PLC ladder logic is modelled as a Finite State Machine (FSM). The system transition can be defined by the set $S = \{S_{Idle}, S_{Detect}, S_{Fill}, S_{Index}, S_{Cap}, S_{Exit}\}$.

Transitions between states occur based on discrete sensor inputs (Inductive, Proximity, and Capacitive). Transitions between the Finite State Machine (FSM) states are governed by Boolean logic triggers. For example, the transition T_1: $S_{Detect} \rightarrow S_{Fill}$ is defined in Equation (4):

$$T_1 = \left(P_{sensor} \wedge B_{size\_valid}\right) \quad (4)$$

where

P_{sensor}: The logic state of the proximity sensor (True when a bottle is positioned under the nozzle). B_{size_valid}: The verification of height and diameter thresholds required for a specific bottle format. This state-based formalism guarantees that PLC execution is deterministic, i.e., it is not possible to reach a state S_{Fill} without verification of safety interlocks and height thresholds for a specific bottle format by ladder logic.

A simplified flowchart of the control sequence is as follows (this corresponds to the PLC ladder logic program): (1) Start – The operator presses the start button on the HMI or control panel, and the system becomes active. (2) Bottle Sensing – As bottles arrive on the conveyor, sensors detect a bottle and identify its size (small, medium, or large) via pre-set sensor height thresholds or a combination of sensor triggers. (3) Filling – The conveyor halts precisely when the bottle is under the fill nozzle; the PLC then triggers the linear actuator to lower the nozzle to the correct height for that size and activates the pump for a timed interval to dispense the exact volume. (4) Transfer – Once filled, the nozzle retracts, and the conveyor restarts to move the bottle to the capping area. (5) Capping – The star wheel mechanism indexes the bottle into position; a cap is released onto the bottle; the capping actuator drives down and secures the cap, then retracts. (6) Completion – The star wheel rotates to send the now-capped bottle onto the exit conveyor. The cycle can repeat immediately for the next bottle.

2.6 Panel Board

The entire control system is neatly organized inside a rugged, powder-coated steel enclosure on standard DIN-rails (Figure 3). Power enters the panel via a 16 A, 2-pole miniature circuit breaker (MCB) with an integrated end-of-line terminal, which then feeds two dedicated switch-mode power supplies: a 24 V/10 A unit and a 12 V/10 A unit. The 24 VDC bus is distributed via a dedicated brown (+) bus bar and a blue (0 V) rail, and powers the Delta DVP-12SE PLC (using its UP/SS and ZP/SS terminals), the RS-485 HMI interface, and both TB6600 stepper-motor drivers. The 12 VDC bus also distributed busbar drives, all high-torque DC gear motors and the 12V brushless water pump.

All field-wired PNP and NPN sensors connect through numbered, spring-clamp terminal blocks, with care taken to link the PLC's SS common terminal to +24 V for NPN devices and to 0 V for PNP devices, ensuring proper sourcing or sinking as required. PLC outputs (Y1–Y8) are each wired to the A1 coil terminals of industrial DIN-rail relays; the corresponding A2 terminals go to +24 VDC. The common pole (COM, terminal 11) of each relay is tied to +24 VDC, and the normally open (NO, terminal 14) and normally closed (NC, terminal 12) contacts switch motor and actuator polarities, enabling forward/reverse control of the linear actuators without external H-bridges.

Signal and power wiring are segregated in wire ducts with snap-on covers, and all conductors are ferrule-terminated with clear numeric labeling to simplify commissioning and maintenance. Status LEDs on the power supplies and relays provide at-a-glance diagnostics, while an earth-ground stud and incoming PE conductor ensure all metalwork is properly bonded per IEC 60204-1. Finally, the HMI COM port is hard-wired to the PLC's RS-485 A/B terminals via shielded cable, with the shield drained to earth in the panel, guaranteeing noise-free communication even in electrically harsh environments. This highly modular, standards-compliant layout not only makes the system robust and serviceable but also future-proof for any expansions or upgrades.

