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Advanced Pressure Regulation System for Agricultural Sprayers using Model Predictive Control

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Abstract- **Since Pakistan's economy is heavily dependent on agriculture, the country must prioritize the research and development of cutting-edge farming techniques that are both productive and environmentally friendly. In the scope of this study, the creation of an intelligent control algorithm for variable-rate agricultural sprayer robots that is based on Model Predictive Control (MPC) is the primary focus. More specifically, this algorithm is intended to regulate the goal pressure. Model Predictive Control (MPC) is like having a crystal ball for controlling systems. It's a method that allows for optimizing control actions by making predictions about how a system would behave in the future. In this research, an MPC-based intelligent control algorithm was created for variable-rate agricultural sprayer robots in order to regulate the goal pressure. The MPC algorithm was described after the modeling and simulation of the spraying system had been established in a MATLAB/Simulink environment. Using the Simulink Support Package for Arduino Hardware in MATLAB/Simulink, the MPC algorithm was implemented in real-time on an Arduino Mega 2560 controller board to verify the accuracy of the simulation results. In this study, MPC was compared to conventional PID control for regulating system pressure. Furthermore, MPC is a revolutionary approach to nonlinear system control that, in comparison to the results obtained with a PID controller, decreases chemical waste and lessens toxicological and environmental risk by achieving zero steady-state error, low transient response, and reduced peak overshoot. In summary, this research demonstrated that MPC is a powerful approach to nonlinear system control. It allows for predicting future behavior and optimizing control actions in real-time. By using this method to control the spraying of agricultural chemicals, this research was able to reduce the risk to the environment and human health, while increasing efficiency and reducing waste.**

***Index Terms*—Agricultural Sprayer, Simulink, PID Controller and Arduino Mega 2560.**

I. INTRODUCTION

Agriculture, being a cornerstone of human civilization, has always been driven by continuous advancements in technology. Precision agriculture, in particular, has emerged as a key factor in enhancing crop productivity while minimizing environmental impacts [1]. Among the various techniques employed in precision agriculture, the use of agricultural sprayers has proven to be highly effective for the targeted application of fertilizers, pesticides, and other crop treatment agents. However, achieving optimal performance in spray applications requires precise control of the sprayer's operating parameters, such as pressure, flow rate, and droplet size. This research paper presents an advanced pressure regulation system for agricultural sprayers using model predictive control (MPC), which promises to improve efficiency and accuracy in the spraying process [2]. Traditional pressure regulation systems in agricultural sprayers often rely on simple control schemes, such as proportional-integral-derivative (PID) controllers, which may not be able to accommodate complex dynamics, varying environmental conditions, and non-linearities inherent in the spraying process. These limitations could lead to suboptimal spray coverage, increased drift, and higher chemical usage, ultimately affecting both economic and environmental aspects of agricultural practices [3-4]. The price of crop protection products accounts for around half of the overall cost of producing food in agricultural land. More and more people are concerned that the use of these chemicals would have negative consequences for human health and the environment. Successful application methods that target individual plants while having minimal off-target effects are now a top priority. This concept, known as "precision agriculture," seeks to reduce expenses and facilitate tighter regulation of agrochemical application. Tools and techniques that allow for accurate control of spraying pressure, confirmation of appropriate droplet size, and restriction of drift are required for this. This study discusses the pressure shifts that occur during selective spraying when solenoid-valve nozzles are opened and closed. The goal is to maintain a constant pressure in the spraying system to prevent these shifts from occurring. Sprayers that maintain a constant pressure produce droplets of uniform size, reducing the likelihood of the sprayed substance spreading.

To overcome these challenges, this study proposes an advanced pressure regulation system based on model predictive control, a powerful control strategy that leverages mathematical models to predict and optimize the system's future behavior. MPC has been widely adopted in various industrial applications, and its application to agricultural sprayers presents an opportunity to address the limitations of conventional control methods [5].

The primary goal of this research is to develop an MPC-based pressure regulation system for agricultural sprayers that could dynamically adjust pressure based on real-time information, such as the sprayer's speed, nozzle type, and target application rate. This system aims to ensure optimal droplet size, coverage uniformity, and chemical efficacy, while minimizing spray drift and chemical waste. Moreover, the proposed approach takes into account the constraints and uncertainties associated with agricultural sprayers, making it well-suited for real-world implementation.

