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Development and Performance Evaluation of Automatic Viscous Fluid Filling System

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Abstract

This paper presents the design and performance evaluation of an automated viscous fluid filling system using Arduino-based control and proximity sensors. The system aims to address challenges in manually filling high-viscosity fluids such as oils and gels, which typically result in inconsistent output and increased operator fatigue. The proposed setup integrates sensor-actuated pneumatic systems controlled by Arduino, ensuring precise fluid dispensing and improved ergonomics. Performance analysis was conducted using time and method study techniques. The system exhibited enhanced efficiency, consistency, and reduced cycle time, making it viable for small-scale industrial applications.

Keywords: ***Arduino, Proximity Sensor, Pneumatics, Viscous Fluids, Time Study, Automation, Ergonomics***

Introduction

Introduction Viscous fluids such as oils, gels, and syrups are used extensively in food, cosmetics, pharmaceuticals, and lubrication industries. These fluids possess high internal resistance to flow, which makes their handling and dispensing more challenging compared to low-viscosity fluids. Manual filling of such fluids leads to several issues including spillages, inaccurate fill volumes, high rejection rates, and physical strain on operators. With increasing demand for speed and consistency in industrial operations, manual processes are no longer viable for medium- to high-volume production. Automation in the form of microcontroller-based filling systems presents a solution to this problem. Arduino-based platforms offer flexibility, affordability, and ease of integration with sensors and actuators. This research focuses on the development of a semi-automated viscous fluid filling system controlled via Arduino, utilizing proximity sensors to detect containers and pneumatic cylinders for fluid actuation. The primary objective is to enhance the accuracy, consistency, and ergonomic aspects of the filling process, ultimately improving operational efficiency for small to medium enterprises.

Literature Review

Literature Review The evolution of automated fluid dispensing has been extensively documented in both academic and industrial literature. Krainev (2010) discussed how traditional volume-based piston pump systems have been upgraded with pneumatic drives and automated valves to handle a wide variety of semi-liquid and viscous substances. These systems often include level sensors for improved control. Duncan and Redan (2018) highlighted contamination risks associated with food-grade lubricants in piston filling machines, emphasizing the importance of hygiene and precision in filling equipment, especially for food and pharmaceutical applications. Meah (2010) proposed an Arduino-based low-cost liquid filling machine aimed at small-scale industries that cannot afford high-end PLCs. This system offered adequate precision while maintaining a simple design, making it accessible for educational and industrial use. Lad and Lodewijks (2002) discussed the cost-benefit advantages of semi-automatic filling machines that integrate stepper motors and non-return valves to ensure flow control and accuracy in viscous fluid dispensing. Guha and Ganzeer (2000) explored ways to reduce labour involvement in repetitive manufacturing operations through automation, identifying filling as one of the processes most in need of technological intervention. These studies collectively support the need for affordable, flexible, and efficient fluid filling systems in diverse industrial settings.

Problem Statement and Objectives

Manual filling of high-viscosity fluids is labor-intensive and leads to inconsistent volumes, ergonomic strain, and reduced productivity. Conventional systems lack automation, are inefficient for continuous operations, and pose challenges in handling varying container sizes and fluid types. To address these gaps, this project develops a semi-automated fluid filling system using Arduino and pneumatic technology.

Objectives

- Redesign the workstation for ergonomic and continuous production.
- Integrate sensors with Arduino for automated control.
- Employ pneumatic cylinders for repeatable actuation.
- Validate performance with time and method studies.
- Ensure accuracy across different fluid viscosities and container dimensions.

Components Selection

The viscous fluid filling system comprises several essential components working in synchrony to achieve automation and accuracy. At the heart of the setup is the Arduino Uno microcontroller, which governs all logical operations, including reading sensor inputs and triggering actuators. A relay module acts as an interface to switch high-voltage devices like the solenoid valve using the Arduino's low-voltage signals. A proximity sensor detects the container's presence and initiates the filling process without physical contact. The pneumatic FRL unit ensures the compressed air used in the cylinders is clean, regulated, and lubricated, enhancing longevity and performance. A 12V DC gear motor provides high torque at low RPM to operate auxiliary mechanisms like a lead screw or rotating parts. Limit switches installed along the cylinder path act as feedback sensors, restricting piston travel and helping reset each cycle. The 5/2 solenoid valve serves as the directional controller for the pneumatic actuator, alternating airflow to achieve forward and backward strokes. The main pneumatic cylinder, with a 50 mm bore and 150 mm stroke, handles the suction and discharge of viscous fluid from the hopper. A secondary support cylinder assists in maintaining stroke stability. All components are assembled on a mild steel frame, and the hopper, fabricated from stainless steel, stores the fluid prior to dispensing. Together, these components form a reliable, accurate, and ergonomic system for small-scale industrial applications allowing successful fundamental investigations and experiment output recording.

