

Design, Development, and Automation of an Automatic Bottle Filling System for Efficient and Precise Liquid Dispensing

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Abstract - The present work focuses on the design, development, and automation of a bottle filling system for accurate and continuous liquid dispensing. The proposed system integrates a conveyor mechanism, sensors, solenoid-operated filling valves, pneumatic bottle positioning, Programmable Logic Controller (PLC), and Human-Machine Interface (HMI). Bottle detection and indexing are performed using optical or infrared sensors, while the conveyor speed is controlled using a Variable Frequency Drive (VFD). To improve filling accuracy, a load-cell-based feedback system is incorporated into the PLC control loop. A dual-stage fast-fill and slow-fill strategy is used to reduce turbulence, foaming, splashing, and overfilling. The developed concept is suitable for food, beverage, pharmaceutical, and chemical applications where repeatability, hygiene, productivity, and precise liquid dosing are important. The system reported in the study targets filling errors within approximately $\pm 0.51\%$.

Key Words: Robotic Automation, Magnetic Gripper, Pick and Place, Pneumatic Actuation, Vision Inspection, Material Handling.,

1. INTRODUCTION

Bottle filling is an important operation in food, beverage, pharmaceutical, cosmetic, and chemical industries. Conventional manual and semi-automatic filling processes require considerable human involvement and may suffer from inconsistent filling volume, spillage, contamination, high labour requirements, and reduced production efficiency. Automated filling systems overcome these limitations by integrating conveyors, sensors, actuators, and industrial controllers into a coordinated production system. The proposed bottle filling system consists of a conveyor driven by a motor and VFD, bottle-detection sensors, pneumatic or mechanical bottle stoppers, filling nozzles, solenoid valves, and a PLC-based control system. The PLC receives signals from the sensors and controls conveyor movement and liquid dispensing according to the programmed sequence. An HMI can be used to configure filling parameters and monitor machine operation. A major limitation of conventional timer-based filling is that filling accuracy can change with liquid viscosity, temperature, pressure head, and flow conditions. The proposed system addresses this problem by using real-time mass feedback from a load cell and a closed-loop PLC control strategy. The fast-fill stage provides rapid liquid delivery, while the slow-fill stage provides controlled final dosing. This approach reduces turbulence, foaming, splashing, and liquid wastage while improving filling consistency.

2. WORKING PRINCIPLE OF BOTTLE FILLING PROCESS

The automated bottle filling process begins when empty bottles are placed on the conveyor. The conveyor transports the bottles toward the filling station. An optical or infrared sensor detects the approaching bottle and sends a signal to the PLC. The PLC then stops or indexes the conveyor so that the bottle is accurately positioned below the filling nozzle.



Fig -1: CAD Assembly bottle filling process



Fig -2: Automated bottle filling system with PLC-based control and HMI monitoring.



Fig -3: Calibration of dispensing and sensing units in automatic water filling.

After correct positioning, a stopper or pneumatic mechanism holds the bottle in place. The PLC activates the filling solenoid valve or pump, allowing liquid to enter the bottle.

3. BOTTLE FILLING TECHNOLOGY

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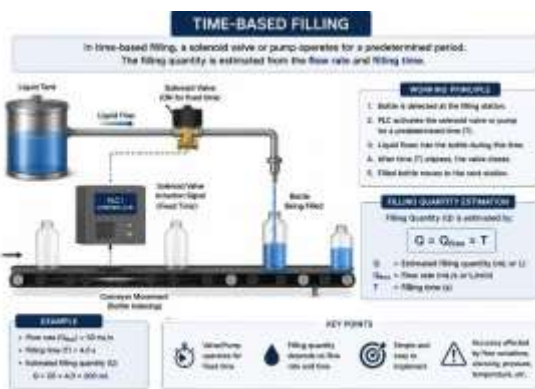


Fig -4: Working principle of time-based bottle filling.

Volumetric filling delivers a predetermined volume of liquid using mechanisms such as piston fillers or calibrated chambers.



Fig -5: Schematic representation of volumetric bottle filling technology.

Gravimetric filling determines the quantity of liquid from its measured mass. A load cell continuously measures the bottle weight and provides feedback to the controller.

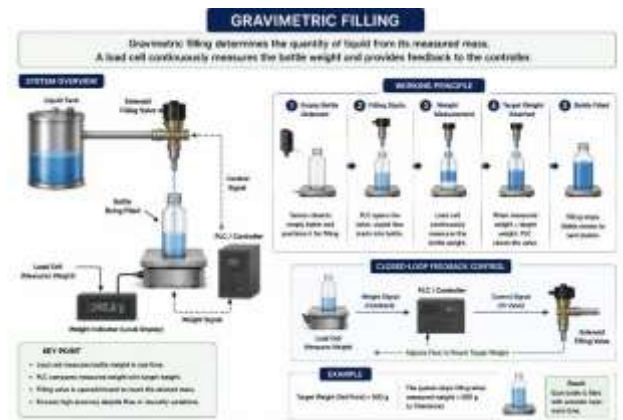


Fig -6: Working principle of gravimetric bottle filling using load-cell feedback.