A. CONSTRAINS OF UNCONTROLLED SPRAYER MECHANISM.

The American corporation believed this technology was essential for optimal production and environmental protection. This method replaces extensive pesticide utilize with targeted sprays in difficulty spots. This method lowered pesticide consumption by 90% [6]. Agrochemicals are used worldwide to increase crop yields. Yet, the WHO reports that hand-spraying pesticides in fields exposes over a million individuals [7]. The disease is fought using three million metric tons of insecticides worldwide. Li et al [8].'s research shows that these herbicides kill weeds and insect pests that lower crop yields and quality. Pakistan can't export much of its Wealth because insect pests destroy 20–25% of its rice production (GDP). Insect infestations diminish rice yields by 37% [9]. Weeds and pesticides compete with crops for water and nutrients in fields. If weeds are not removed quickly, economic losses and produce quality would result. Pesticides make weed removal easy and cause minimal soil damage. Chemicals are vital to farming, and herbicides consume a large share of the sector's financial resources. Broadcast treatment eliminates all weeds by spraying the entire area with the same volume of liquid at the same rate. Yet, weeds grow in clumps rather than uniformly throughout fields. Large pesticide doses to kill weeds are ineffectual and detrimental to the environment. Low weed infestation in agricultural fields does not reduce crop productivity, according to several research. If herbicides are only applied in regions where weed density exceeds an economic threshold, a great number of herbicides could be saved and their costs reduced [11]. If herbicide is used selectively, this is conceivable. In weed-free areas, pesticide employ reduces crop yields and weed outbreaks. Spray misuse raises manufacturing costs and pollutes restricted areas, harming the environment. Traditional sprayers risk injury due to their proximity to the chemicals [12]. 40% of the world's crops may be impacted by uneven spraying. Improper application would lower agricultural productivity, which would jeopardize the economy due to the rising cost of agrochemicals and their dependence on them. As a result, research on an agricultural variable-rate sprayer is needed to reduce environmental damage and save money.

Agrochemical weed control reduces crop yields economically and environmentally. Sprayers apply agricultural insecticides. Self-propelled or tractor-mounted boom sprayers cover large regions. These sprayers break water into droplets using spray nozzles, pumps, and valves. Hydraulic pressure forces the substance through a small aperture, forming a blade before dissolving into droplets [10]. Even though pest damage varies across the territory, pesticide is usually sprayed at the same pace. Due to regional heterogeneity, a variable rate application is needed to account for the different degrees of establishment of introduced plant, fungal, and animal species. Because the phenomenon is spatially heterogeneous. Agrochemicals at various concentrations could fight various infestation levels. Prescription maps list application rate reference values. The computer manages application flow by considering application rates, sprayer expulsion speeds, boom valve number and distance [11]. The fluidic impedance, or flow-to-pressure ratio, influences the maximum useful range of land surface sprayer vehicles in specific situations (single nozzles). Hence, pesticide spray droplet size is critical. The sprayer boom size and thickness depend on the tip type and operating pressure, according to the American Society of Agricultural and Biological Engineers [12]. Wind's ability to spread tiny droplets pollutes drift. While having less drift, thick droplets are less effective at treating the intended region due to the leaves' size limits on water delivery. Modern agriculture's sprayer booms move at different speeds, which might cause application issues (under- or over-spraying the crop). Sprayers should include flow regulation systems for each spray nozzle to prevent mishaps. USC researchers Giles and Comino invented and patented PWM solenoid valves [13]. These devices often have switching frequency above 10 hertz (1992). The solenoid valve's microfluidic resistance, controlled by the PWM signal's duty ratio, allows flow and pressure to be independently managed. Precision agriculture relies on variable rate spray technology since the 1980s. Valuable technology. This strategy considers weeds' irregular geographical distribution and utilizes only the necessary herbicide. Herbicides are usually evenly distributed. Instead, this method uniformly applies the herbicide. Weed data is needed to maximize variable rate spraying. Variable-rate sprayers detect weeds and pests and adjust pressure and flow, two of its most significant roles. Variable rate spraying could be performed in real time using sensors or based on a map, according on weed information. Variable herbicide nozzles are designed for PWM, direct injection, and variable system pressure [14]. Much study has been performed to regulate flow and pressure in a variable-rate sprayer, where each nozzle is actuated separately and a consistent volume of chemical is sprayed in response to weed information, which wastes chemical. Despite manually setting pressure before spraying, pressure changes might cause drift. The planned research would activate each nozzle separately based on spray needs and vehicle speed, adjusting pump rotational speed in real time to modify pressure. The research objectives for the advanced pressure regulation system for agricultural sprayers using model predictive control are:

- To design and develop a pressure regulation system for agricultural sprayers using model predictive control.
- To evaluate the performance of the pressure regulation system in terms of precision, accuracy, and efficiency compared to traditional sprayers.
- To investigate the impact of the pressure regulation system on herbicide application effectiveness and environmental contamination.
- To optimize the control strategy of the pressure regulation system using mathematical models to minimize herbicide application while maintaining crop yield.
- To assess the economic feasibility of the pressure regulation system in terms of production costs and herbicide application savings.
- To provide practical recommendations for the implementation of the pressure regulation system in precision agriculture practices.

The remainder of this paper is organized as follows: Section 2 provides a comprehensive review of the related literature, highlighting the current state of the art in pressure regulation systems for agricultural sprayers and the application of model predictive control in agriculture. Section 3 presents the methodology, including the development of the mathematical model, the MPC algorithm, and the system architecture. Section 4 discusses the results obtained from simulations and experimental validation, demonstrating the efficacy and robustness of the proposed approach. Finally, Section 5 concludes the paper and outlines future research directions.

