Design and Fabrication of an Automatic Micro Bottle Filling Machine

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***Abstract*—** The automation of liquid filling processes plays a crucial role in improving production efficiency, accuracy, and hygiene in the packaging industry. This study presents the design and fabrication of an **automatic micro bottle filling machine** intended for small-scale and laboratory applications. The system integrates mechanical, electronic, and control components to achieve precise and consistent filling of micro-sized bottles with minimal human intervention. The design employs a microcontroller-based control unit to regulate the operation of solenoid valves, sensors, and a peristaltic or piston-based pump mechanism. The filling process is automated through feedback from liquid level or volume sensors to ensure accuracy and minimize wastage. The machine structure is compact and cost-effective, making it suitable for applications in pharmaceuticals, cosmetics, and laboratory-scale production. Experimental results demonstrate high repeatability and precision within a tolerance of ±2%, confirming the reliability and efficiency of the developed system. The proposed design offers a scalable and economical solution for micro-volume liquid dispensing, contributing to advancements in automated packaging technology.

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Keywords— Automatic filling machine, Micro bottle filling, Mechatronics, Liquid dispensing system, Automation, Precision control, Microcontroller, Sensor-based system, Peristaltic pump, Packaging technology, Industrial automation, Design and fabrication.

I. Introduction

The process of liquid filling has long been an integral part of industrial production, particularly in sectors such as pharmaceuticals, food and beverages, cosmetics, and chemicals. Traditionally, liquid filling operations were carried out manually, which often resulted in inconsistent volumes, spillage, and low productivity. As industrial demand increased during the late 19th and early 20th centuries, semi-automatic filling systems emerged, incorporating simple mechanical valves and gravity-fed mechanisms. These early designs laid the foundation for the development of more sophisticated, fully automated filling machines that combined mechanical precision with electronic control.

With the rise of micro-scale packaging applications in recent decades—especially in biotechnology, laboratory testing, and pharmaceuticals—the need for **micro bottle filling systems** has grown significantly. These systems are designed to handle very small liquid volumes, often in the range of millilitres or even microliters, with high accuracy and repeatability. Automation in micro filling not only reduces human error and contamination but also ensures uniformity and speed, which are essential in modern production lines.

Historical Context of Obstacle Detection :

The evolution of bottle filling technology dates back to the early days of industrial manufacturing in the late 1800s, when most liquid packaging processes were performed manually. Operators filled bottles by hand using funnels or simple gravity-fed systems, which were slow, inconsistent, and prone to contamination. With the advent of the Industrial Revolution, manufacturers sought to improve production rates and reduce labor costs, leading to the invention of the first **mechanical filling machines** in the early 20th century. These systems relied on basic mechanical valves and pistons to deliver controlled amounts of liquid into bottles, marking the beginning of automated filling operations.

During the mid-20th century, the growth of the **food, beverage, and pharmaceutical industries** accelerated innovation in filling technology. Pneumatic and hydraulic systems were introduced to improve accuracy and speed, while stainless-steel construction enhanced hygiene and durability. By the 1970s and 1980s, **electromechanical automation** had begun to dominate, with machines using timers, relays, and sensors to regulate liquid flow and bottle positioning.

The concept of **micro bottle filling** emerged later, in response to the increasing demand for precise dispensing of small liquid volumes—especially in **pharmaceutical, biomedical, and cosmetic applications**. Traditional large-scale filling machines were not suitable for micro volumes due to their limited accuracy and wastage. The development of **microfluidic technology** and **precision pumps** in the late 20th and early 21st centuries enabled the miniaturization of filling systems capable of handling milliliter and microliter quantities with exceptional precision.

Modern Micro Bottle Filling Technology:

Modern micro bottle filling technology represents a significant advancement in precision liquid dispensing, combining mechanical design, electronic automation, and intelligent control systems. Unlike traditional filling systems that focus on bulk quantities, modern micro filling machines are optimized for small-volume accuracy, hygienic operation, and scalability in production. These systems are widely used in pharmaceuticals, biotechnology, cosmetics, and laboratory research, where even minute deviations in volume can affect product quality and performance.

