

Design and Evaluation of an Additively Manufactured Smart Infusion Pump with Embedded Control and Pressure-based Safety Monitoring

Murugan A.¹, Sheela M.², Tarunika B.³, Vinothini K.⁴

¹Department of Electronics and Communication Engineering, ^{2,3,4}Department of Biomedical Engineering, Paavai College of Engineering, Anna University, Namakkal, India.

E-mail: ¹rasimurugan2k2@gmail.com, ²sheelamurali42@gmail.com, ³tarunikababu2323@gmail.com,

⁴vinovino6017@gmail.com

Abstract

This research introduces the design and laboratory testing of a smart infusion pump prototype using the principles of additive manufacturing, embedded controller, sensor-based safety monitoring, and wireless communication. Mechanical design utilizes a syringe-based actuator driven by a stepper motor that was fabricated via the process of additive manufacturing to ensure a precise displacement of the plunger, whereas ESP8266-based controller ensures control over actuator actuation, user interface, pressure monitoring, and fault handling. Prototype testing was performed in a laboratory environment using water at present flow rates of 5, 10, 20, 30, and 40 mL/h. Observed delivery rates were 5.1, 9.8, 19.6, 29.4, and 39.2 mL/h, respectively, implying that maximum error was $\pm 2\%$. Repeated-cycles operation proved mechanical integrity of the prototype without any signs of deformations or misalignments. The developed integrated safety response system Occlusion detection based on pressure measurement, end-of-travel detection, motor stoppage, and alarm triggering.

Keywords: Additive-Manufactured Infusion Pump, Stepper-Motor Plunger Actuation, ESP8266 Embedded Control, Pressure-based Occlusion Detection, End-of-Travel Protection, Flow-Rate Calibration, Wireless Infusion Monitoring.

1. Introduction

Infusion pump requires an accurate control of the flow rate in order to achieve the desired rate of fluid flow. Traditional infusion pump designs often include costly mechanical mechanisms, lack design flexibility, and require a high level of human intervention. This issue is especially relevant to the portable and economical infusion devices.

Recent advancements have included use of microcontrollers, stepper motor drive, flow detection, wireless communication, and safety control techniques [1]. The use of digital flow measurement has resulted in an effective estimation of delivery rates and occlusion detection [2]. Inexpensive and IoT based systems have proved the effectiveness of remote infusion monitoring [4]. There have been advancements in control techniques that include proper functioning of motors and flow rate control [5].

Despite these advancements, the combination of additive manufactured mechanical parts with integrated motion control, fault detection, and wireless monitoring is one of the major challenges in designing. The process of additive manufacturing enables quick manufacturing and customized geometry of syringe holder, plunger holder, motor coupling, and housing.

Accordingly, this research proposes the design of a smart infusion pump using additive manufacturing technology with the implementation of a microcontroller-driven stepper motor mechanism, pressure sensors, position sensors, alarm systems, and wireless monitoring capabilities. This model is experimentally analyzed through flow rate tests

2. Literature Review

2. Literature Review The most recent advancements in this field have been towards achieving precision, automation, safety, and cost-effectiveness in infusion pumps. Automation and less manual interference have been achieved by utilizing microcontrollers for multiple-syringe pumps [1]. Accuracy in flow measurements and occlusion detection has been achieved using digital flow imaging technology [2]. Remote monitoring plays a major role in smart infusion systems, making the process of administering fluids via intravenous infusion safer [3]. Researchers have also developed affordable infusion pumps [4].

The control-based investigations have focused on considering precise control and response characteristics for individual-based drug delivery [5]. The personalized algorithms have also been explored for developing intensive care-based infusion applications [6]. The IoT-enabled infusion system has facilitated wireless sensing and remote monitoring [7]. The safety sensor-based infusion system has additionally helped in the automatic detection of abnormal operating conditions [8]. The occlusion model has played a role in flow obstruction analysis and pump safety [9].