II. LITERATURE REVIEW

In developing countries like Pakistan, farmers utilize uncontrolled spray methods to control weeds and pests. The severity of the sickness, canopy size variation, and plant population are unknown to these farmers. Agrochemicals applied in areas without vegetation or crop pose an environmental risk and waste expensive agrochemicals [15]. Because to their proximity to the toxins, farmers using traditional sprays may also be at risk. Traditional sprayers are inefficient and inconvenient for spraying current crops like cotton, rice, and sugarcane because of their multiple growth stages. Inaccuracies in spraying could cause 40% crop loss. A poor application would diminish crop production, which, along with the rising cost of agrochemicals and farmers' reliance on them to boost productivity, constitutes an economic risk. Ground-based crop protection spray devices have shown limited field adaption and poor operating results in recent years. This is mostly due to geography and crop development. This is why aerial farming is becoming popular in many countries. Yet, using too much pesticide may increase farming costs and harm the ecosystem. Droplet deposition and pesticide application in precision agricultural aircraft are the focus of global research. In the ongoing attempt to reduce pesticide use, adaptive and variable rate spraying is a promising research strategy [16]. Hence, an agricultural variable-rate sprayer is necessary. This sprayer should be able to adjust spray intensity to field circumstances, decreasing waste, saving money, and conserving the environment.

A. AGRICULTURAL SPRAYER

In the agriculture industry, sprayers such as the 12-volt weed sprayer and the pesticide sprayer are indispensable tools. These sprayers serve several functions in farming.

a) LOW- & HIGH-PRESSURE SPRAYER

Low-pressure sprayers maintain nozzle pressure. These sprayers could be hitched to tractors, trailers, or roof racks. Considering the size of the vehicle and the area to be covered, choose a low-pressure sprayer with an adequate liter capacity. These sprayers work better than hand-held ones and could be employed on large farms. Convenient, but expensive to buy and maintain. The equipment could easily spray through dense undergrowth and towering trees due to its high pressure. Compared to low-pressure sprayers, this one is more expensive and difficult. It could relieve pressures up to 1,000 pounds per square inch. It's great for spraying all kinds of orchards, especially those with tall, thick trees. Compared to a low-pressure sprayer, it is harder to use and more expensive.

b) MIST BLOWER, AIR CARRIER, & HAND OPERATED SPRAYER

Foggers and mist blowers distribute liquid insecticides. Insecticides are spread throughout the environment without sprayers.

A fogger evaporates liquid from a tank using an electric motor. This device is prevalent in greenhouses and other places where pesticides are used on various crops. Foggers are less efficient in windy conditions, so farmers must take extra steps to keep herbicide from escaping. High-speed air distributes insecticides at 80 to 150 mph in this pest management technology, which goes by several names. Mist blowers and air-carrier sprayers are examples. Air-carrier sprayers utilize potent pesticides due to evaporation. This makes filling the tank with water faster.

Hand-held pesticide sprayers allow for more precise dosing. Turning it on produces high-pressure air from the nozzle because it has its own air pump. Hand-operated sprayers aren't good for mass distribution because you have to wait for pressure to build up before spraying again. It is the cheapest sprayer on the market, making it ideal for farms. Agriculture frequently uses aerial and ground spraying. Sprayers apply herbicides, fungicides, insecticides, and fertilizers. Agricultural sprayers have booms with regularly distributed nozzles.

B. VRA SPRAYER WITH REAL-TIME SENSORS

Pest spraying in nurseries and orchards yields more and better fruit. Despite these advances, conventional sprayers fail because they apply the same quantity of chemicals to the field regardless of crops, canopy structure, or leaf foliage density. Uniform application rates may not be optimal because crop canopies vary in size and shape. Agriculture often over- or under-sprays crops, causing ecological issues and pest management issues [12]. Farmers, environmentalists, and the public are pressuring lawmakers to reduce chemical runoff. Precision farmers utilize less pesticides by spraying only where needed at the right volume. Knowing a crop's geometry helps apply insecticides correctly. Using this technology with cutting-edge real-time sensors improves agricultural spray processes [16].