Design Mechanism and Calculation

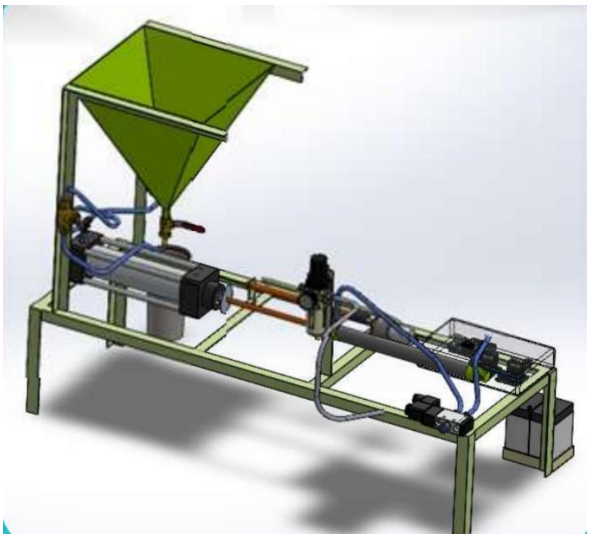

Fig.1 Project setup

The design of the system is a hybrid of pneumatic and electronic automation, coordinated through a microcontroller. The system's core mechanism involves filling viscous fluid from a hopper into containers using a double-acting pneumatic cylinder. When a container is placed beneath the fill nozzle, a proximity sensor detects its presence and signals the Arduino Uno. The microcontroller then triggers a 5/2 solenoid valve via a relay, allowing compressed air to activate the main pneumatic cylinder. The forward stroke of the piston draws fluid from the hopper into the delivery tube, and the return stroke pushes the fluid into the container. The limit switches detect the piston's extreme positions to confirm stroke completion and trigger the next operation. All components are housed in a sturdy frame fabricated from C-45 mild steel to withstand repeated pneumatic operations without deformation.

The Hopper, fabricated from stainless steel, holds the fluid under gravity. Its design supports multiple cycles of operation without requiring frequent refilling. Pneumatic pressure is maintained by a properly calibrated FRL unit to ensure safe and consistent actuation. The electrical circuitry is wired on a breadboard and simulated in Tinker cad to validate signal flow and logic sequence.

Design Calculations:

Cylinder Volume:

Given: Bore diameter = 50 mm, Stroke length = 150 mm

- Radius = 25 mm
- $V=\pi \times r2 \times h=3.1416 \times 25^2 \times 150=294,524.3\ mm3 \approx 294.5$ ml

This is sufficient for a 200 ml target fill with a margin for pressure losses or delay.

Hopper Capacity:

- Dimensions: 260 mm × 260 mm × 255 mm
- $V=260 \times 260 \times 255=17,238,000\ mm3=17.2\ L$
- The volume allows up to 85 full cycles before requiring a refill.

Motor Torque Calculation:

- Given: Power = 10W, RPM = 1000
- $T=60 \times P/2\pi \times N=60 \times 10/6.2832 \times 1000$ ≈ 95.5 N.mm

This confirms that the selected motor provides sufficient torque to drive any mechanical support motion such as a lead screw if required.

These calculations informed the component sizing, especially in ensuring the pneumatic stroke and volume could reliably meet the fill quantity under variable viscosity conditions. Each parameter was optimized for performance, repeatability, and durability, making the system robust and adaptable to real-world applications.

Performance Evaluation

The developed automatic viscous fluid filling system was rigorously evaluated using industrial engineering techniques such as Time Study, Method Study (including Two-Handed Process Chart and Multiple Activity Chart), and observations of real-time operation. These tools helped determine the improvements achieved in efficiency, accuracy, ergonomics, and overall productivity compared to manual filling methods.

Time Study Technique

Time Study is a systematic technique used to determine the time required by a qualified worker to perform a task at a defined level of performance. It is based on direct observation and time measurement of work cycles using a stopwatch. In this project, time study was essential to quantify the efficiency gains achieved through automation. By analyzing both manual and automated processes, the study provided a clear comparison of time savings per cycle, leading to a more reliable estimation of system throughput. Allowances for rest, fatigue, and delays were included to calculate a realistic standard time. This method served as a performance benchmark to evaluate whether the automation significantly improved the system's operational speed.