Stepper motor control has been researched to enhance flow stability and minimize pulsation [10]. Multifunctional pump systems have solved the problems of portability and built-in therapeutic function [11]. Infusion monitoring from afar has shown how connected sensing systems can reduce human supervision [12]. Security research has pointed out vulnerabilities related to manipulation of the infusion pump control process [13]. Security-driven design has stressed the importance of designing security mechanisms into medical syringe pumps [14].

However, limited research integrates all aspects of additive manufacturing, embedded control system, safety monitoring using sensors, and wireless communication for such an inexpensive and configurable infusion pump. In this regard, the current research addresses the integrated additively manufactured infusion pump and investigates its accuracy in flow rate, mechanical reliability, safety, and wireless monitoring.

3. Proposed Methodology

The proposed methodology integrates the 3D-printed infusion mechanism, control unit based on ESP8266 microcontroller, stepper motor driving, sensors, safety module, user interface, and wireless communication into an integral infusion system. From Figure 1, the ESP8266 microcontroller controls the pump via acquisition of pressure, position, and occlusion signals from sensors, and stepper motor driving to operate syringe plunger. The user interface allows infusion settings to be configured locally, while the safety module detects anomalies during the process of infusion and triggers an alarm response. Wireless communication module sends the operating data to the remote monitoring device. This method involves the following stages: requirements, mechanical design and 3D printing, embedded control, monitoring, safety, wireless communication, and experiment.

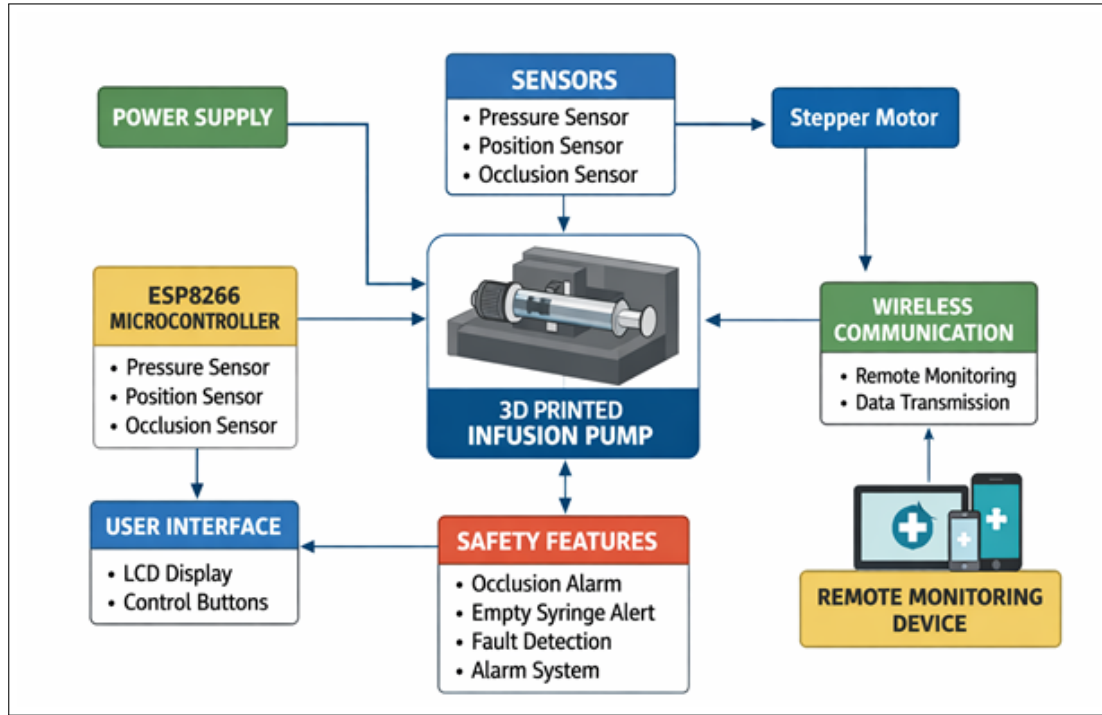


Figure 1. Proposed smart infusion pump architecture using additive manufacturing

3.1 System Requirement Analysis

The prescribed fluid volume and time of infusion are employed in setting up the reference flow rate that will be used as the reference value by the control system. This makes sure that the motor actuation that follows comes from a known delivery requirement and not a motor speed. The reference flow rate is determined as

$$Q = \frac{V}{t} \quad (1)$$

where Q is the required flow rate (mL/h), V is the prescribed fluid volume (mL), and t is the infusion duration (h).