C. PWM SPRAYER

Spraying crops with pesticides should employ the minimum quantity possible to protect people and the environment. Pesticide application tactics may help achieve these goals. Electronic controls are used in these methods. Modern pulse-width modulation (PWM) sprayers utilize precise electrical technologies [21] to reliably achieve flow rates, pressure, and droplet sizes. One technique uses an automatic boom with nozzle controls, effective overlap, and a turnable flow rate across the boom. To avoid overlap, electrical impulses are timed differently for each boom nozzle. Electronically triggered solenoid valves pulse regularly to control pressure and flow (typically 10 Hz). Each solenoid's open time affects flow rate (duty cycle). PWM SVNs reduce the detrimental effects of other rate controllers and maintain spraying pressure regardless of flow rate. Hence, spraying pressure is constant. Variable-rate flow control systems that utilize application pressure may affect droplet size and nozzle performance. PWM studies have shown that duty cycle barely affects spray droplet size. PWM sprayers allow pesticide applicators to adjust flow rate by up to 10:1 without pressure or nozzle variations [22]. This makes PWM sprayers versatile. Boom sprayers employ nozzles with wider orifice diameters (bigger droplet sizes) and lower carrier quantities, but PWM maintains spray integrity [23]. Droplet velocity decreased with duty cycle in PWM studies. In vertically oriented plant canopies like maize, this could raise drift prospects and decrease canopy penetration. For a particular flow rate, duty cycle affects droplet deceleration more than application pressure. Increase the nozzle aperture size and shorten the duty cycle to increase droplet velocities and spray kinetic energy without affecting pressure. PWM sprayers created spray kinetic energy that was steadier and less duty cycle-dependent than pressure-based changes [24]. With equal flow rates, PWM sprayers are better than pressure-based adjustments. PWM sprayers reduce drift, improve canopy penetration, and impaction. Researchers used a camera and artificial neural network [25] to identify cultivated plants from weeds. Imaging processing estimated weed coverage and dispersion, and fuzzy control determined the herbicide spray volume. Image control determined herbicide spray volume. Herbicide coverage should be 80–90%, according to experiments. Wen et al. developed a variable-rate spray system for UAVs using PID and PWM [6]. Studies show that employing the PID control method to adjust pump power to manage flow rate speeds up the system's return to steady state following disturbances. The flow rate regulation approach showed this. The technique does not address bug or illness-related flow rate decreases. Liu et al PWM's solenoid valve-based electronic flow control technology allowed individual nozzle regulation [26]. His technique involves a laser sensor to recognize rows of trees and active nozzles to spray a steady volume of agrochemicals. When active nozzles were changed at different duty cycles, pressure varied. If the pressure is altered, the spray pattern and droplet size would change, increasing the chance that unintended areas would be sprayed. Silva et al. [27] found a substantial pressure variation when all forty nozzles were operating, and the duty cycle was 60–100%. Butts et al. study how duty cycle, gauge application pressure, and venturi nozzle technology effect pressure and droplet size distribution at the nozzle tip [28]. When the duty cycle decreased by 1%, the droplet size increased by 0.48um at a pre-defined pressure gauge. The reverse pattern was also observed. Spray drift is boosted by high-duty cycle droplets. After experiments at a 20% duty cycle showed spray pattern and droplet size inconsistencies, the researchers concluded that the ideal duty cycle for a PWM sprayer is greater than 40%. Huang et al. [29] utilize MATLAB fuzzy control and a microcontroller to regulate flow automatically. In reaction time, overshoot, and steady state settling, the combination outperforms a standard PID controller. Zhu et al. derive a non-linear regression equation between source pump voltage and pressure change [30]. They employ a constant-frequency pulse width modulator (TL494). Pressure and the pump's input voltage are non-linear, yet flow and duty cycle are linear. Deng et al. [31] individually adjust flow and pressure using two methods. A closed-loop PID control signal adjusts the speed of an AC-rotational motor to maintain pressure. Although a programmable logic controller (PLC) sends a pulse width modulation (PWM) signal to change flow rate, spray pattern and distribution must be considered. PID close-loop control was faster and more accurate in maintaining constant pressure regardless of flow rate than open-loop control. After dozens of flow rate-varying trials, this conclusion was established. The researchers found that increasing the pressure to 0.3Mpa enhanced the spray angle substantially. When numerous nozzles are operational, the spray angle and pattern would never vary by more than 0.87 degrees. Gonzalez et al. [32] modify pressure to improve spray droplet size in response to ground speed and an ultrasonic sensor instead of flow. Bypass valves return access pressure to the tank. A non-linear PI (Proportional and Integral) controller created the proportional valve control signal, and the pole-zero cancellation approach modified the PI parameters. This technology's biggest limitation is that flow rate and spray pressure cannot be effectively managed together due to the square root relationship. Fu et al. [16] designed a boom sprayer online inspection auxiliary anti-drift device to improve spray penetration. The spray per unit area is calculated theoretically, then tested at various vehicle speeds. The setup reduced mean error to 5–6%, according to the findings. Nevertheless, natural wind combines with extra wind-curtain air flow to increase spray penetration to unintended locations, making this approach unsuitable for row crops. Wang et al fuzzy-controlled's vision-based adaptive variable-rate sprayer [4] sprayed rice. The suggested crop naturally has gaps between rows. Thus, a fuzzy algorithm and vision system were used to turn off nozzles in vacant areas. To fix the issue. While pressure affects covering area more, PWM value decreases droplet fluctuation coefficient. Tewari and colleagues used image processing in a variable-rate sprayer to control paddy crop diseases [33]. Variable spraying uses 34% less chemical than continual spraying. The vehicle's speed affects the flow rate since the control decides the trigger signal while it's driving. Fu et al. [34] developed a vehicle speed-based automatic flow control and auxiliary anti-drift system. Pesticide utilizes increased from 26.76 percent to 37.98 percent, but timely feedback reduced it by 12 percent.