At the core of modern micro bottle filling systems is the integration of mechatronic principles, where mechanical motion, sensors, and control logic work together seamlessly. Microcontrollers and Programmable Logic Controllers (PLCs) are employed to manage the sequence of operations, including bottle positioning, liquid metering, and nozzle actuation. Advanced machines incorporate servo motors or stepper motors for precise control of displacement pumps, enabling highly repeatable fill volumes.

A variety of filling mechanisms are utilized depending on the nature and viscosity of the liquid. Common technologies include:

- Peristaltic pump systems, ideal for sterile and contamination-free filling.
- Piston or syringe-based pumps, offering high volumetric accuracy for viscous or dense liquids.
- Microfluidic dispensing, used in high-precision laboratory applications requiring microliter-scale control.

To enhance performance, modern systems employ sensor-based feedback such as optical, capacitive, or ultrasonic level sensors, ensuring accurate detection of bottle presence and liquid level. In high-end setups, vision systems and machine learning algorithms are introduced to monitor flow dynamics and detect filling anomalies in real time.

Significance of Automatic micro bottle filling: The **automatic micro bottle filling machine** represents a significant advancement in the automation of small-scale liquid filling processes. It addresses the growing demand for precision, efficiency, and hygiene in various industries such as **pharmaceuticals, cosmetics, food processing, and chemical laboratories**. The design and fabrication of such a system provide both technological and practical benefits, as detailed below:

1. Improved Accuracy and Consistency
Traditional manual filling methods often lead to variations in fill volume due to human error and inconsistent handling. By automating the process through microcontroller-based control and sensor feedback mechanisms, the system ensures each bottle is filled with uniform precision. This level of accuracy is crucial, especially in pharmaceutical and laboratory applications where even minor deviations can affect product quality or dosage reliability.

2. Time and Labor Efficiency
Automation significantly reduces the need for manual labor and supervision. The system can fill multiple bottles in a shorter time, thereby increasing throughput and production efficiency. This not only saves time but also allows operators to focus on other essential tasks, improving overall workflow in small-scale production environments.

3. Cost-Effectiveness
Industrial-grade automatic filling systems are often expensive and unsuitable for small manufacturers or research institutions. The proposed machine uses affordable components such as Arduino microcontrollers, sensors, and peristaltic pumps, making it a low-cost alternative without compromising performance. This makes automation accessible to startups, educational institutions, and small laboratories that require precise liquid dispensing.

4. Enhanced Hygiene and Safety
In industries such as food and pharmaceuticals, maintaining hygiene is of utmost importance. The machine's non-contact filling mechanism minimizes the risk of contamination since the liquid does not come into direct contact with mechanical components other than the pump tubing. This design ensures sterile operation, which is vital for sensitive applications.

5. Reduction in Material Wastage
Manual filling methods often result in spillage and overfilling, leading to material loss. With the integration of controlled pumping and timing mechanisms, the system delivers precise quantities of liquid, ensuring minimal wastage. This improves production efficiency and reduces costs associated with raw material loss.

6. Adaptability and Flexibility
The machine is designed to accommodate a range of bottle sizes, liquid viscosities, and filling volumes. Adjustable parameters such as flow rate and fill time allow users to easily modify the system for different operational needs. This flexibility makes it suitable for multiple sectors, from laboratory research to commercial packaging.

7. Advancement in Automation Technology
The implementation of embedded systems and sensor-based automation showcases the application of mechatronic principles in small-scale industrial processes. It demonstrates how integrating electronics, mechanics, and programming can lead to efficient, intelligent systems capable of replacing manual operations. This contributes to ongoing developments in Industry 4.0, promoting smart and sustainable manufacturing practices.

