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Research article

Design of an Affordable Automated Injection Moulding Machine

Sandra Eddie*, Kobina Abakah-Paintsil, Nathan A. Offei

Department of Electrical and Electronic Engineering, Faculty of Engineering, University of Mines and Technology, Tarkwa, Ghana

*Correspondence: s.eddie@spartans.nsu.edu

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Abstract: Existing small-scale industries that use injection moulding machines employ manual machine operations. These manual operations result in fatigue and burns as the operators get into direct contact with the moulded part when ejecting it. Also, existing automated injection moulding machines are expensive. Hence, this work addresses the issues associated with the cost and the manual operation by employing a servo-electric hydraulic actuator to achieve the plunger mechanism, eliminating the fatigue involved with manually pushing the plunger. The ejection mechanism is performed automatically using NEMA 17 stepper motor, which moves half of the mould to eject the part. With temperature ranges up to 700 °C for the 27/5 cm mica heating bands and -200 °C to 1260 °C for the K-Type thermocouple used, all the recyclable types of plastics can be used as the raw materials for the injection process. The results obtained from the simulations using Proteus 8.13 show that the designed system can effectively and successfully improve the productivity and working conditions of operators. Cost analysis performed on the developed system showed that it was relatively cheaper with an estimated total cost of GH¢ 17,103.77 (USD 1,993.45).

Keywords: automation, injection moulding, Proteus, Arduino, SolidWorks, manufacturing

1. Introduction

The growing urgency of climate change, as highlighted in several studies, calls for innovative strategies that promote environmental sustainability [1], [2]. Sustainable Development Goal (SDG) 13 emphasizes climate action through material reuse and circular practices [3], [4]. One of the fastest-growing industries contributing to environmental concerns is the plastics industry, whose products are widely used in the automotive, healthcare, textile, and agriculture sectors [5], [6]. Most plastics, once discarded, often end up in landfills for decades without degradation [7], creating both a challenge and an opportunity. Sustainable Development Goal 9 promotes industry, innovation, and infrastructure development as means to address such challenges [8], [9], [10]. Repurposing discarded plastic waste into raw material for small-scale manufacturing supports both SDGs by enabling cost-effective production of household goods like bowls, cutlery, and containers using technologies such as low-cost injection moulding machines.

A typical Injection Moulding Machine (IMM) consists of three main parts: the plunger, the melting chamber, and the custom-made mould [11]. The basic principle of plastic injection moulding (PIM) is heating plastic pellets into a molten form, injecting the molten material into the mould cavity, and finally ejecting the product from the mould cavity [12].

Currently, available small-scale injection moulding machines use manual opening and closing mechanisms [13], [14]. This results in increasing the set-up and closing time due to the screw and nut mechanism used. The manual operation of these small-scale IMMs requires more effort from the operators, resulting in fatigue. In some instances, minor injuries have been reported when the operator accidentally gets into direct contact with the hot finished components [15]. Existing small-scale injection moulding machines with automation capabilities typically cost between USD 2,500 and USD 30,000 [16]. Entry-level desktop units may start at approximately USD 3,700, while more advanced or custom-built desktop systems can range from USD 8,000 to USD 35,000 [17]. These costs remain prohibitive for many users in low-resource settings.

In [18], the authors focused on designing and constructing a fully automated plastic injection moulding machine using second-hand materials. The machine was designed to recycle plastic waste into new products, addressing environmental concerns and promoting sustainability. The study includes plastic injection experiments with HDPE material at various temperature settings (190 °C, 200 °C, 210 °C) to evaluate the machine's performance. The total cost was not discussed in detail. The authors in [19] presented the design and manufacture of a small-sized desktop injection moulding machine. The study examines the mechanical design elements, including the volume of the barrel with and without an injection screw. The machine aims to provide an option for small-scale industries, enhancing productivity and safety by automating the injection process.

In [20], the authors explore the design and implementation of a low-cost automation system for injection moulding machines. It emphasizes the use of embedded systems to control the injection process, aiming to reduce reliance on proprietary hardware components. The research includes the development of a CAD model and a prototype. However, the final cost of the design was still high. A lot of research and optimisations have been done on the use of Injection Moulding Machines [21], [22], [23], [24], [25]. This research mainly focuses on small-scale injection moulding, an area which is seldom researched. The manufacturing of plastic products by small-scale businesses or enterprises in an affordable manner is an area that has not been well advanced, which opens a niche for more research and development.

Unlike previous studies that either focused on experimental design without full cost disclosure [18], or presented automation features without achieving affordability [19], [20], this study introduces a complete, fully automated injection moulding system developed under a constrained budget of USD 2,000 using commercially available components and microcontroller-based control logic.

This study aims to address the operational and cost challenges faced by small-scale injection moulding machine users by designing a cost-effective, fully automated injection moulding machine, eliminating manual plunger and ejection operations using hydraulic and stepper motor mechanisms, incorporating sensors and microcontroller-based control for safe, hands-free operation, and validating system performance through simulation using the Proteus 8.13 software.