III. METHODOLOGY

This study recommends a robot system with a sprayer and a 40-litre chemical tank. The device could barely handle three gallons per minute (GPM). The sprayer's boom could spray ground and air crops (orchard). Five solenoid values could move along the 9-foot boom. Solenoid valves regulate stirring speed. Brass nozzles with 0.3 GPM flow rates and cone angles from 43 to 120 degrees applied herbicides and insecticides post-emergence. The controller employs flow and pressure sensors to make judgments and fine-tune settings. To maintain 20 psi, a 12V, 2A solenoid valve controls fluid flow. Agricultural pesticides are best dispensed with a DC electric pressure diaphragm pump that could reach 80 psi and 1.6 gallons per minute. We could lower the pump's rated power (its electric rated parameters are 12V, 8A, and it could be adjusted by a pwm voltage signal) to increase flow and pressure. The motor driver BTS7960 could supply 43A to a diaphragm pump's DC motor with a changeable rated voltage. The Arduino controller uses sensor data to control flow and pressure. One 12V 72Ah battery powers the entire spraying gear (rechargeable battery). This study managed pressure separately to optimize spraying despite pressure and flow being connected. This increased canopy spray dispersion and droplet size. Pressure sensors are more precise than flow sensors for the same price. The biggest problem is that a membrane pump pulses flow and pressure constantly. Noisy pressure signals result. The pressure-controlled unit's Simulink circuit design featured a moving average filter to fix the problem. To find a solution, Precision agriculture spraying is shown in Figure 1. while the agricultural sprayer spraying system, architecture is given in Figure 2. The spraying architecture shows how every electronic, mechanical, and fluidic component works.

