Design and Performance Analysis of an Automatic Plastic Mulch Cutting and Punching Machine Using PID Control

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***Abstract*— Plastic mulch is widely used in horticulture to improve soil moisture retention, regulate temperature, and suppress weed growth. However, manual cutting and hole-punching processes are time-consuming, labor-intensive, and produce inconsistent results. This study presents the design and performance analysis of an automatic plastic mulch cutting and punching machine using a PID (Proportional–Integral–Derivative) control system. The system is based on an Arduino Nano. It integrates a DC motor for mulch feeding, a NEMA 17 stepper motor for the punching mechanism, a heater band controlled by an AC dimmer, and a photoelectric sensor for length feedback. PID parameters were initially determined using the Ziegler–Nichols method (Kp=13.5, Ki=2.8, Kd=7.1) and optimized experimentally to Kp=10, Ki=2, and Kd=1. Experimental results show that the optimized PID controller achieves a stable motor response with no oscillation and minimal overshoot, enabling accurate stopping at the desired set point. The system produces a consistent hole spacing of approximately 43.96 cm. Minor deviations were caused by sensor noise and environmental interference.**

Keywords—Plastic Mulch, PID Control, Photoelectric Sensor, Agricultural Automation

I. INTRODUCTION

Plastic mulch is widely used in horticultural cultivation as a soil covering material to improve crop productivity and growing conditions. Its application helps maintain soil moisture and temperature stability, suppresses weed growth, prevents erosion, and enhances the yield of crops such as tomatoes, chili, eggplant, melon, and watermelon [1]. Among various types, black–silver plastic mulch is the most commonly used, where the black side functions to inhibit weed growth and retain soil moisture, while the silver side reflects sunlight to reduce excessive evaporation.

Despite its advantages, the practical implementation of plastic mulch still faces operational challenges, particularly in the cutting and hole-punching processes. These processes are commonly performed manually, which requires significant labor, consumes considerable time, and often produces inconsistent results [2]. Farmers typically perform repetitive bending motions to create holes using heated tools or manual cutting devices, leading to physical fatigue and reduced productivity. In addition, longitudinal cutting of mulch sheets cannot be efficiently performed by a single operator, as it requires simultaneous pulling and cutting actions [3].

Several studies have proposed the development of tools to improve the efficiency of plastic mulch processing. For instance, automatic hole-punching systems based on LED–LDR sensors have been developed to regulate hole spacing [4], while push-type mechanical tools with adjustable handles have been designed to improve ergonomic usability [6]. Furthermore, microcontroller-based systems using ATMega 328 have been introduced to automate cutting and punching processes with variable motor speeds [10]. However, these approaches still exhibit limitations in achieving precise length control and consistent hole spacing, particularly under continuous operation conditions.

To overcome these limitations, the application of closed-loop control systems becomes essential to improve accuracy and system stability. The Proportional–Integral–Derivative (PID) controller is widely used in control systems due to its simplicity and effectiveness in reducing steady-state error, minimizing overshoot, and improving dynamic response [9]. By incorporating feedback mechanisms, PID control enables more precise regulation of system behavior compared to conventional open-loop approaches.

Therefore, this study aims to design and optimize an automatic plastic mulch cutting and punching machine based on an Arduino Nano using a PID control method. The proposed system integrates a photoelectric sensor as feedback for length measurement, a DC motor for mulch feeding, a stepper motor for the punching mechanism, and a heater band controlled by an AC dimmer for thermal hole formation. By applying PID control, the system is expected to improve precision, consistency, and operational efficiency compared to manual and previous automated methods.

II. MATERIALS AND METHODS

A. System Architecture

The proposed system consists of several main components integrated into a closed-loop control system. An Arduino Nano (ATmega328) is used as the main controller due to its flexibility and suitability for embedded control applications [12]. The feeding mechanism is driven by a DC motor controlled using a BTS7960 motor driver, which is commonly used for high-current motor applications [17].

The punching mechanism utilizes a NEMA 17 stepper motor with an A4988 driver operating in 1/8 microstepping mode to achieve smooth motion and sufficient torque [18]. A heater band controlled through an AC dimmer circuit is employed for thermal hole formation, while temperature monitoring is performed using a type-K thermocouple with a MAX6675 module [15].