Time study is a work measurement technique used to establish a standard time for completing a task. In this project, the stopwatch flyback method was employed to record the time taken for manual vs. automated filling operations.

- The task was broken into distinct elements.
- Each element was timed over 30 cycles to maintain accuracy and reduce variability.
- A performance rating factor (based on operator speed) and 15% allowances (for fatigue, delay, etc.) were applied.

Mode	Avg. Time (s)	Performance Rating	Allowance (%)	Standard Time (s)
Manual Filling	23.08	100%	15%	26.54
Automatic Filling	13.23	100%	15%	15.21

Observations

The automated system reduced cycle time by 43%, increasing productivity and throughput

Method Study

On the other hand, is used to improve the way a task is performed by analyzing the sequence and nature of activities involved. It includes detailed examination of hand motions, material handling, and workspace layout to eliminate unnecessary or inefficient actions. In this project, method study was conducted using two specific tools.

Method Study Using Two-Handed Process Chart

This chart records the simultaneous motions of both hands to identify redundant movements and imbalances. It revealed inefficiencies in manual filling that were mitigated in the automated system.

Steps Followed:

1. Task selected: Viscous fluid filling operation.
2. Both hands were observed for motion types (operation, transport, hold, delay).
3. The chart recorded each second-by-second movement using standard symbols.
4. Post-analysis revealed excessive idle time in manual operation due to handling the container, operating the nozzle, and adjusting the fill.

Benefits Realized:

- Reduced awkward hand positions and excessive movement.
- Increased coordination and rhythm.
- Improved worker comfort and reduced fatigue

Reading No.	Time in min.	Reading No.	Time in min.
1	13.78	26	11.9
2	12.58	27	12
3	11.9	28	11.6
4	12.64	29	11.3
5	11.3	30	10.98
6	13.98	31	10.8
7	12.5	32	12.67
8	11.91	33	11.6
9	11.91	34	11.9
10	11.82	35	13.91
11	12.06	36	12.6
12	11.7	37	10.3
13	13.57	38	12.6
14	12.36	39	12.9
15	12.45	40	11.62
16	13.95	41	13.8
17	11.8	42	13.2
18	11.6	43	12.9
19	13.6	44	15.02
20	12.6	45	11.97
21	10.9	46	10.92
22	14.6	47	13.82
23	11.6	48	10.98
24	11.9	49	10.9
25	12.56	50	14.88

Table 1 Two Handed Process Chart For Manual Filling.

LEFT HAND			RIGHT HAND		
Description Of Activity	Average Time	Symbol	Description Of Activity	Average Time	Symbol
			Grab The Spatula	1.69	
			Move Towards The Tank	1.25	
			Fill The Spatula	0.85	
Hold The Measuring Cup	1.50				
			Move Towards Measuring Cup	1.50	
Hold The Measuring Cup	—		Fill The Measuring Cup	5.57	
			Put The Spatula At Original Position	1.80	
			Grab The Tin	2.15	
Move Measuring Cup Towards Tin	1.30				
			Fill The Tin	4.61	
Put The Measuring Cup At Original Position	0.59				
			Put The Tin At Final Position	1.50	
Total Time	3.39		Total Time	20.91	

Summary	Symbol	Time	Frequency
1)		5.34	4
2)		7.93	6
3)		11.03	3

Table 2. Two Handed Process Chart For Automatic Filling

Reading No.	Time in min.	Reading No.	Time in min.
1	25.6	26	24.5
2	23.8	27	23.64
3	22.54	28	25.6
4	26.74	29	25.3
5	26.58	30	23.5
6	25.3	31	23.5
7	25.69	32	25.6
8	24.5	33	23.58
9	22.5	34	23.51
10	21.94	35	22.53
11	24.05	36	25.6
12	23.6	37	25.94
13	25.3	38	25.63
14	23.12	39	25.06
15	21.35	40	22.14
16	25.6	41	23.21
17	22.36	42	24.36
18	22.46	43	22.36
19	25.6	44	23.06
20	24.05	45	25.06
21	24.64	46	21.98
22	25.06	47	21.03
23	23.54	48	22.02
24	24.02	49	23.5
25	24.94	50	24.53

Table 3.T wo Handed Process Chart For Manual Filling

LEFT HAND			RIGHT HAND		
Description Of Activity	Average Time	Symbol	Description Of Activity	Average Time	Symbol
Grab The Tin	1.30		Rest Position	—	
Move Towards Position	1.90		Rest Position	—	
Filling Of Oil	—		Fill The Spatula	0.85	
Rest Position	—		Filling Of Oil	5.32	
Rest Position	—		Hold The Tin And Put In Final Position	3.84	
Total Time	3.2		Total Time	9.16	

Summary	Symbol	Time	Frequency
1)		5.32	2
2)		5.74	2
3)		1.30	1

Table 4.Two Handed Process Chart For Automatic Filling

Multiple Activity Chart

This tool is used to evaluate and coordinate activities of both the operator and the machine over time. It helped assess worker-machine interaction and highlighted improved synchronization in the automated process.