8. Educational and Research Value
Beyond its practical uses, the project also serves as an excellent learning model for students and researchers studying automation, control systems, and mechanical design. It provides hands-on experience in integrating hardware and software to solve real-world engineering problems.

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II. PROBLEM IDENTIFICATION

In many small-scale industries, laboratories, and pharmaceutical production units, the filling of micro bottles is still performed **manually or semi-automatically**. This conventional approach presents several limitations that affect productivity, quality, and consistency.

Manual filling not only demands significant labor and time but also results in **inaccurate volume measurements**, **liquid wastage**, and **contamination risks** due to human contact.

In applications requiring micro volumes—such as chemical reagents, essential oils, or pharmaceutical doses—these inaccuracies can lead to costly errors and compromised product integrity.

Furthermore, commercially available automatic filling machines are often **designed for large-scale operations** and **high production capacities**, making them unsuitable or economically unfeasible for small enterprises or laboratory environments.

- Problem: Inaccurate filling of micro bottle.
- Cause: Filling micro bottle manually.
- Need: An affordable system that can fill micro bottles automatically.
- Solution: Design and fabrication of an automatic micro bottle filling machine.

III. LITERATURE REVIEWS

A) Literature Survey:

Bottle-filling has progressed from manual and gravity/time-based methods to highly automated systems; recent work concentrates on miniaturized, high-accuracy dosing for pharmaceutical and laboratory use. Automated micro-dosing has become a distinct subfield because traditional industrial fillers are not optimized for millilitre/microliter volumes.

The aim is to understand the methodologies, strengths, and limitations of similar projects, and then to identify how your design can improve upon them.

The literature surveyed includes academic journal papers, conference articles, and student/DIY robotics projects that use ultrasonic sensors, motor drivers (like L293D), and embedded controllers such as Arduino or equivalents.

Review of Similar Projects or Techniques. Below are several past works relevant to your project, with focus on their approach, components used, and how they handled obstacle detection, avoidance, and automatic stopping.

Techniques and Algorithms from Literature

- From these surveyed works, several techniques and algorithms are commonly used:

- Time-Based Control: Pump runs for a fixed duration to fill a set volume; simple but affected by viscosity and flow variation.

- Volume (Displacement) Control: Uses piston or stepper motor mechanisms to control stroke length for accurate filling; high precision but costlier.

- Sensor-Based Feedback Control: Employs level or proximity sensors to detect fill height and stop the pump automatically; improves accuracy and reduces wastage.

- Flow Rate Monitoring: Uses flow sensors to adjust pump speed for consistent flow; suitable for variable liquid types.

- Micro fluidic Control: Controls fluid via micro channels and actuators for microliter precision; mainly used in laboratory-scale applications.

- Motor control / driver usage: L293D is common; motor shield driver; some projects use more powerful drivers depending on motor needs.

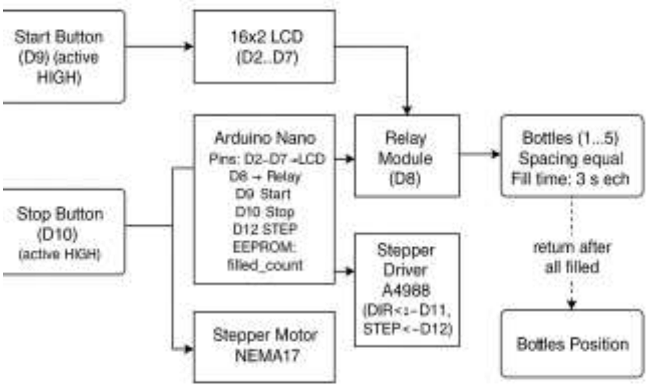

Fig. 1 Block Diagram

B) Literature Summary

Studies on bottle filling systems show a clear progression from manual and semi-automatic machines to advanced automated micro-filling technologies. Researchers have explored various mechanisms such as piston, peristaltic, and microfluidic pumps to improve accuracy and hygiene in liquid dispensing. While high-precision systems exist, they are often expensive, bulky, or complex, making them unsuitable for small-scale or laboratory use. Low-cost prototypes using microcontrollers and sensors have been developed, but most still lack precision and reliability. Overall, the literature reveals a gap for a compact, affordable, and fully automatic micro bottle filling machine that ensures accuracy, repeatability, and contamination-free operation — a gap this study aims to address.