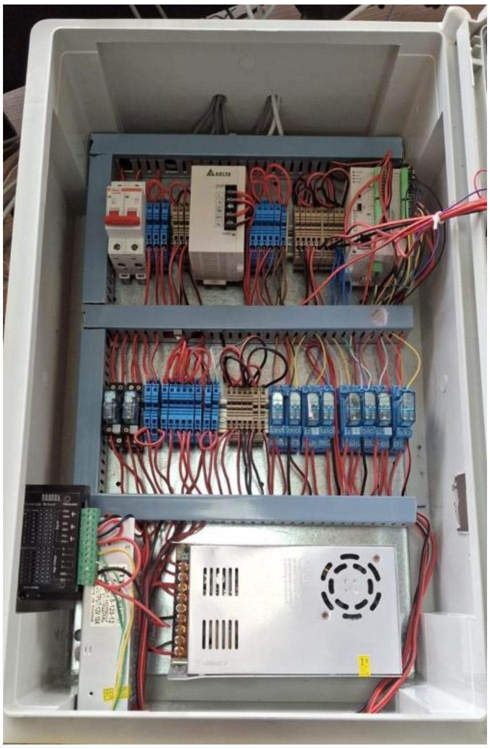

Fig. 3: Panel Board
Source: Created by the Authors

2.7 Human Machine Interface (HMI)

The HMI provides the operator with a single, intuitive touchscreen from which all system functions can be accessed and adjusted (Figure 4). On power-up, the main page displays navigation buttons for viewing the live status of inputs and outputs, selecting manual control mode, and entering each calibration submenu. From this page, the operator may open the I/O Monitor screen to observe the real-time state of sensors, relays, and motor drives, or switch to Manual mode to jog conveyors, actuators, and the star-wheel stepper independently. Calibration is performed through dedicated screens: one for pump run-time adjustment and three separate screens to enter the precise actuator heights for 0.25 L, 0.5 L, and 1 L bottles, ensuring nozzle alignment without needing ladder-logic changes. Additional menus allow tuning of the capping actuator descent time and the star-wheel rotation angle so that torque and indexing position remain consistent across bottle formats. All numerical inputs are validated against safe ranges before being written to non-volatile PLC registers, guaranteeing that parameters persist after power cycles. A software "E-Stop" icon mirrors the physical emergency-stop circuit, allowing any motion to be halted instantly from the touchscreen. This HMI design enables operators with minimal training to switch bottle sizes or intervene in real time, without interrupting the PLC program or compromising production continuity.

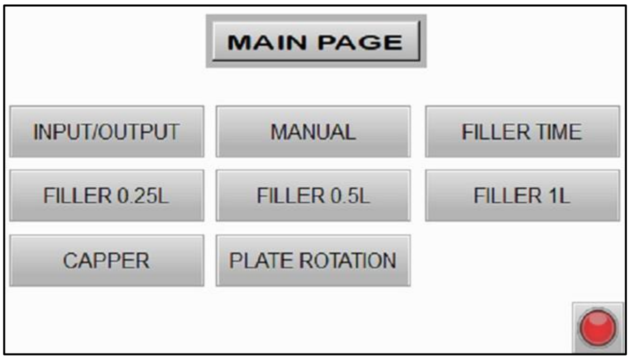

Fig. 4: Main HMI page with navigation buttons for system status, manual control, and calibration.
Source: Created by the Authors

3 Results

3.1 Prototype Layout and Workflow

Figure 5 presents the physical prototype laid out on a single workbench, combining all the major subsystems into a compact, modular assembly. Bottles are manually placed at the right-most end of the infeed conveyor (top right of Figure 5) and guided by two adjustable centring rails into the filling station. Just upstream of the nozzle, an inductive diameter sensor and a stack of three capacitive "height" sensors detect the presence and size of each incoming bottle. Once the PLC confirms a valid bottle is in position, it halts the conveyor, energizes the 24 V DC linear actuator to lower the stainless-steel nozzle into the neck, and switches on the 12 V brushless pump for the exact calibrated duration (set via the HMI). As soon as the pump cycle completes, the actuator retracts and the conveyor restarts, carrying the now-filled bottle toward the star-wheel indexer (top left of Figure 5).