A photoelectric speed encoder is used to measure roller rotation as feedback for length control, while limit switches are installed to define the upper and lower boundaries of the punching mechanism. An LCD 20×4 module with an I2C

interface is used to display system parameters and operational status.

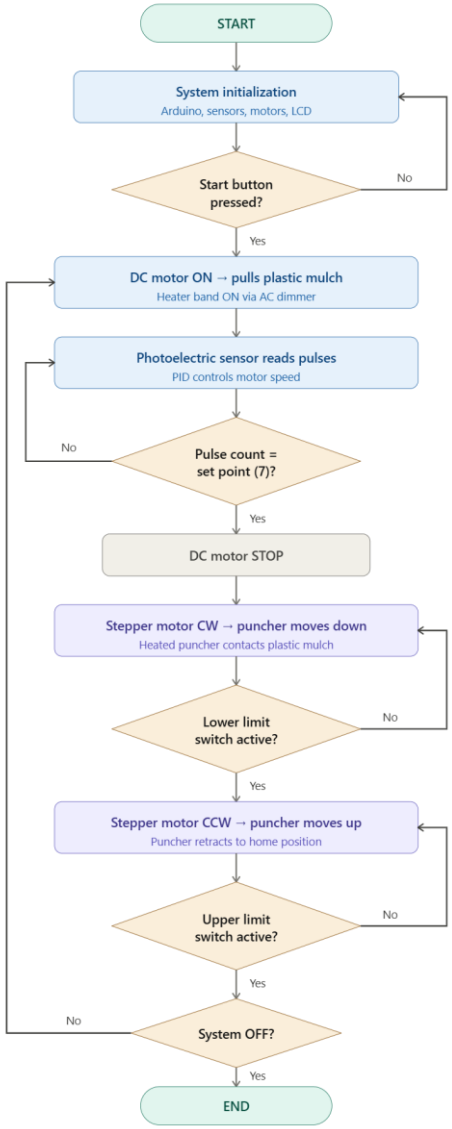


Fig. 1. System Flowchart of the Automatic Plastic Mulch Cutting and Punching Machine

TABLE I. MAIN COMPONENT SPECIFICATIONS

Component	Model/Type	Specification
Microcontroller	Arduino Nano	ATmega328, 16 MHz, 32KB Flash
DC Motor	24V Gear Head	24V DC, 16.2 RPM max, BTS7960 driver
Stepper Motor	NEMA 17	1.8°/step, 1.2A, 1/8 microstepping (A4988)
Heater	Heater Band	220V AC, controlled via AC Dimmer (Triac)
Temp. Sensor	Thermocouple Type K	0–1024°C, MAX6675 module, 12-bit
Photoelectric	Speed Encoder	NPN output, 5V, roller dia. 2 cm
Display	LCD 20x4 I2C	5V, I2C address 0x27, SDA=A4, SCL=A5
Power Supply	24V DC	24V, 20A, with step-down regulator to 5V

B. Hardware Configuration

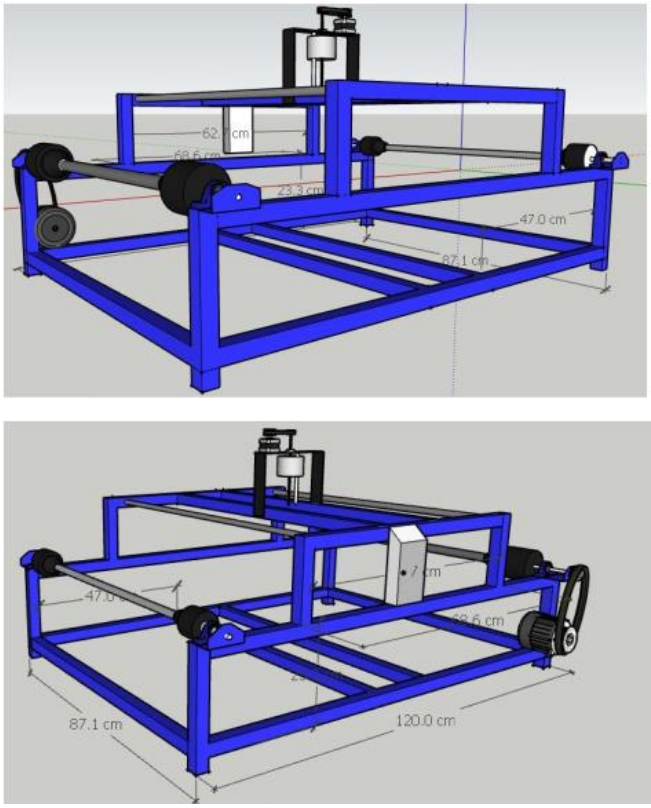


Fig 2. Mechanical design of the automatic plastic mulch cutting and punching machine