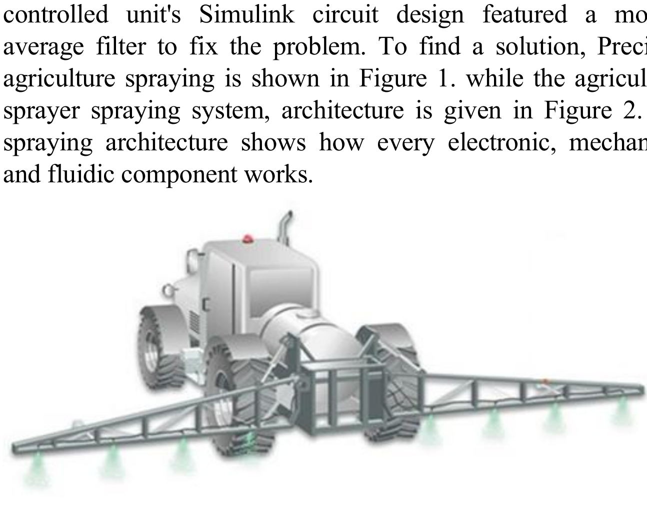

FIGURE 1: Agricultural Sprayer

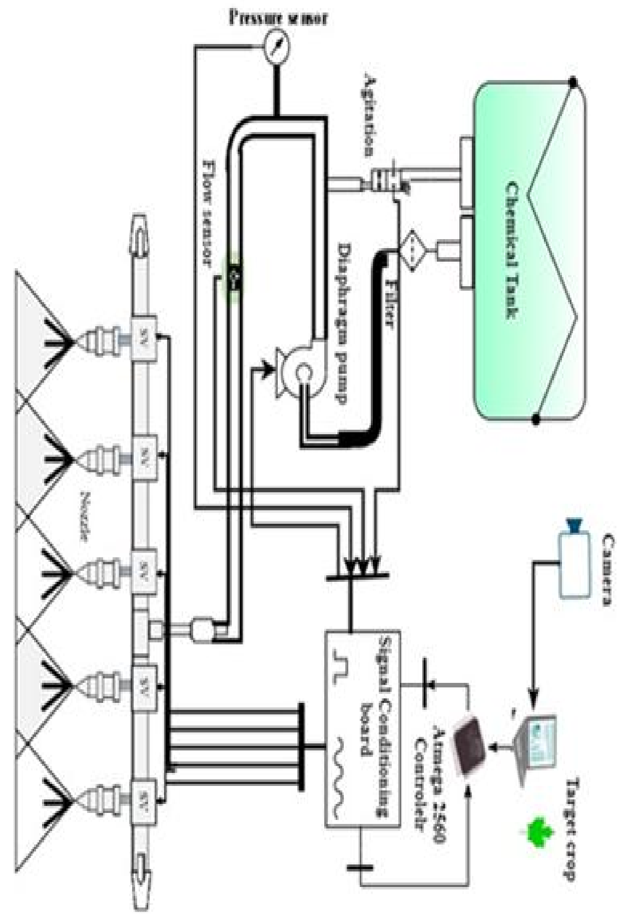

FIGURE 2 Agricultural Sprayer Spraying System Architecture

A. IDENTIFYING THE SPRAYING SYSTEM'S DYNAMIC MODEL & SYSTEM

Black box modelling—also termed experimental modelling—uses process data to create models. Empirical modeling considers data quality, model complexity, linearity, and generalizability. Integrated moving average squares, time series modeling, neural network modeling, fuzzy modeling, and neuro-fuzzy modeling are empirical or "black box" methodologies. The analytical model accurately described critical functional behavior because it was based on chemical, physical, and process dynamics. The process's input-output structure also determines black-box models' behavior. Black-box models aren't transparent because they're tested. Scientific experiments often employ "experimental models" as examples. Black-box models could be classified by their non-linearity, complexity, and structural technique for system dynamics. System identification involves creating mathematical models of dynamic systems from input and output signals. Time- or frequency-domain measurements of input and output signals are needed to accurately identify the system. Choose a suitable model framework. Estimation model configurable parameters should be dependable. Validating the anticipated model ensures it meets goals. The user-friendly, iterative computer simulation MATLAB System Identification toolkit has been published in [35], [36], and [37].

This simulation determines which model best estimates and validates a system. This analysis used Sprayer data to build a model. This article utilizes MATLAB's system identification toolkit to build a discrete-time state-space model to approximate system dynamics. MATLAB's system identification toolset estimates a second-order discrete-time state-space model of the system's dynamics using experimental data. Figure 3 and equations 1 and 2 show the data sampling process. As seen in Dynamic Systems and Models, our spraying system's input variable is the pulse width modulation (PWM) to the pump, and the output variable is the system's pressure (psi). The following vectors of observed values are collected at 10 Hz:

$$U=[\ u(1)\ ,u(2)....u(N)] \quad (1)$$

$$Y=[\ y(1)\ ,y(2)....y(N)] \quad (2)$$

The equation depicts the relationship between the duty cycle of the applied voltage (PWM Signal), represented by 'U', the system pressure at each sample, denoted by 'Y', and the total number of measurements, symbolized by 'N'. The model's stability is depicted in Figure 4, where, if the gain margin is less than one and the phase margin doesn't cross the 180° phase shift, the open loop system is deemed stable. Figure. 3 showcases the output response with an impressive 88.64% estimation accuracy, achieved through fitting the data.

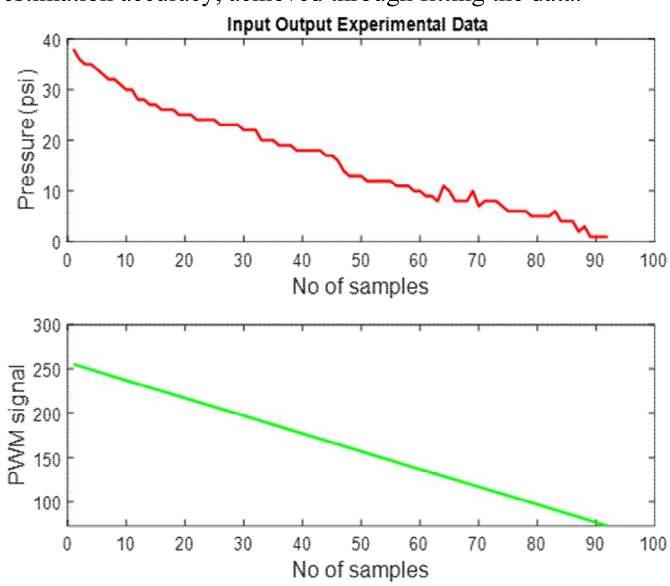

Figure 3: Input/output data for Pressure and PWM

The MPC operates with a pulse, functioning in discrete time intervals. To capture this, a state space model with a tiny 0.02-second sampling time was precisely estimated using the power of the MATLAB system identification toolkit, with: $x(k+1) = Ax(k) + Bu(k) + ke(k)$ and $x(k) = Cx(k) + Du(k)$.