The calculated Q is then translated into the required syringe-plunger movement. As the volume of fluid dispensed from the syringe is dependent on the barrel surface area and movement of the plunger, the necessary volume dispensed is determined by

$$V = A\Delta x \quad (2)$$

where A is the internal cross-sectional area of the syringe barrel mm^2 , and Δx is the plunger displacement (mm). This correlation connects the amount of fluid needed to the mechanical motion that should be produced by the pump mechanism.

The plunger displacement is then correlated to the stepper motor movement via the lead screw system:

$$\Delta x = \frac{NP}{N_s} \quad (3)$$

where N_p is the number of motor steps, p is the lead-screw pitch (mm rev), and N_s is the number of motor steps per revolution. Thus, the requirement analysis establishes a direct volume to plunger displacement to motor-step relationship, which is used in the subsequent mechanical design and embedded control stages. where D is the digital sensor reading, V_s is the sensor output voltage, V_{ref} is the reference voltage, and n is the ADC resolution. The selected flow range, syringe dimensions, and safety requirements are therefore used as the design constraints for the remaining system components.

3.2 Additive Mechanical Design and Fabrication

The mechanical system is responsible for the conversion of the displacement calculated by the algorithm into a motion of the syringe. The syringe holder, plunger guide, motor coupling, and case are designed with the aid of CAD software depending on the dimensions of the chosen syringe and the needed plunger displacement. The syringe holder fixes the syringe at its place, whereas the plunger guide ensures that the plunger moves in one direction without any lateral displacement.

These components are manufactured through 3D printing technology, which enables adjustment of the mechanical system dimensions according to the syringe design. The rapid manufacturing of the additively manufactured component ensures iterative changes in the pump geometry. Following the manufacturing process, the components are mounted in combination with the stepper-motor system, and proper alignment of the motor shaft, lead screw, plunger holder, and syringe is performed. Alignment is crucial since dimensional errors and surface friction in the 3D-printed component affect plunger motion and hence flow rate delivery.

3.3 Embedded Control System Design

Embedded control unit synchronizes stepper motor control, user-inputted infusion parameters, and sensor information. Inputted value for flow rate in ESP8266 module gets converted into a reference signal that translates into motor operation. Motor operation causes displacement of the plunger and maintains the desired flow rate of the substance. The frequency of the motor steps is calculated based on the desired flow rate and the displacement properties of the syringe system. In operation, the control unit calculates the control error by comparing the desired and actual flow rates:

$$et = Q_{\text{set}} - Q_{\text{measured}} \quad (4)$$

where Q_{set} is the programmed flow rate and Q_{measured} is the measured flow rate. This error forms the starting point of the correction process for the actuation of the motor by the firmware embedded in the system. The process of control creates the connection between the user infusion setting, motor actuation, and fluid delivery process. The controller also works in coordination with the sensors and safety functions.

3.4 Sensor Integration and Real-Time Safety Monitoring

This subsystem provides feedback on the operational status of the pump physically. Pressure and plunger-position sensors have been incorporated with the ESP8266 to constantly sense the delivery system. The sensor readings are captured by the controller using the analog or digital input port and compared against the normal operational state to find any deviation. The digital sensor readings can be represented as

$$D = \frac{V_s}{V_{\text{ref}}} (2^n - 1) \quad (5)$$

where D is the digital sensor reading, V_s is the sensor output voltage, V_{ref} is the reference voltage, and n is the ADC resolution.