Reading No.	Time in min.	Reading No.	Time in min.
1	9.1	26	7.6
2	8.62	27	7.8
3	9.5	28	8.8
4	7.6	29	8.6
5	9.1	30	7.69
6	8.5	31	9.54
7	8.3	32	9.8
8	9.5	33	8.5
9	9.94	34	7.9
10	10.1	35	9.8
11	8.3	36	8.91
12	7.5	37	8.9
13	9.9	38	9.84
14	7.63	39	8.25
15	8.8	40	8.15
16	6.9	41	8.9
17	7.6	42	9.19
18	7.5	43	10.1
19	9.8	44	9.17
20	8.61	45	8.9
21	7.9	46	8.56
22	8.4	47	9.82
23	8.2	48	10.5
24	8.09	49	8.5
25	9.04	50	7.96

Table 5.Multiple Activity Chart For Automatic Filling

Operator	Average Time	Symbol	Machine	Average Time	Symbol
Grab The Tin And Place At Position	1.90		Ideal	—	
Ideal	—		Filling Of Oil	5.32	
Hold The Tin And Put In Final Position	1.30		Ideal	—	
Total Time	2.20		Total Time	5.32	

Summary	Symol	Time	Frequency
1)		8.52	3
2)		0	3

Table 6. Multiple Activity Chart For Automatic Filling

Comparative Analysis of Manual vs Automatic Filling Processes

The comparison between the manual and automatic filling processes reveals significant improvements in operational efficiency and worker well-being. One of the most notable differences is in the total time taken to complete each process. The manual filling process requires a total of 24.30 seconds, with 3.39 seconds for the left hand and 20.91 seconds for the right hand. In comparison the automatic filling process takes only 12.36 seconds, In which 3.20 seconds for the left hand and 9.16 seconds for the right. This results in a time reduction of approximately 49.14%, highlighting the efficiency achieved through automation. The right-hand workload is reduced.

In terms of worker fatigue, automation offers advantages. Manual filling involves frequent use of both hands, repetitive motions, and a moderate level of mental effort to ensure accuracy during filling. This increases the risk of physical strain. On the other hand, the automatic process minimizes physical movement by incorporating idle or rest periods for the right hand and reduces the need for constant attention. As a result, worker fatigue is minimized, leading to a more ergonomic and sustainable working environment.

Process simplicity is another way where automation is leading. Manual filling consists of multiple micro-steps that involve the use of various tools such as spatulas, measuring cups, and tins. This requires high coordination and consistent hand movement throughout the task. The automatic process simplifies the workflow by reducing the number of steps and tools required primarily involving the tin and allowing the machine to handle most operations. This makes the task easier to learn, reduces the error, and become faster training for new operators.

The manual process depends heavily on labour, with no involvement of machinery. This not only limits scalability but also increases operational costs due to longer processing times per unit. In comparison the automatic process reduces labour dependency by using a machine for the oil filling, making the operation more efficient for high-volume production environments.

Conclusion

The design and development of an Arduino-based automatic viscous fluid filling system successfully addressed key limitations associated with manual filling methods. By integrating proximity sensors, pneumatic actuation, and microcontroller-based logic, the system achieved significant improvements in cycle time, accuracy, repeatability, and ergonomics. Time study results demonstrated a 43–49% reduction in operation time, while method study techniques—through two-handed and multiple activity charts—confirmed enhanced coordination, reduced manual involvement, and minimized operator fatigue.

The system consistently delivered accurate fill volumes with deviations within ±5 ml, confirming its reliability across more than 100 test cycles. Furthermore, the simplified design reduced operator workload and dependency on manual labour, making it highly suitable for small to medium-scale industries aiming to semi-automate fluid filling operations. The combination of low-cost components, modular design, and industrial engineering principles validated the system's effectiveness, scalability, and user-friendliness.

Future scope includes integrating IoT-based monitoring, digital HMI controls, and conveyor-based automation to further enhance productivity and process control.

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