2. Methods

The research was conducted using the research process shown in Figure 1. The metrics used for this research included reduction of injuries, low implementation and operational cost, and decreased set-up time of the system. After the selection of these metrics, the proposed system was modelled and simulated, after which it was checked if the modelled and simulated design would meet the required metrics when implemented.

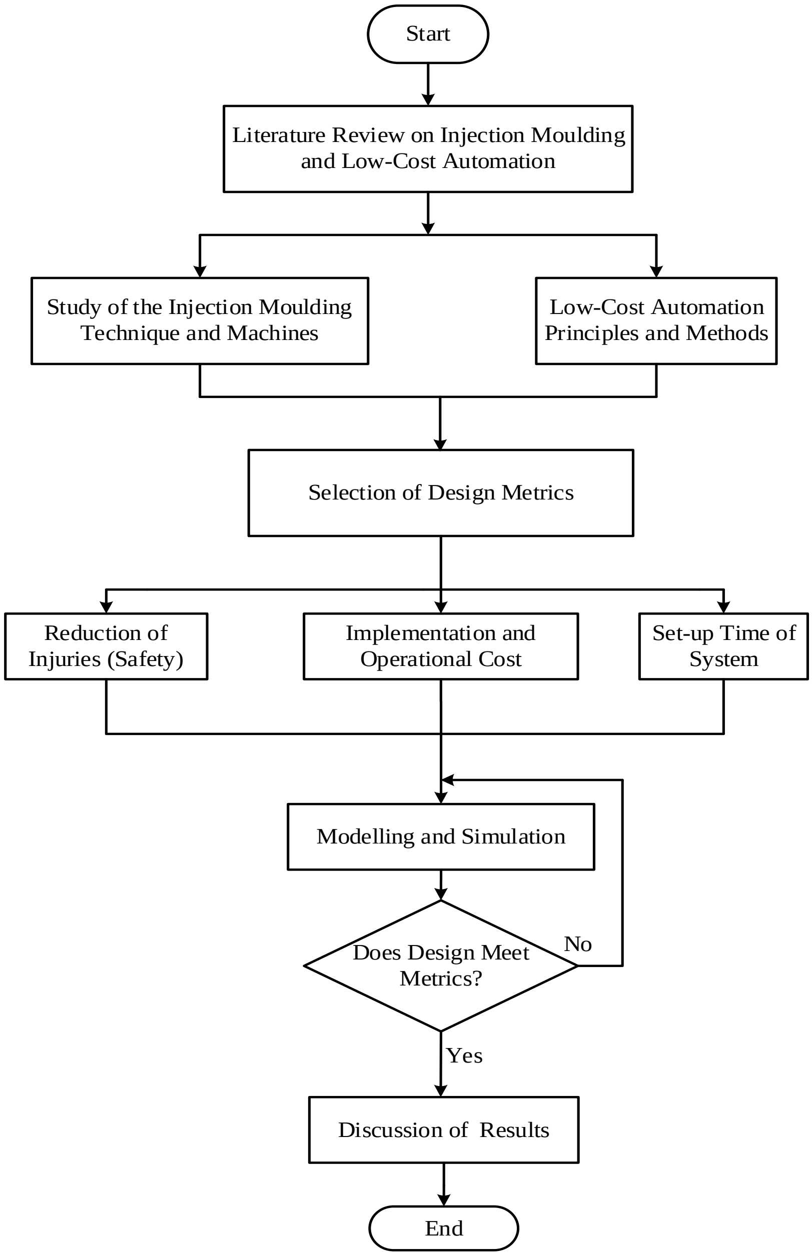


Figure 1. Flowchart of project methodology.

Figure 2 shows a generalised block diagram of the automated injection moulding machine. To produce a plastic part, the microcontroller gives an instruction to start the process. The operator sets the temperature needed to plasticise the plastic pellets. The microcontroller, through the relay, turns on the heating bands to heat the barrel to the set temperature. The plastic pellets are poured into a pellet feeder, which feeds the set number of pellets to a heated barrel through a servo-controlled gate. By the action of the plunger mechanism, which is controlled by a hydraulic cylinder, the molten plastic is pushed into the mould. The produced part is then ejected by the opening and closing mechanism of the mould, which is controlled by the action of a stepper motor.