The collected pressure information is evaluated against a predefined safety threshold.

$$P_{\text{sensed}} > P_{\text{limit}} \quad (6)$$

When the controller interprets the condition as an abnormal pressure or potential occlusion condition. It then interrupts stepper-motor actuation and activates the corresponding audible and visual alarm. Plunger-position feedback and end-of-travel protection additionally prevent excessive mechanical movement. This sensor-driven mechanism provides real-time fault detection for conditions such as flow obstruction, excessive pressure, and syringe completion, linking physical operating conditions directly to the pump's safety response.

3.5 Wireless Communication and Remote Monitoring

The wireless communication subsystem that expands the functionality of the local pump controller through wireless transmission of the infusion status information to the remote monitoring device. The ESP8266 module serves as the communication module and receives operating information from the embedded control process, then transmits the pump status information using wireless communication.

Performance of the communication process is determined by the efficient data transmission rate:

$$R = \frac{B}{T} \quad (7)$$

where R is the transmission rate (bps), B is the number of transmitted bits, and T is the transmission time. Responsiveness of remote monitoring is also reflected in the total communication delay:

$$T_{\text{total}} = T_p + T_t + T_r \quad (9)$$

where T_p is the processing delay, T_t is the transmission delay, and T_r is the reception delay. The information thus conveyed enables the remote-control unit to monitor the operational status of the pump and helps in observing any anomalies sensed by the local detection and safety subsystems.

3.6 Integrated System Operation and Experimental Validation

After integration of the mechanical, control, sensor, and communication subsystems, the whole prototype is run as an integrated infusion system. First, the flow rate that has been programmed is fed into the controller, and it calculates the number of stepper motor operations and moves the syringe plunger using the mechanism developed. While the whole process is going on, pressure and position sensors send feedback signals to the controller, while the safety subsystem looks out for abnormal situations. In the case of occlusion, high pressure, and completion of infusion, motor operation stops and the corresponding alarm sound generated.

The integration prototype is then tested experimentally through controlled laboratory settings using water as the testing medium. Flow rate performance is analyzed at flow rates of 5, 10, 20, 30, and 40 mL/h, after which mechanical repeatability and safety response tests are conducted. This produces data from which flow rate error, mechanical repeatability, safety response, and wireless monitoring efficiency are measured.

3.7 Performance Evaluation Criteria

The experimental performance of the integrated infusion pump is conducted based on four main factors: flow rate accuracy, mechanical stability, safety performance, and wireless performance. Flow rate accuracy is tested by comparing the programmed flow rate and the measured flow rate, and then finding the percentage error between the two values. Mechanical stability is checked through multiple operational cycles to detect displacement errors or alignment errors in the 3D printed part. Safety performance is conducted by testing abnormal situations like blockage and checking whether the pressure sensor system is able to detect any abnormalities and shuts down the motor with audible and visual alerts.

4. Results and Discussion

The experimental evaluation of the developed infusion pump took place in a controlled environment within the laboratory with water serving as the medium. The evaluation was carried out in terms of the physical design of the additive-manufactured device, programming-to-measured flow rate relation, mechanical reliability through repetitive functioning, and the reaction to unusual operation.

4.1 Simulated Prototype and System Integration

The simulated prototype of the proposed smart infusion pump design is shown in Figure 2 by showing different views in order to show how the system is integrated both mechanically and electronically. This prototype has several components which include a 3D printed syringe actuator mechanism, geared motor mechanism, syringe and plunger mechanism, LCD interface, motor driver circuits and control circuits. The mechanical system holds the syringe and plunger in place while the geared motor system is used to provide the necessary displacement. The different electronic components of the system are connected to the actuation system in order to give motor control and operation locally.