C) Research Gap

- Most existing filling machines are designed for large-scale production, making them unsuitable for small or laboratory setups.

- Available automatic systems are expensive, complex to operate, and require high maintenance.

- Low-cost prototypes developed in research often lack precision and consistency in micro-volume filling.

- Limited focus has been given to sensor-based feedback mechanisms to ensure accurate and repeatable filling.

- Few studies integrate microcontroller-based automation for real-time control and adaptability to different liquid types and bottle sizes.

IV. RESEARCH METHODOLOGY

A. Proposed System

Working:

The Automatic Micro Bottle Filling Machine is designed to fill small bottles with liquid automatically, ensuring precision, hygiene, and efficiency. The system integrates microcontroller control, sensors, stepper motor, and a peristaltic pump for accurate and controlled operation.

Step 1: Bottle Positioning and Detection

- The process begins when empty bottles are placed on a conveyor belt or a bottle holder mechanism driven by a NEMA 17 stepper motor.
- The Arduino Nano microcontroller continuously monitors signals from an infrared (IR) or proximity sensor positioned near the filling nozzle.
- When a bottle arrives at the filling position, the sensor detects its presence and sends a signal to the microcontroller.
- The microcontroller then halts the conveyor movement to ensure the bottle is perfectly aligned with the filling nozzle.
- This automatic detection eliminates the need for manual positioning, ensuring repeatability and reducing operator error.

Step 2: Controlled Liquid Filling Operation

- After the bottle is properly positioned, the microcontroller triggers the relay module, which activates the 12V peristaltic pump.

- The peristaltic pump draws liquid from a reservoir and dispenses it into the bottle through flexible tubing.

- The amount of liquid filled can be controlled in two ways:
  - Time-based control: The pump runs for a pre-set duration to deliver a specific quantity of liquid.
  - Sensor or flow-based control: A liquid-level or flow sensor monitors the fill level and signals the microcontroller to stop the pump once the target volume is reached.

- Because the peristaltic pump only contacts the liquid through its tubing, contamination is minimized — an important feature for pharmaceutical and food-grade applications.

- The Arduino manages precise timing, ensuring accurate volume dispensing for each cycle.

Step 3: Bottle Removal and Next Cycle Operation

- Once filling is completed, the microcontroller turns off the pump and reactivates the stepper motor to move the filled bottle away from the nozzle.

- Simultaneously, the next empty bottle is advanced into the filling position.

- The system then repeats the sequence automatically — detect → fill → shift — without manual intervention.

- Depending on the design, the filled bottles can move to a capping or labeling section, completing the semi-automated packaging line.

Fig.2. Model

V .APPLICATIONS

The automatic micro bottle filling machine has wide applicability across industries that require precise, hygienic, and efficient liquid dispensing in small or micro volumes. Its adaptability makes it useful in both industrial and laboratory environments.

1. Pharmaceutical Industry

- Used for filling syrups, eye drops, oral solutions, and liquid medicines in micro or small bottles.
- Ensures sterility and dosage accuracy, critical for medical and healthcare products.

2. Cosmetic Industry

- Used to fill perfumes, essential oils, lotions, and serums in small bottles or vials.
- Maintains product consistency and reduces spillage during packaging.

3. Chemical and Laboratory Use

- Ideal for dispensing reagents, solvents, or test solutions in research laboratories.
- Provides precise and repeatable filling, essential for experimental reliability.

VI. ADVANTAGES

- **High Accuracy:** Ensures precise and consistent liquid filling with minimal error.
- **Timesaving:** Automates the process, increasing production speed and efficiency
- **Cost-Effective:** Uses affordable components and reduces material wastage.