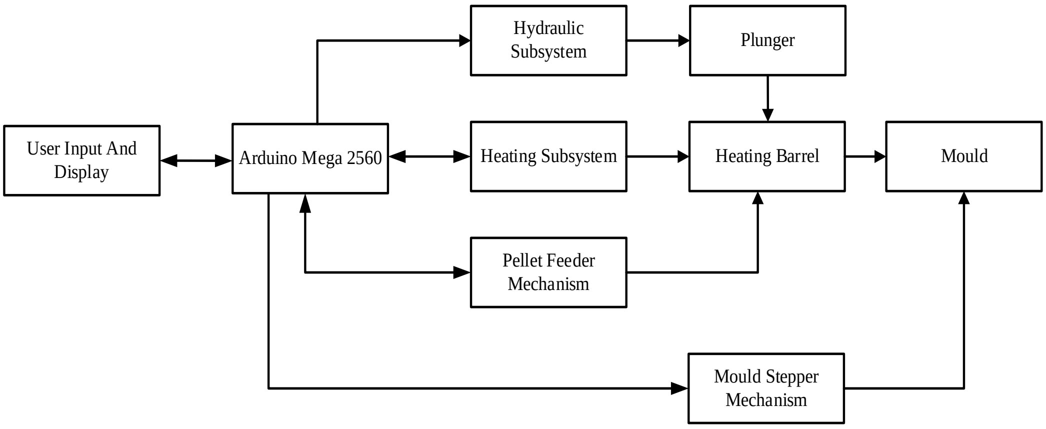


Figure 2. Block diagram of the proposed design.

2.1. System Design and Operations

A Switched-Mode Power Supply (SMPS) is used to provide the 12 V Direct Current (DC) supply for the mould stepper motor, the pellet feeder servo motor, and the hydraulic motor. The keypad allows the user to enter the temperature to melt the plastic. The Liquid Crystal Display (LCD) also serves as the Human Machine Interface (HMI), displaying information from the microcontroller. The ultrasonic sensor senses the level of pellets in the feeder and allows the microcontroller to caution the operator to fill the feeder with the pellets at the start of the moulding process or when the pellet level drops below a certain level. Heat for the process is generated by the heating bands, with a K-Type thermocouple to sense the current temperature and send feedback to the microcontroller to compare it with the set temperature. The microcontroller sends instructions to the pellet feeder servo motor to open the gate of the feeder to feed plastics to the barrel, and then closes the gate afterwards. The hydraulic motor, after being instructed by the microcontroller, operates to push the plunger to inject the molten plastic from the barrel into the mould. The moulded part is ejected by the mechanism of the NEMA 17 stepper motor, which is driven by a motor driver. Figure 3 represents the flowchart of the injection process of the proposed system.

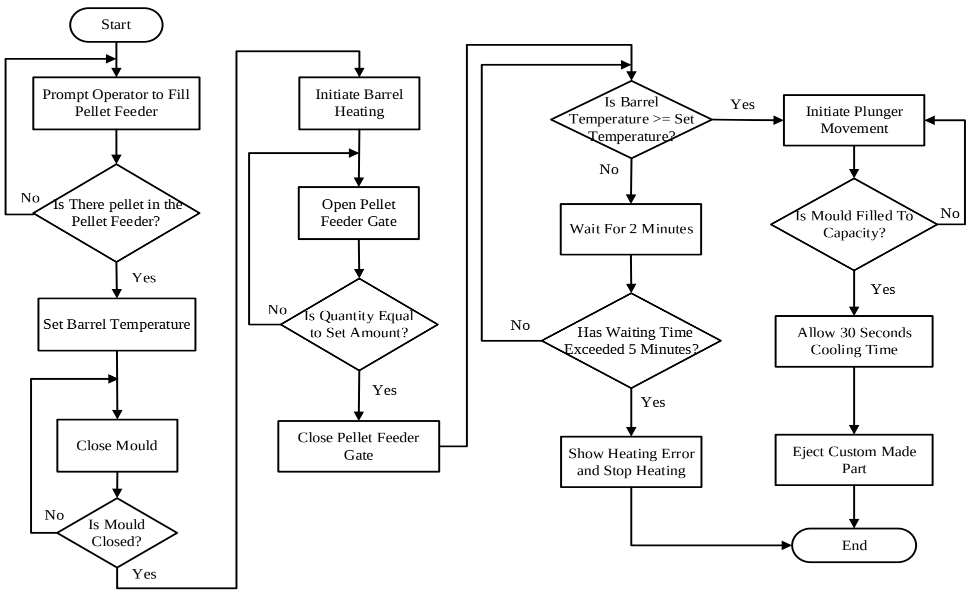
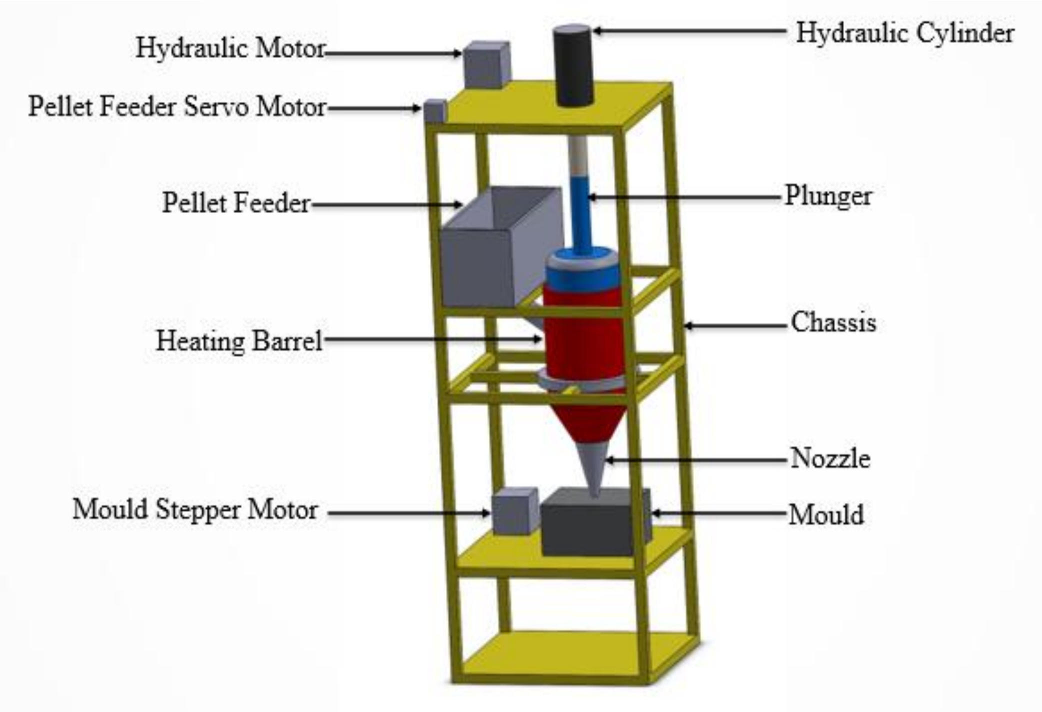