The mechanical structure of the proposed system is shown in Fig. 2. It consists of a rigid frame supporting the feeding and punching mechanisms. The plastic mulch is pulled by rollers driven by a DC motor, while secondary rollers are used to stabilize the material movement. The punching mechanism is positioned above the feed path and driven by a stepper motor, enabling precise vertical movement during the punching process. The integration of the mechanical structure with the control system allows for synchronous operation between the feeding and punching processes.

The system's hardware configuration includes an Arduino Nano (ATmega328) as the primary controller. The feeding mechanism is driven by a DC motor controlled by a BTS7960 driver, while the punching mechanism uses a NEMA 17 stepper motor with an A4988 driver. A photoelectric sensor is used to provide rotational feedback for length measurement, and a K-type thermocouple with a MAX6675 module is used for temperature monitoring. The thermal punching process is carried out using a heating tape controlled by an AC dimmer circuit. In addition, limit switches are installed to determine the upper and lower limits of the punching mechanism, and a 20×4 LCD with an I2C interface is used to display system parameters and operational status.

C. Working Principle of the System

The system operates sequentially based on user input. When the start button is pressed, a DC motor begins pulling the plastic mulch. A photoelectric sensor detects the rotation of the roller and generates pulses corresponding to the length traveled. When the number of pulses reaches a predetermined point (e.g., 7 pulses equals approximately

43.96 cm), the DC motor is stopped. A stepper motor is then activated to move the heated punching mechanism downward until it reaches the lower limit switch. Once the punching process is complete, the stepper motor reverses direction until it reaches the upper limit switch. This process is repeated automatically to achieve uniform cuts and hole spacing along the plastic mulch.

D. Length Measurement and Hole Spacing Calculation

The distance between holes is determined based on the circumference of the roller used in the feeding system. The circumference is calculated using:

$$C = \pi \times d \quad (1)$$

where d is the roller diameter, for a roller diameter of 2 cm, the circumference is:

$$C = 3.14 \times 2 = 6.28\ cm$$

To achieve a hole spacing of approximately 40 cm, the system uses 7 pulse counts from the photoelectric sensor:

$$7 \times 6.28 = 43.96\ cm$$

E. PID Control Design

The PID controller is used to regulate the DC motor speed and ensure precise stopping at the desired set point. The control law is defined as:

$$(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (2)$$

Where $e(t)$ is the error between the desired and measured position, and K_p, K_i and K_d are the proportional, integral, and derivative gains. Initial PID parameters were determined using the Ziegler–Nichols tuning method, resulting in:

$K_p = 13.5$
$K_i = 2.8$
$K_d = 7.1$

These values were further refined through experimental trial-and-error tuning to improve system stability and response.

III. Result and Discussion

A. DC Motor Performance

The performance of the DC motor was evaluated to analyze its response to a PWM input signal. The experimental results showed a proportional relationship between the PWM value and the motor speed (RPM), indicating stable motor behavior under no-load conditions.

As shown in Table II, the motor exhibited a linear response to the PWM input. At lower PWM values, the error was negligible, while at higher PWM values, a maximum deviation of 4.4 RPM was observed. This indicates that the motor is suitable for use as a feeder actuator, although control is required to ensure precise stopping at the desired position.

TABLE II. DC Motor Performance under Different PWM Values

PWM	Measured RPM	Calculated RPM	Error (RPM)
150	9.4	9.4	0
175	10.9	10.9	0
200	12.4	12.0	0.4
225	14.2	9.8	4.4
255	16.2	15.8	0.4

B. Photoelectric Sensor Performance

The photoelectric sensor was tested to evaluate its performance in detecting roller rotation as feedback for length measurement. The results in Table III show that the detection time increases with decreasing PWM value, confirming a direct relationship between motor speed and sensor output. The sensor provides consistent feedback for length measurement. However, minor inaccuracies are observed due to environmental disturbances such as ambient light and electrical interference.