where:

$$A = \begin{bmatrix} 0.6946 & 0.6946 \\ 0.356 & -0.2384 \end{bmatrix}, B = \begin{bmatrix} 0.4181 \\ -0.7868 \end{bmatrix}$$

$$C = [4.327 \quad -3.924]\ , \quad D = [0],\ \&$$

$$B = \begin{bmatrix} -0.05989 \\ -0.0235 \end{bmatrix}$$

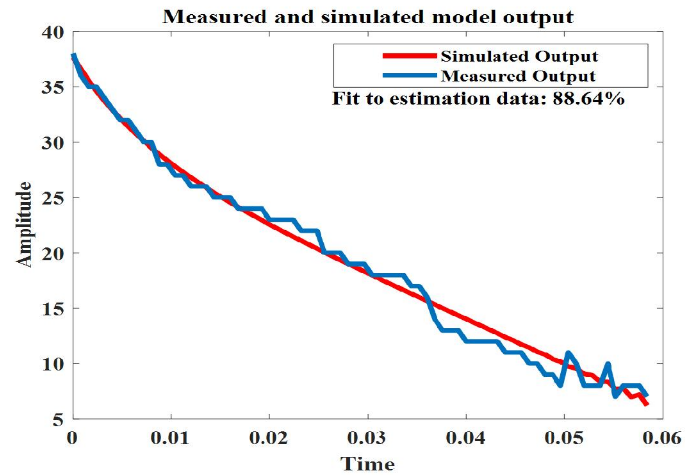

FIGURE 4: Output Response of the Model

Figure 5 shows the Bode plot of the system.

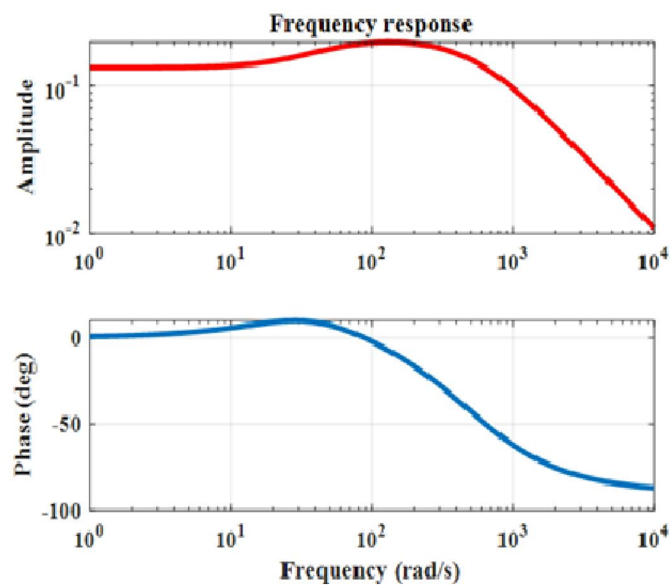

FIGURE 5: Frequency/Bode Plot

B. PID CONTROLLER SYSTEM DESIGN:

Due to the complexity of the feedback rules, their application is not always straightforward. Because fluid control systems tend to be slow, it's important to have a good method for controlling and monitoring the process. The PID control method is widely used in the control engineering industry. In order to offer effective control, it has been demonstrated that a basic P feedback controller must be supplemented with an integral (I) and a derivative (D) controller. The formula for a typical PID controller is shown in equation 3:

$$u_{Paid}\ (t) = k_p e(t) + k_i \int_0^t e(t)dt + K d\dot{e}\ (t) \quad (3)$$

In the realm of control systems, the enchanting trio of Kp, Ki, and Kd emerge as the positive definite masters of proportional, integral, and derivative gains. These elements gracefully dance together, orchestrating the performance of a PID controller. The e(t) signal, a poignant manifestation of discrepancy, embodies the error signal and is birthed from the divergence between the reference and feedback pressure. Venturing into the intricate labyrinth of PID controller optimization, the quest for the perfect values of these parameters proves to be a formidable challenge. However, fear not, for the sagacious Ziegler-Nichols method arises as a guiding beacon, illuminating the path to tuning the PID settings with precision and finesse.

Designing Using Model Predictive Controls*:* In essence, the prowess of Model Predictive Control (MPC) lies in its ability to anticipate the future output of a system by harnessing the power of past input and output data. By doing so, it meticulously calculates the optimal control signal from the present moment, extending to a predetermined future time, taking into account the horizon. MPC's remarkable adaptability in managing constraints and disturbances has catapulted it into the limelight as one of the most prevalent controller designs. Boasting its inherent versatility, MPC is readily adjustable and adept at handling multiple factors concurrently. It projects the forthcoming output y(k+1) by relying on the present control action u(k) and the historical memory y(k). At every time step, MPC extracts its control input from the first element of the open-loop optimal sequence, which is derived from the resolution of a finite horizon optimal control problem. The corresponding open-loop response of MPC is illustrated in Figur*e.* The plant's explicit state-space model is formulated as follows:

$$x_{k+1} = A_d x_k + B_d u_k \tag{4}$$

$$y_k = c_d x_k + d_d u_k \tag{5}$$

This equation is a representation of the integrator that is utilized to ensure that the output system follows the reference as i*/p.*

$$u_k = u_{k-1} x_k + \Delta u_k \tag{6}$$

In which case, equation (7), which represents the whole stat-space model in its enhanced form, and (8).