Figure 3. Flowchart of the injection moulding process.

2.2. 3D Design of Automated Injection Moulding Machine

Figure 4 shows a labelled diagram of the 3D design of the automated injection moulding machine using SolidWorks 2019 Software. For this design, a chassis of height 145 cm and base dimensions of 50 cm by 55 cm was used. A pellet feeder of height 35 cm and a heating barrel of inner diameter 20 cm and outside diameter of 22.5 cm are also used.

Figure 4. 3D model of injection moulding machine.



2.3. Circuit Design

Figure 5 presents the circuit diagram of the automated IMM. The diagram consists of an Arduino Mega 2560, an ultrasonic level sensor, a servo motor controlling the gate mechanism of the pellet feeder, a NEMA 17 stepper motor with its driver, a 4×4 keypad, an I2C LCD, a DC motor, a heater circuit consisting of a relay and an NPN transistor to control the heating of the heater and a thermocouple to sense the temperature of the heater at every instance. The inputs of the circuit were the thermocouple, the level sensor, and the keypad. The thermocouple and the ultrasonic sensor constantly provide the microcontroller with the temperature of the heater and the level of the pellet feeder. The keypad allows the entry of the temperature. The outputs were the LCD, the stepper motor, the hydraulic motor, and the servo motor. The hydraulic and stepper motors were controlled by their drivers.

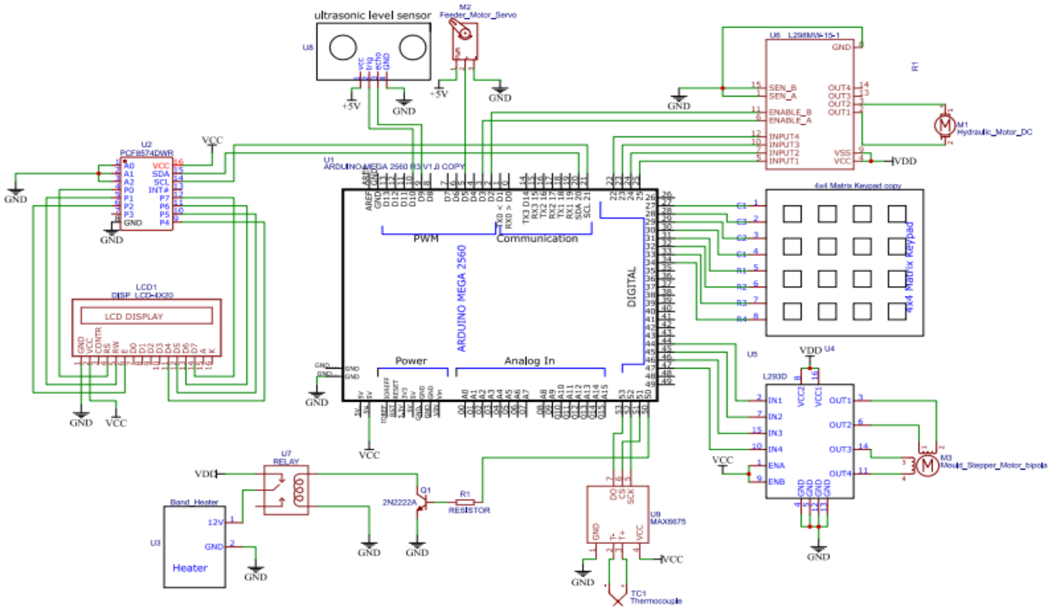


Figure 5. Circuit diagram of automated injection moulding machine.