At the indexer, a round rotary plate driven by a NEMA 17 stepper through a TB6600 driver captures one bottle at a time. A second PNP proximity sensor mounted beside the wheel signals the PLC when the bottle is seated in the capping pocket. Simultaneously, the cap-feeder chute (visible just above the rotary plate in Figure 5) drops a cap onto the neck. The PLC then triggers the second 24 V linear actuator (mounted above the star wheel) to descend and torque-twist the cap until the pre-set HMI-defined timer elapses, ensuring consistent seal strength without over-tightening.

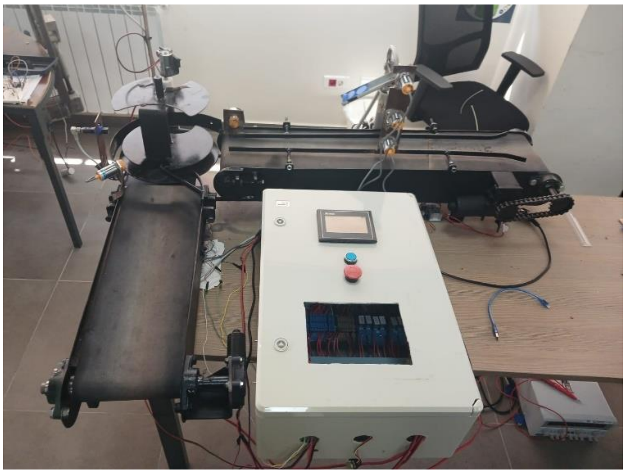
Fig. 5: Overall view of the Size-Shift Fill-Cap prototype, showing the filling station and capping station linked by the conveyor.
Source: Created by the Authors

Once capping is complete, the stepper rotates the wheel to release the bottle onto the outfeed conveyor (bottom left of Figure 5). A final capacitive "exit" sensor confirms departure, resets the rotary plate to home, and readies the system for the next cycle. The large steel control enclosure in the foreground houses the 16 A mains breaker, dual DC supplies (24 V and 12 V), PLC, HMI, relay bank and wiring harness. Emergency-stop buttons at both stations and interlock wiring (e.g., pump enabled only when a bottle is detected) are hard-wired through the enclosure's terminal blocks. All motion axes and fluid operations are therefore fully supervised by ladder-logic in the Delta DVP-12SE controller, with live status and manual-override controls accessible via the touchscreen. This integrated layout not only streamlines the fill-index-cap sequence but also allows rapid reconfiguration for new bottle formats simply by adjusting a few HMI parameters, with no mechanical change parts required.

3.2 Prototype Performance Evaluation

A functional prototype of the Size-Shift Fill-Cap system was constructed and evaluated using three bottle sizes as test cases (small 330 ml bottle, medium 500 ml bottle, and large 1.5 L bottle). The filling accuracy was assessed by comparing the dispensed volume to the target volume for each size. Across all trials, the maximum absolute percentage error between the dispensed and target volume did not exceed 2% (i.e., ±2% denotes the worst-case deviation observed among all measurements). To validate the system's precision, a series of $n = 30$ trials was conducted for each bottle size (small, medium, large). For each set, we report the sample mean μ, the sample standard deviation σ, and the coefficient of variation $(CV) = \left(\frac{\sigma}{\mu}\right) \cdot 100\%$, summarized in Table 1.