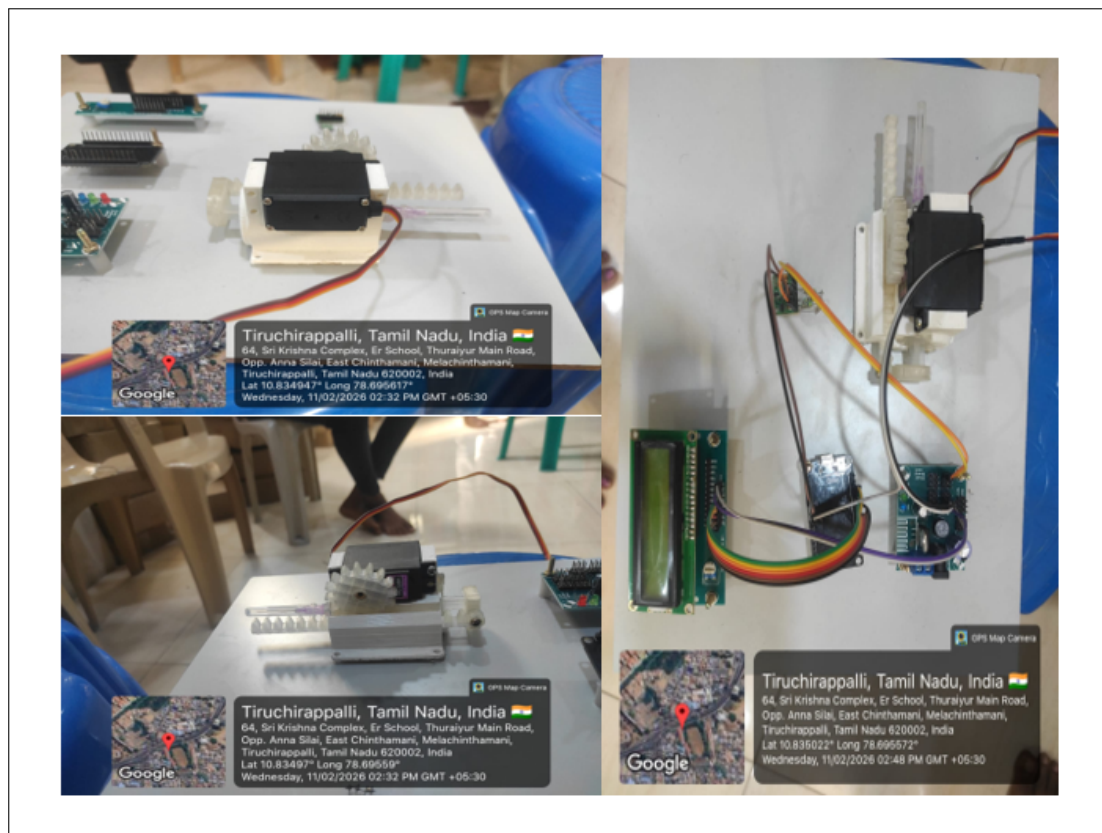


Figure 2. Simulated prototype of the proposed smart infusion pump

4.2 Flow-Rate Accuracy Evaluation

The accuracy of the delivery was assessed at five flow rate levels pre-set between 5 mL/h and 40 mL/h. According to Table 1, the measured values were 5.1, 9.8, 19.6, 29.4, and 39.2 mL/h for the pre-programmed values of 5, 10, 20, 30, and 40 mL/h correspondingly. The highest level of deviation was no higher than $\pm 2\%$ across the entire range of flow rates. This consistency of the

error level shows that the calculation of the motor step frequency and the plunger displacement was repeatable. The deviations occurred due to the manufacturing tolerance of the 3D-printed parts and the limited resolution of stepper motor micro-stepping.