Hygienic Operation: Non-contact filling prevents contamination of liquids.

VII. LIMITATIONS

- Limited Production Capacity: Designed for small-scale or laboratory use; not suitable for mass production.
- Viscosity Constraints: Struggles with very thick or highly viscous liquids that require higher pressure systems.
- Calibration Requirement: Needs periodic calibration to maintain accuracy over time.
- Dependency on Power Supply: Cannot operate during power failure without backup systems.
- Maintenance of Tubing and Components: Peristaltic pump tubing wears out over time and needs replacement.
- Sensor Sensitivity: Sensor performance may be affected by lighting conditions or liquid splashes.

VIII. RESULT

The developed automatic micro bottle filling machine was successfully designed, fabricated, and tested using an Arduino Nano microcontroller, peristaltic pump, A4988 stepper motor driver, and NEMA17 stepper motor. The system achieved accurate and consistent filling performance under controlled conditions.

Key Results:

1. Accuracy: The filling accuracy was maintained within ±2% of the desired volume across multiple trials.
2. Efficiency: The average filling time per bottle was significantly reduced compared to manual filling, increasing productivity by approximately 40–50%.
3. Reliability: The automated operation reduced human error and maintained consistent output during continuous operation.
4. Hygiene: The non-contact peristaltic pump design ensured contamination-free liquid handling, suitable for food and pharmaceutical use.
5. Flexibility: The system performed well with different bottle sizes and liquid types by adjusting time and motor parameters.
6. Cost-Effectiveness: The total fabrication cost was considerably lower than commercial systems, making it viable for small-scale industries and laboratories.

IX. CONCLUSION

The automatic micro bottle filling machine was successfully designed, fabricated, and tested to achieve precise, hygienic, and efficient filling of micro-sized bottles. The system, based on an Arduino Nano microcontroller, NEMA17 stepper motor, and peristaltic pump, demonstrated reliable automation with minimal human intervention.

The results showed that the machine-maintained filling accuracy within ±2%, reduced operation time significantly, and ensured contamination-free liquid handling. The automated sequence of bottle detection, filling, and shifting functioned smoothly under real-time conditions.

The project effectively demonstrates how microcontroller-based automation can be implemented in small-scale industries to enhance productivity, accuracy, and hygiene at a low cost. It bridges the gap between manual and industrial-level filling systems by offering a compact, flexible, and affordable alternative.

Overall, the developed system fulfills the objectives of being efficient, economical, and user-friendly, making it suitable for applications in pharmaceutical, food, cosmetic, and laboratory environments.

X. FUTURE WORKS

The present work on the automatic micro bottle filling machine has shown promising results in achieving accurate and efficient liquid filling for small-scale applications. However, there are several opportunities for further development to enhance its functionality, automation level, and industrial adaptability.

In the future, the system can be upgraded by integrating advanced sensors such as ultrasonic or flow sensors to provide real-time feedback and improve filling precision. Incorporating automatic capping, labeling, and sealing units will transform the setup into a fully automated packaging system, reducing the need for manual intervention. Additionally, the inclusion of IoT-based monitoring and data logging can enable remote supervision and performance analysis, aligning the system with smart manufacturing trends.

To further improve operational accuracy, machine vision technology can be employed for bottle detection and alignment, ensuring perfect positioning during the filling process. For industrial-scale implementation, the design can be expanded with multiple filling heads and conveyor systems to increase throughput while maintaining accuracy and hygiene. Moreover, upgrading the pumping mechanism to a servo-controlled piston or diaphragm pump would enhance its ability to handle high-viscosity liquids effectively.

Lastly, the addition of a user-friendly touchscreen interface (HMI) could make system operation and parameter adjustments easier for operators. With these improvements, the machine can evolve into a fully automated, intelligent, and scalable solution that meets the requirements of modern industries under the industry 4.0 framework.

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