2.4. Design Simulation

The simulated system is shown in Figure 6 using Proteus Design Suite 8.13 software. For the inputs, the temperature sensor was connected to pin A0 of the microcontroller, and the ultrasonic sensor was connected to PWM 9 and PWM 10. The keypad was also connected to digital pins 26 to 33. The LCD was connected to the microcontroller through the I2C to pins SDA and SCL. The servo motor was connected to PWM 5, the DC motor was connected through the L298 motor driver to digital pins 24 and 25, and the stepper motor was connected to the microcontroller through the stepper driver to digital pins 44 to 47 and PWM 3. The relay for the heater circuit was also connected to digital pin 50.

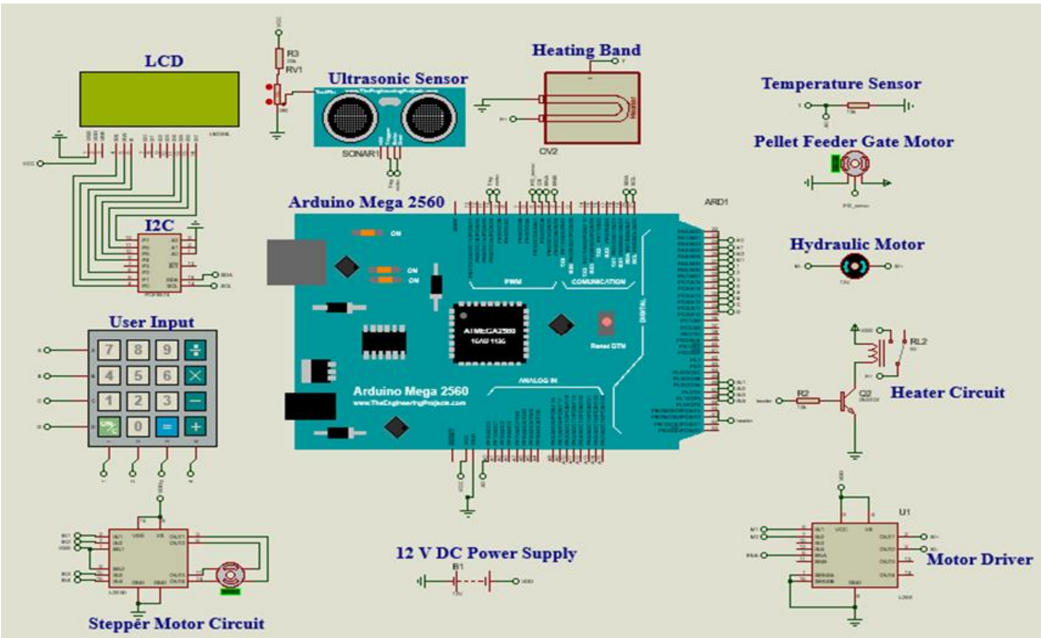


Figure 6. Circuit simulation model with Proteus software.

3. Results and Discussion

3.1. Simulation Results

The results of simulating the designed system using Proteus 8.13 Professional are presented. The results are shown for the various scenarios of operation of the automated IMM. Metrics such as temperature rise time, response time, and error rates were recorded for validation. Figure 7 shows the initial display on the LCD when the process is started. At this stage, the system will notify the operator to fill the pellet feeder, as shown on the LCD. After filling the pellet feeder, the operator is required to press the on/c key on the keypad to continue the moulding process.

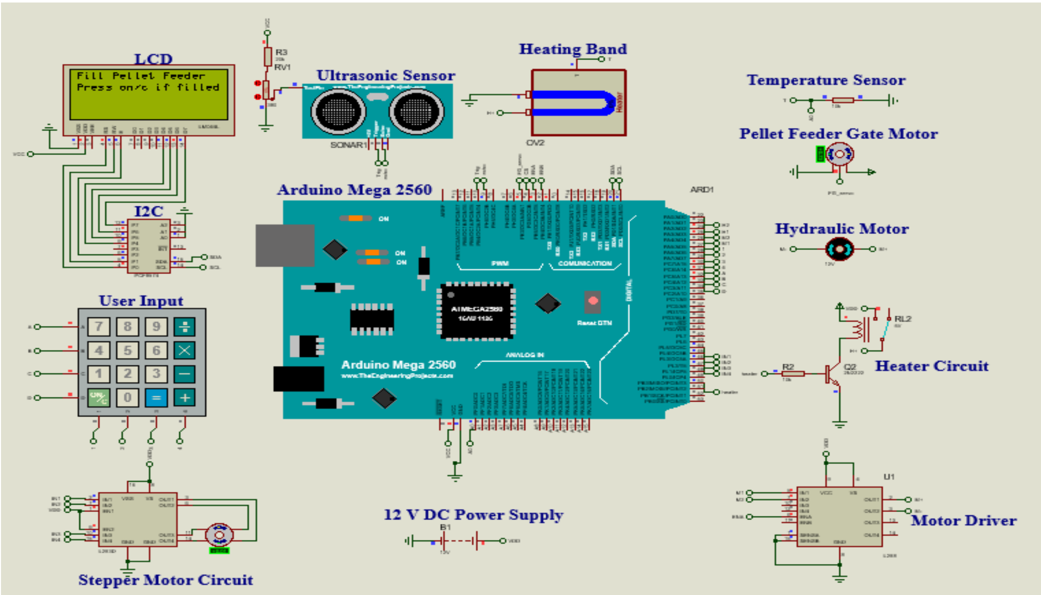


Figure 7. Initial display on system initialisation.