Table 1. Statistical Analysis of Filling Accuracy ($n = 30$ per bottle size)

Bottle Size	Target Vol. (ml)	Mean Vol. μ (ml)	Std. Dev. σ (ml)	Coeff. Of Variance (CV)
Small	330	331.2	1.5	0.45%
Medium	500	501.2	1.8	0.36%
Large	1500	1504.0	4.8	0.32%

Source: Created by the Authors

There were no cases of overfill or underfill encountered during the trials, and this is because of the precision of the pump timing and the use of a proximity sensor to ensure that the nozzle is inserted to an optimal depth for a given bottle. The fill volume was consistent even with bottles fed into the machine in alternating order of sizes, thus showing that the machine is able to do this on the fly without having to stop and reconfigure.

Concerning its throughput rate, the automated machine can perform a cycle of 8-10 seconds for a single bottle (from detection to complete capping of a 500 ml bottle). By contrast, manual filling and capping by an operator was estimated to handle at most 2–3 bottles per minute for similar volumes, with greater inconsistency. Thus, the Size-Shift Fill-Cap machine potentially doubles the throughput while maintaining higher accuracy. The reduction in cycle time is due to the parallelism and coordination that the PLC affords, for instance, the next bottle is positioned at the filling station while the previous one is still being capped, optimizing the use of time. The total cycle time per bottle, T_{cycle}, can be modeled as the sum of discrete state durations, as given in Equation (5):

$$T_{cycle} = t_{detect} + \max(t_{fill}, t_{cap}) + t_{index} \quad (5)$$

where the variables are defined as:

- T_{cycle}: Total time from bottle detection to exit.
- t_{detect}: Time taken for sensors to identify the bottle size.
- t_{fill}: Duration of the pump activation and nozzle movement.
- t_{cap}: Duration of the capping actuator descent and torque-twist.
- t_{index}: Time required for the star wheel to rotate 60°.

The term $\max(t_{fill}, t_{cap})$ signifies the simultaneous execution of both the filling and capping stations. The PLC program ensures that these processes are executed in parallel, thus making sure that the only limitation in the sequence is the time required by the longest of these processes.

Moreover, no downtime is needed for changing the sizes of bottles since the machine can automatically adjust to different bottles, compared to a conventional machine designed for single-size bottles, in which changing the bottle type may require several minutes of adjustments.

The machine's torque for capping was adequate for sealing bottles during testing. The gear motor used for capping was able to tighten caps at a uniform torque of 0.5 N.m for plastic caps used in the test runs, which was adequate for sealing the bottles since no leakage was experienced during testing. No caps came loose or got crossed during testing runs. The high torque of the 12 V DC gear motor was adequate for ensuring uniform torque for each type of cap used in the test runs, since no adjustments were needed for different cap sizes. In addition, the star-wheel mechanism was reliable for positioning each bottle since it was able to achieve less than 5 mm positional error for each bottle. The accumulated positioning error is avoided by the PLC logic, which makes use of the 'home' sensor reset at the end of each rotation to eliminate any slight step errors on the NEMA 17 motor. Additionally, the process uses parallel processing, where the capping of one bottle is done while the next bottle is being filled at the upstream station.

This ensures that the star-wheel indexing is in sync with the conveyor timing.

The HMI of the system was very helpful for monitoring and control. It was very easy to select the bottle size mode or to let the system work in fully automatic detection mode. The real-time information provided on the HMI regarding the sensors, such as "Bottle detected Size Large," and a countdown timer during the process of filling and capping were very helpful for supervising the process. In fact, once the parameters were set, the system could be said to be working autonomously, with the HMI requiring minimal intervention apart from start/stop commands. This shows how an operator with minimal training can be able to handle the system, thanks to the intuitive nature of the HMI and the elimination of the need to adjust between bottle sizes.