Table 1. Flow rate measurement results

Set Flow Rate (mL/h)	Measured Flow Rate (mL/h)	Error (%)
5	5.1	2.0
10	9.8	-2.0
20	19.6	-2.0
30	29.4	-2.0
40	39.2	-2.0

4.3 Mechanical Stability During Repeated Operations

Stability of the manufactured device mechanically was tested during multiple infusion cycles to see if continued actuation caused any structural deformations or misalignments. The results in Figure 3 suggest stable mechanical behavior throughout all the tested cycles. There have been no structural deformations or any misalignments found during base testing. This means that the 3D-printed syringe holder, guiding structure and actuating parts remained geometrically functional during repeated movement of the plunger. Nevertheless, surface roughness was present due to FDM manufacturing process causing some losses from friction in the system. This was addressed by firmware calibration. Hence, the mechanical device had enough stability dimensionally for the following infusion tests, with surface friction being an important factor for actuator performance.

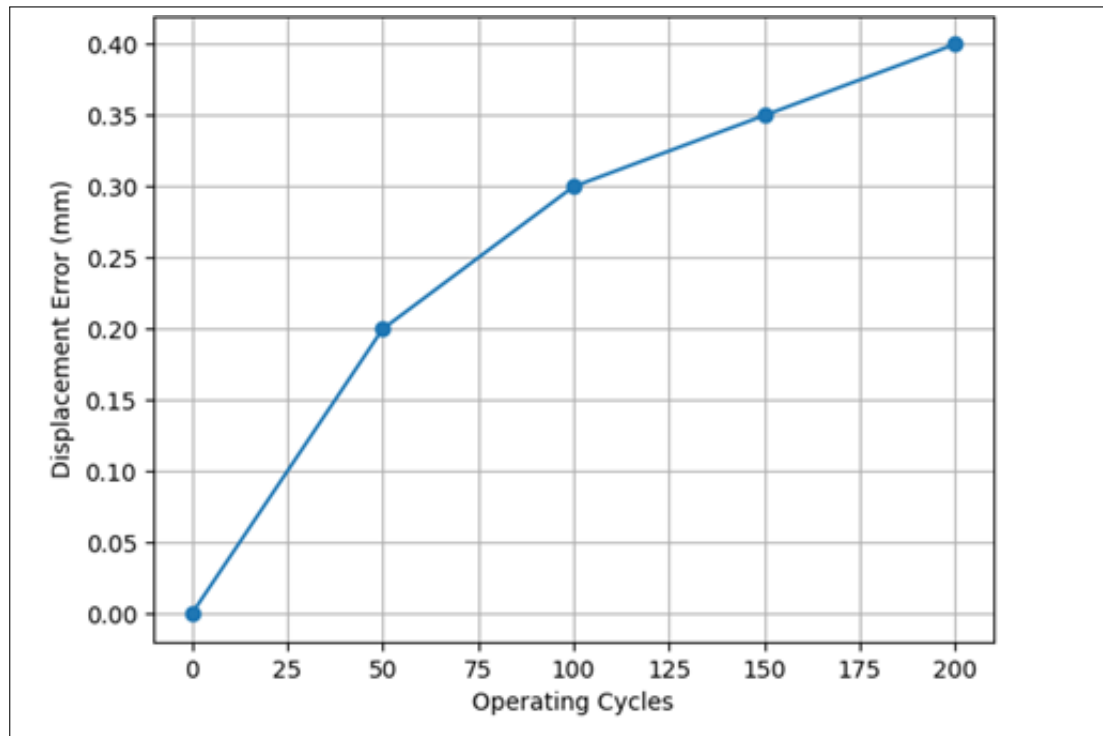


Figure 3. Mechanical stability during repeated infusion cycles

4.4 Safety Response and Plunger Overrun Protection

The pressure response of the proposed infusion pump is shown in Figure 4. In standard operating conditions, the measured pressure is kept below the set threshold value of 40 kPa. With increasing occlusion of the infusion route, the pressure increases gradually from about 20 kPa to over 60 kPa. The point where the measured pressure exceeds the threshold level, which marks the shift from normal to abnormal pressure state, occurs at around 45 kPa. Upon detection of the pressure value exceeding the set threshold value, the safety procedure is activated by the controller in the form of motor shut-down and alarming signal. Thus, the controlled system ensures protection against excessive pressure due to the direct connection between the sensor signal and actuator deactivation.