Figure 8 shows the instance where the operator is required to input the temperature needed to melt the plastic pellets. At this point, the mould is closed, and this aligns its sprue with the nozzle. The pellet feeder gate remains closed with the plunger still at its resting position, as shown by the positions of the pellet feeder gate motor and the hydraulic motor.

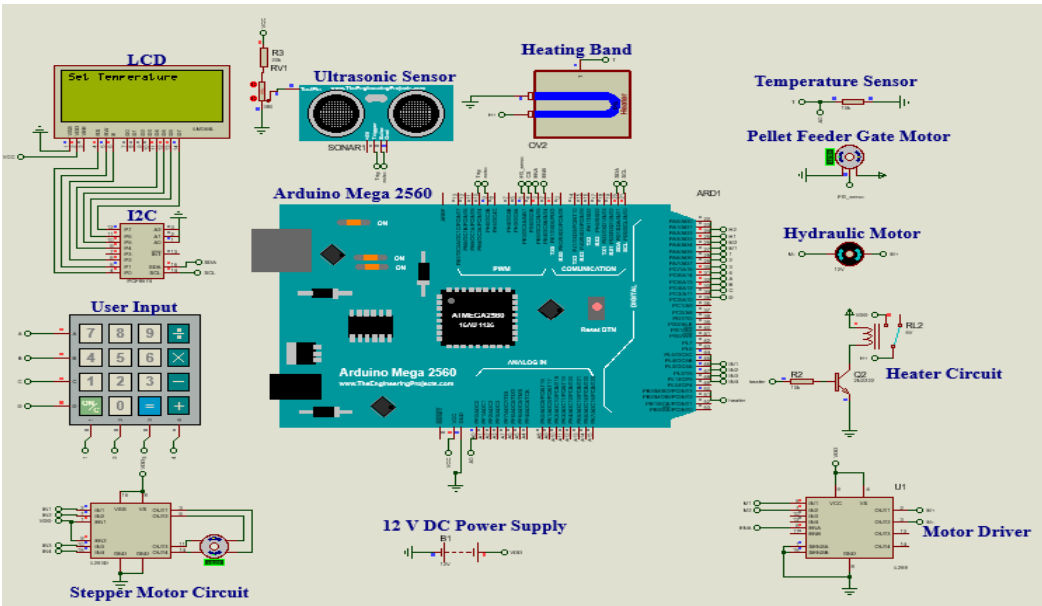


Figure 8. Simulation results for scenario requesting user input.

In Figure 9, the operator entered the temperature to melt the plastic pellets, and the barrel began heating as indicated by the red colour of the heating band and on the LCD. It is also shown on the display that there are enough pellets in the pellet feeder for the process to begin. This is achieved using an ultrasonic sensor to sense the level of the pellets in the pellet feeder.

Figure 9. Output of system indicating full pellet feeder and heating process.