The prototype had an emergency stop button placed on the panel board. During the test, pressing the E-stop button resulted in an instant stop of all motions and pumps. This is as expected. Once reset, the PLC successfully went into normal operation without any issues. This is because there is a programmed routine for the PLC to re-home the actuators. There were no issues of spilling during the instant stops. This means that the interlock switches for closing the nozzle valve and the pumps were effective. The electrical protection against an overload (a 16-Amp circuit breaker on the mains power supply) was also effective since there were no issues during continuous running for several hours. The machine performed well during several test runs. This again highlights the success of the PLC in maintaining synchronization and the machine in dealing well with repetitive motion.

3.3 Performance Comparison

To highlight the gains achieved by the Size-Shift Fill-Cap system, we compare three key performance metrics, cycle time, filling accuracy, and changeover time against traditional manual filling/capping and a representative published PLC-based system, [1] (Table 2). The Size-Shift Fill-Cap reduces cycle time by roughly 33–50 % compared to the published design and by up to 65 % versus manual operation. Filling accuracy improves from ±10 % manually and ±5 % in the reference design to ±2 % with our system. Most notably, format changeovers typically requiring 5–10 minutes are eliminated, dropping to zero minutes and enabling truly on-the-fly multi-size operation.

The primary analytical advantage of the Size-Shift Fill-Cap system is the elimination of Changeover Time (T_{CO}), which represents the unproductive idle period required for manual mechanical adjustments in traditional systems. For a production run of N bottles requiring a format change, the total production time (T_{total}) can be modelled as given in Equation (6):

$$T_{total} = \left(N \cdot T_{system}\right) + T_{CO} \tag{6}$$

In the proposed system, $T_{CO} = 0$, whereas traditional manual or semi-automated systems require $T_{CO} \approx 5 - 10$ minutes. By reducing T_{CO} to zero, the system transforms a discrete-batch process into a continuous-flow operation, maximizing throughput efficiency and eliminating labor-intensive reconfiguration downtime.

Table 2. Performance comparison between manual, published PLC system [1], and Size-Shift Fill-Cap

Metric	Manual Filling/Capping	PLC System [1]	Size-Shift Fill-Cap
Cycle time (s / bottle)	20-30	12-15	8-10
Filling accuracy (%)	±10	±5	±2
Changeover time (min)	10	5	0

Source: Created by the Authors

3.4 Cost Analysis

The total hardware cost for our Size-Shift Fill-Cap prototype, including PLC, HMI, sensors, actuators, motors, relays and enclosure amounts to approximately USD 1430. To put this in perspective, Table 3 compares our system with a widely marketed monoblock water-bottling machine, capable of rinsing, filling and capping bottles from 200 mL up to 2000 mL on a single rotary platform, which retails at about USD 11000, [6].

Table 3. Cost comparison of water-bottle filling/capping systems

Column heading	Approximate Cost (USD)
Size-Shift Fill-Cap	1430
Monoblock 3-in-1 Rotary Rinse/Fill/Cap Machine, [6]	11000

Source: Created by the Authors

Although the 3-in-1 system provides high throughput and space savings through integration, it requires manual changeovers for multi-bottle formats and does not provide programmable

PLC/HMI calibration. In contrast, our Size-Shift Fill-Cap system provides real-time multi-size adaptability, programmable ladder logic, and a human-machine interface touchscreen for one-seventh the cost. We believe that this substantial cost advantage makes our system particularly well-suited for small and medium enterprises. Moreover, the low-cost control architecture can be expanded with remote monitoring and alert functions, using an IoT-based supervision approach for real-time monitoring, alert generation, and remote control, [7].