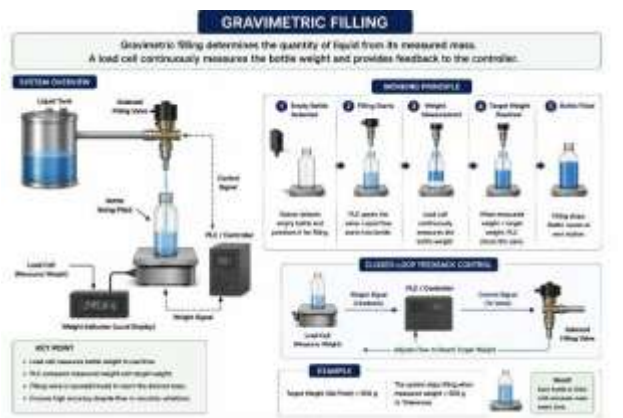


Fig -7: Working principle of level-based bottle filling using a level sensor and PLC-controlled filling valve for accurate and uniform liquid levels.

In level filling, the filling process is controlled according to the liquid level inside the container.



Fig -8: PLC-controlled bottle positioning and filling mechanism.

This method is useful where a visually uniform fill level is more important than exact volume.



Fig -9: Electrical integration and signal integrity in an automatic water filling system.

Flow meter-based systems are particularly useful for continuous industrial filling where high accuracy and production speed are required.

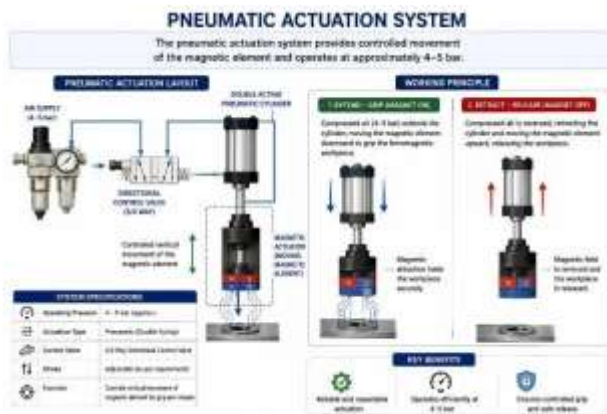


Fig -10: Robot- Pneumatic actuation system for controlled movement of the magnetic element at an operating pressure of approximately 4–5 bar.

4. CHALLENGES AND FUTURE RESEARCH

The development of an automated bottle filling system involves several technical challenges. The major challenge is maintaining filling accuracy when liquid viscosity, temperature, pressure, and flow characteristics change. Timer-based filling is particularly sensitive to these variations. The use of load-cell feedback can improve adaptability, but sensor calibration, response time, vibration, and mechanical stability must also be considered. Another challenge is controlling turbulence, foaming, splashing, and dripping during high-speed filling. The proposed fast-fill/slow-fill method reduces these effects, but further optimization of nozzle geometry, flow rate, valve response, and filling trajectory can improve performance. Recent research also shows that viscosity, nozzle size, pump speed, and surface tension can significantly influence filling accuracy. Future research should focus on intelligent adaptive filling in which PLC or industrial edge controllers automatically adjust flow rate according to liquid properties and real-time feedback. Machine-learning-based prediction could also be investigated for automatic compensation of viscosity and temperature variations.

5. CONCLUSIONS

The present study focused on the design, development, and automation of a bottle filling system for accurate and efficient liquid dispensing. The proposed system integrates a conveyor, bottle-detection sensors, pneumatic positioning, solenoid-operated filling valves, PLC-based control, HMI, VFD, and load-cell feedback to achieve automated bottle handling and filling. The use of closed-loop mass-based feedback improves filling accuracy by compensating for variations in liquid flow, temperature, pressure, and viscosity. The dual-stage fast-fill and slow-fill technique further reduces turbulence, foaming, splashing, and liquid wastage during dispensing. The system targets a filling error within approximately $\pm 0.51\%$, while automated bottle indexing improves production consistency and reduces manual intervention. Overall, the developed automation concept provides a reliable and flexible solution for industrial bottle filling applications. Future improvements can focus on adaptive filling control, automatic adjustment for different bottle sizes, flowmeter integration, intelligent fault detection, IoT-based monitoring, and improved hygienic design. These developments can further enhance filling accuracy, productivity, flexibility, and reliability in automated packaging industries.

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