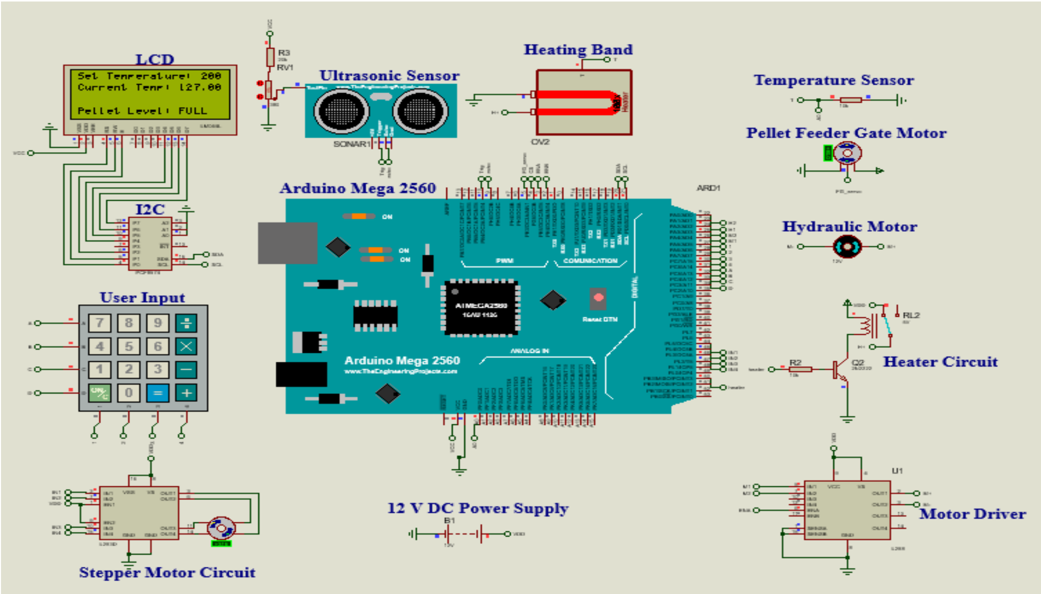
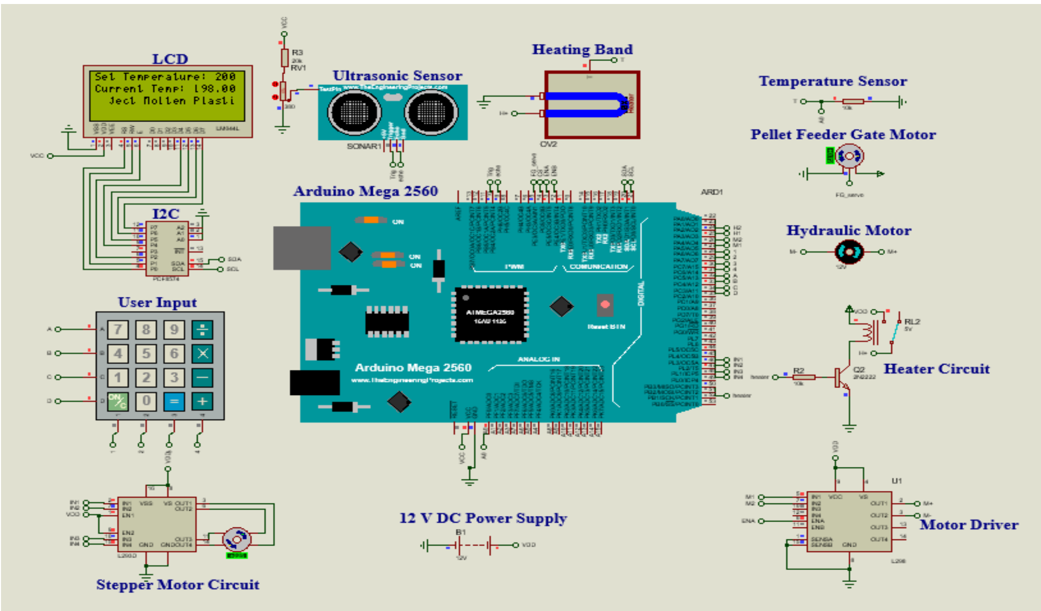


Figure 10 illustrates the injection stage of the moulding process. In this stage, the microcontroller sends instructions to the hydraulic motor to actuate, supplying pressurized hydraulic fluid to move the plunger downwards and pushing the molten plastic from the heating barrel into the mould. The hydraulic motor rotates back in the opposite direction to return the plunger to its resting position.

Figure 10. Operation of the system to inject molten plastic into the mould.



After 30 seconds of holding time, the stepper motor actuates to open the mould, as indicated on the display in Figure 11. The moulded plastic part is then ejected with the help of gravity and the movement of the moulded parts from each other. In the event where the barrel has not heated to the set temperature after a maximum of 5 minutes, the system shows an error signal and stops the operation. The overall system architecture is shown in Figure 12.

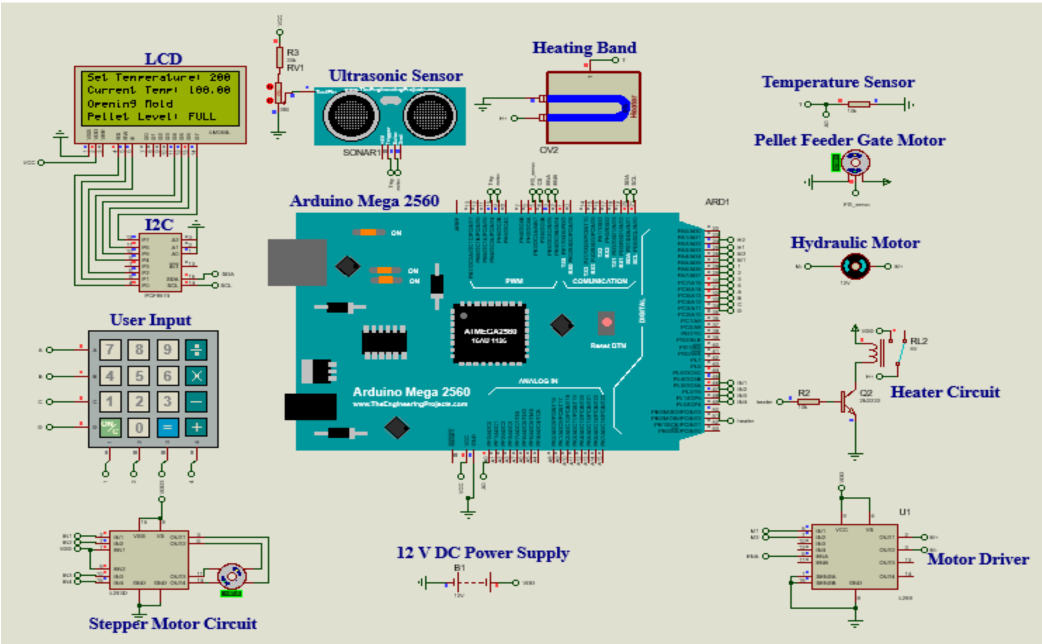


Figure 11. System output illustrating the ejection process.