4 Conclusion

Automated filling and capping machines are now essential in production environments where demand is high for products such as food, beverages, cosmetics, and pharmaceuticals. These machines are effective in maintaining the quality and standards of the products, since filling is consistent and capping is secure. The development of the Size Shift Fill Cap machine is a contribution to the advancement of the field, since it is flexible enough to accommodate various sizes of bottles without having to make alterations in the machine. For example, the machine can be adjusted from filling small bottles to filling large bottles without having to replace machine parts, which is time-consuming. In our development, the flexibility of the machine is achieved without having to make many mechanical alterations, and this is a significant advantage since production can be optimized, for example, in filling small bottles for promotional purposes and then moving on to filling large bottles for families without compromising efficiency. As the saying “time is money” goes, the less idle time and human intervention, the more money saved. While the proposed system may not directly cut costs, it can certainly minimize changeover time, improve filling accuracy, and reduce the chances of human error, thus improving system throughput and output consistency. In fact, the prototype testing has already validated the filling accuracy of ±2% for all three bottle sizes and cycle times of only 8-10 seconds per bottle, effectively doubling the manual system’s throughput without any loss of changeover time. Furthermore, the total hardware cost of around USD 1430 provides a seven-fold savings over a commercial mono-block machine.

The success of the prototype in testing proves the concept of the idea because it can adjust according to different heights and volumes of the bottle on the go without the need for any hardware components. The simplicity of the human-machine interface allows for easy handling by anyone who needs it without the requirement for extensive training. This proof of concept can be built upon or expanded for use in an industrial setting. The modular nature of the design allows for it to be easily integrated into existing systems or expanded upon by the addition of other components, such as a labeller or sealer. In addition, the use of standard industrial components like the PLC, sensors, and stepper motors makes the system more robust and easier to maintain. Conclusion: The Size-Shift Fill-Cap system illustrates how flexible control strategies can be integrated into packaging machines to greatly enhance their versatility, productivity, and cost-effectiveness in response to the increasing demand for flexible manufacturing solutions.

Future work will focus on advancing the Size-Shift Fill-Cap system into a fully autonomous, ready solution. One immediate goal is to incorporate closed-loop metering, whether through flow or gravimetric sensors, to deliver real-time volumetric feedback and adapt pump timing automatically to variations in fluid properties, pushing error well below the current ±2 % range. We also plan to add OPC UA (OPC Unified Architecture) and MQTT (Message Queuing Telemetry Transport) connectivity for seamless integration with MES (Manufacturing Execution System) and ERP (Enterprise Resource Planning) systems, enabling remote monitoring, predictive maintenance and complete batch traceability, [8], [9]. To meet the hygiene requirements of pharmaceutical and high-purity food production, an automatic Clean-In-Place module and compliant sanitary design will be developed according to recognized hygienic design principles for food-processing equipment, [10]. Expanding the system’s adaptability by integrating a machine-vision measurement station would allow it to handle an even wider array of container shapes and sizes without hardware changeovers. Leveraging edge-computing and machine-learning techniques within the PLC or an attached industrial controller could yield self-optimizing fill and cap parameters, continuously reducing cycle times under changing upstream conditions. Finally, implementing an augmented-reality-assisted maintenance interface and remote calibration toolkit will shorten setup and servicing from hours to minutes, making the machine accessible to operations of any scale. These enhancements will transform the current prototype into a scalable, smart bottling platform that meets the most stringent demands of tomorrow’s production lines.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Elie Antoun, Georges Fares, and Moustapha EL Hassan conceptualized the research.
Elie Antoun, Georges Fares, and Moustapha EL Hassan developed the methodology.
Ali Chrakie, Elie Antoun, Georges Fares, and Moustapha EL Hassan formulated and analyzed all mathematical models.
Elie Antoun, and Georges Fares simulated the proposed algorithm.
Moustapha El Hassan carried out the validation.
Ali Chrakie, Elie Antoun, Georges Fares, and Moustapha EL Hassan conducted the formal analysis.
Ali Chrakie, and Moustapha El Hassan were responsible for the investigation.
Ali Chrakie, Elie Antoun, and Georges Fares, provided the necessary resources and managed data maintenance.
Ali Chrakie wrote the initial draft.
Moustapha El Hassan reviewed and edited the manuscript.
Ali Chrakie, Elie Antoun, and Georges Fares, prepared the visualizations.
Moustapha El Hassan was responsible for supervision.
Moustapha El Hassan managed the project.

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