TABLE III. Photoelectric Sensor Testing Results

PWM	Pulses	Time (s)	RPM
255	7	11,73	68,8
225	7	12,10	68,1
200	7	13,40	58,3
175	7	15,26	30,9
150	7	16,99	23,3

C. Temperature Control Performance

The heating system performance was evaluated using thermocouple sensors to analyze temperature stability. Table IV shows that the system experienced a temperature spike of approximately 7–10°C above the specified range. This behavior is caused by the response delay of the thermocouple sensors and the characteristics of the AC dimmer control. Nevertheless, the achieved temperature range (75–86°C) is sufficient for effective thermal hole formation.

TABLE IV. Thermocouple Measurement Results

No	Set Temperature Range (°C)	Measured Temperature (°C)
1	60–65	~72
2	70–75	~83
3	80–85	~91

D. Stepper Motor Performance

Stepper motors were tested under different microstepping configurations to determine optimal operating conditions. As shown in Table V, the 1/8 microstepping mode provided the best balance between torque and smoothness. Lower stepping modes resulted in rougher motion, while higher microstepping significantly reduced torque.

TABLE V. Stepper Motor Microstepping Performance

Mode	RPM	Current (A)	Voltage (V)	Description
Full Step	0	1.2	24	High torque, rough motion
1/2 Step	0	1.2	24	Still rough
1/4 Step	0	1.2	24	Insufficient torque
1/8 Step	225.9	1.2	24	Optimal
1/16 Step	57.3	1.2	24	Low torque

E. PID Control Performance

The effectiveness of the PID controller was evaluated by comparing the system response before and after parameter tuning. Table VI shows that the initial parameters obtained from the Ziegler–Nichols method produce oscillatory behavior. After tuning, the optimized parameters (Kp=10, Ki=2, Kd=1) produce stable system performance with minimal overshoot and no oscillations. This confirms the effectiveness of PID tuning in improving control accuracy.

TABLE VI. PID TUNING RESULTS

No	Kp	Ki	Kd	System Response
1	13	6	9	Large overshoot, oscillation
2	13	9	5	Unstable
3	16	5	2	Aggressive response
7	12	5	3	Minor oscillation
8	11	3	6	Slow response

F. System Performance Evaluation

The overall system performance was evaluated through repeated experiments. The results in Table VII show that the system is capable of producing consistent hole spacing with an average error below 0.2 cm. Small variations are primarily due to sensor attenuation, ambient light interference, and electromagnetic noise. Despite these limitations, the system demonstrates improved precision and operational consistency compared to manual methods.

TABLE VII. HOLE SPACING CONSISTENCY RESULTS

Trial	Pulse Count	Expected Distance (cm)	Measured Distance (cm)	Error (cm)
1	7	43.96	43.80	0.16
2	7	43.96	44.10	0.14
3	7	43.96	43.70	0.26
4	7	43.96	44.00	0.04
5	7	43.96	43.90	0.06
6	7	43.96	44.20	0.24
7	7	43.96	43.85	0.11
8	7	43.96	44.05	0.09
9	7	43.96	43.95	0.01
10	7	43.96	44.10	0.14

IV. CONCLUSION

This study successfully designed and implemented an automated plastic mulch cutting and punching machine using a PID-based control system. The integration of a DC motor for mulch feeding, a stepper motor for the punching mechanism, and a photoelectric sensor for feedback enabled synchronous and automated operation. The PID controller significantly improved system performance by ensuring stable motor response and accurate stopping at the desired position. Optimized parameters (Kp=10, Ki=2, Kd=1) provided minimal overshoot, eliminated oscillations, and improved control stability compared to the initial Ziegler–Nichols setup. As a result, the system was able to produce a consistent hole spacing of approximately 43.96 cm with a low average error. Experimental results showed that the proposed system improved operational efficiency and consistency compared to manual processing methods. However, slight deviations were observed due to sensor noise and environmental interference, particularly affecting pulse detection accuracy.

Future work could improve the system by implementing signal filtering techniques to reduce sensor noise, implementing more sophisticated control strategies to increase robustness, and improving mechanical components to enhance system reliability under continuous operation.

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