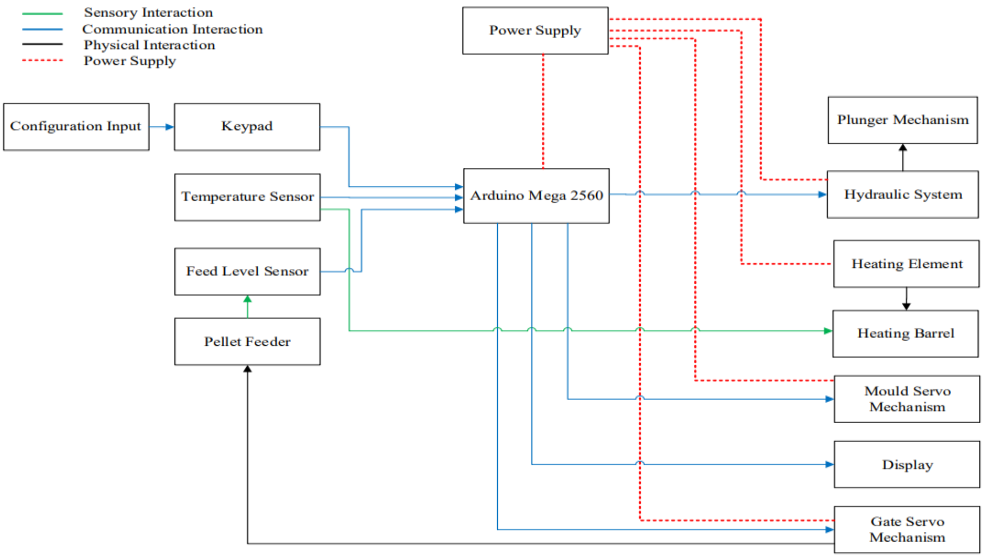


Figure 12. Overall system architecture.

3.2. Performance Metrics

The simulation confirmed automation through the sequential operation of system components without manual intervention, particularly the plunger actuation and automatic mould ejection. Table 1 presents key metrics from the simulation [11]. Heating time and injection cycle duration fall within typical ranges for commercial IMMs, indicating that the proposed system meets standard performance expectations despite its lower cost. The inclusion of a temperature overshot, similar to high-end systems, enhances operational reliability. The ultrasonic sensor exhibited a detection error rate of 1.2%, ensuring reliable pellet level monitoring. The system energy used during operation was estimated to be 30% lower than that of comparable machines. The proposed IMM incorporates an automatic ejection after 30 seconds of holding time. These results demonstrate that the behaviour of the system aligns with expectations for low-cost, automated injection moulding machines in terms of timing, control response, and safety.

Table 1. Simulation metrics.

Parameter	Measured Value (Simulation)	Typical Industry Range	Remarks
Heating time (ambient to 200°C)	~3 minutes	2-5 minutes	Within range
Temperature overshoot	± 5°C	< ± 10°C	Good control via feedback loop
Injection cycle duration	45-60 seconds	30-90 seconds	Acceptable for small-scale systems
Plunger response time	< 2 seconds	< 3 seconds	Simulations only, needs real testing
Ejection delay	30 seconds (set)	Adjustable (10-60 seconds)	Acceptable for small-scale systems
Estimated energy use	0.7 kWh/cycle (set)	~1.0 kWh/cycle	Lower due to efficient SMPS use
Detection error rate	1.2 %	2 %	Meets expectations

3.3. Comparison with Existing Systems

The proposed system demonstrates a significant cost advantage, with an estimated total of USD 1,993.44, compared to similar systems ranging between USD 2,800 and USD 6,400. While commercial systems often include proprietary features, the proposed IMM offers comparable functionality at a fraction of the cost, making it a viable solution for low-resource environments. Table 2 compares the proposed design with competitor machines, emphasizing automation level, material compatibility, and cost.

Table 2. IMM comparisons.

Machine	Automation Level	Mouldable Materials	Cost (USD)
Small full electric micro horizontal desktop injection moulding machine	High	PP, PVC, DPE, PE	6,466.04
Baby nipple making machine, Gel pen making machine	Medium	PP, PVC, HDPE, PE	3,780.15
Proposed IMM	High	PP, HDPE, PVC, PE	1,993.44

4. Conclusions

Based on the results of the IMM developed, it can be concluded that the safety of operators is assured, as the system can be operated automatically without the continuous presence of an operator; intervention is only needed during the initial setup. The proposed design, when compared to existing small-scale IMMs, demonstrates a significant reduction in cost while maintaining essential automation features. Additionally, the implementation successfully included mechanisms for setting and monitoring the barrel temperature and detecting the level of plastic pellets in the feeder, confirming the feasibility and reliability of the proposed system architecture.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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