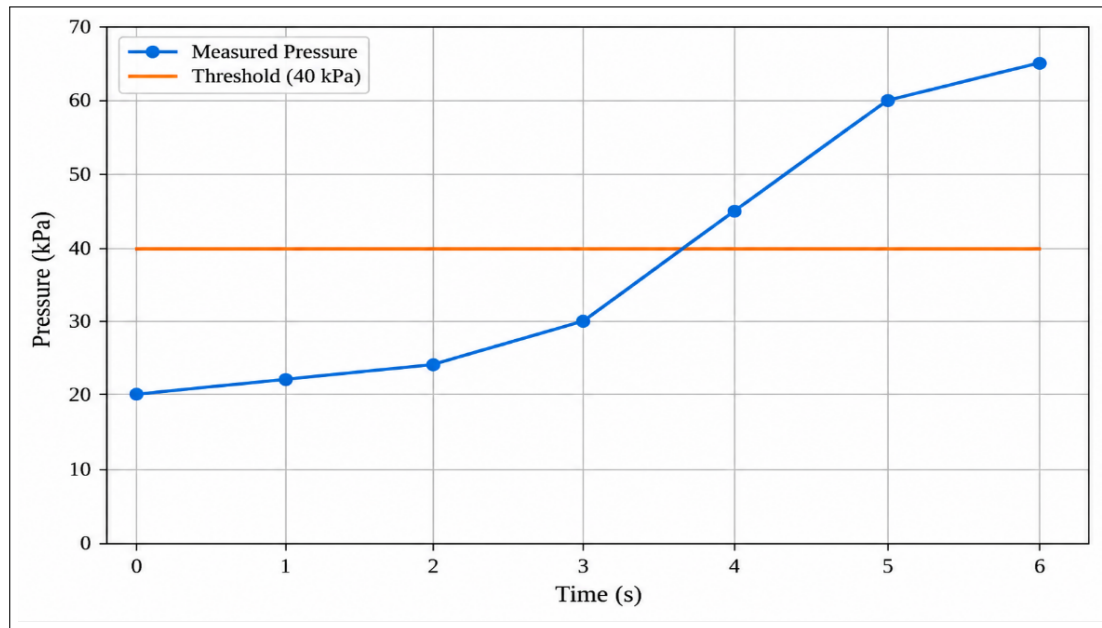


Figure 4. Pressure-based occlusion detection

4.5 Integrated System Performance

The experimental findings clearly show the interaction of the mechanical and electronic subsystems during the infusion process. First of all, the flow rate experiments have proved that the plunger mechanism operated by a stepper motor is able to replicate the pre-set delivery parameters with a maximum error of $\pm 2\%$. Furthermore, the repetitive cycle test has shown that the additively manufactured construction retains its mechanical structure without deformation or misalignment. From the perspective of security, there are several fault handling mechanisms in the form of pressure occlusion detection, motor stop, end-of-travel, and visual or sound alarms.

5. Conclusion and Future Work

The proposed smart infusion pump prototype provides an indication of the viability of integration of additive manufacturing, stepper-motor operation, ESP8266 embedded system, pressure measurement, and wireless monitoring in the designed system. Evaluation in the laboratory environment for flows in the range of 5-40 mL/h resulted in accurate flow measurements with an error of no more than $\pm 2\%$, indicating successful implementation of plunger actuation and flow regulation. The multiple cycle tests confirmed stable mechanics and no distortion of mechanical parts. The implemented safety feature additionally facilitated occlusion detection by pressure, motor stopping, alarm trigger, and end of travel. Nevertheless, this experiment was

performed under laboratory conditions using water; hence, the results do not provide clinical validation. Future research should consider closed loop flow regulation, sensor resolution improvement, print material and mechanical tolerance optimization, evaluation of wireless performance quantitatively, long-term testing, and clinical validation.

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