$$\begin{bmatrix} x_{k+1} \\ u_k \end{bmatrix} = \begin{bmatrix} A_d & B_d \\ 0 & l_m \end{bmatrix} \begin{bmatrix} x_k \\ u_{k-1} \end{bmatrix} + \begin{bmatrix} B_d \\ l_m \end{bmatrix} \Delta u_k \tag{7}$$

$$y_k = \begin{bmatrix} c_k & 0 \end{bmatrix} \begin{bmatrix} x_k \\ u_{k-1} \end{bmatrix} \tag{8}$$

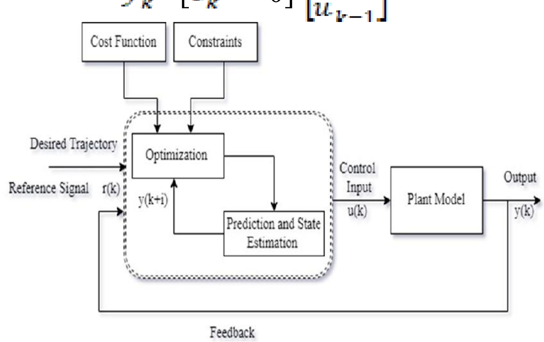

FIGURE 6: Model Predictive Control Block Diagram

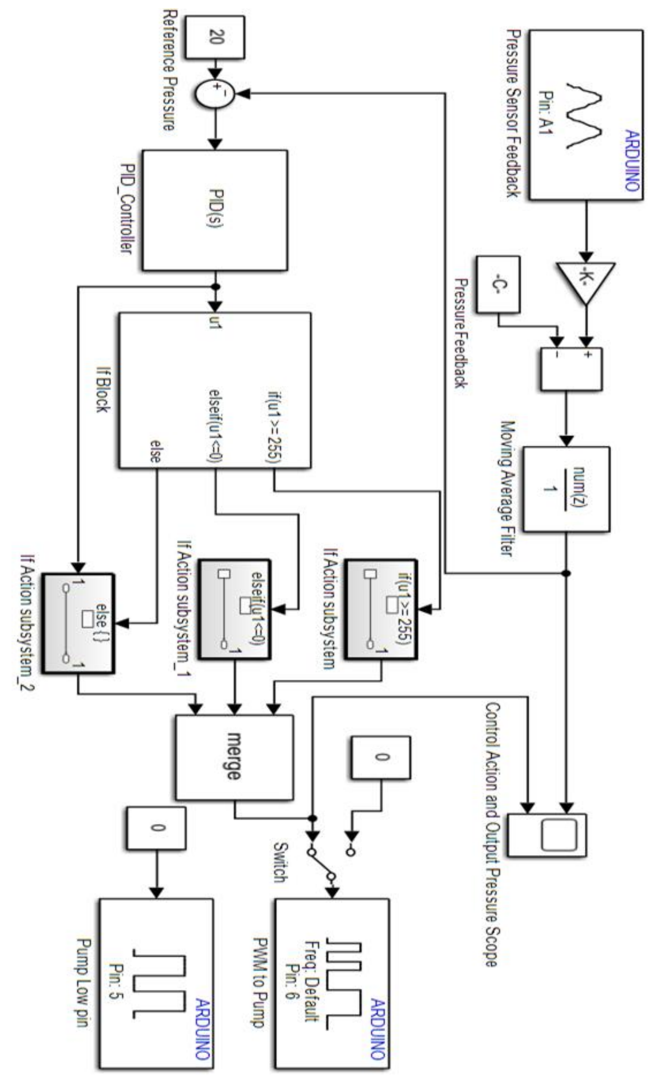

FIGURE 7: Schematic of PID Controller for Agricultural Robotic Sprayer

For the predictive control system to be successful, the output that it predicts must be as similar as feasible to the signal that is being used as a reference. This is commissioned at a certain sample time, ki, in relation to a specific reference signal, r, in order to reduce the error function that exists between the reference and the output that was anticipated (ki). After that, the "best" control parameter vector u is determined by employing the architecture that was produced as a result. The ultimate objective is to optimize the degree of accuracy.

$$j(k) = \sum_{i=1}^{N_p} (\hat{y} - r_{k+i})^T Q(\hat{y}_{k+i} - r) + \sum_{i=o}^{N_u - 1} (\Delta u^T{}_{k+i} R \Delta u_{k+i}) \tag{9}$$

In a realm where Nc and Np represent the mystical control and prediction horizons, r emerges as the coveted target value. Y, the anticipated outcome of the process, intertwines with u, the envisioned shift in control values, where u elegantly unveils itself as uk u(k1). Two magnificent matrices join this dance: Q(i), the Output Error Weight Matrix, and R(i), the Tuning Parameter/Control Weight Matrix. As the symphony unfolds, minimizing the objective function uncovers the hidden treasure

–the control signal. The accompanying parameters, like precious gems, glisten and gleam in the ensemble of Table I.

TABLE I
TUNING PARAMETERS FOR THE MPC OBJECTIVE FUNCTION

Parameter	Values
Np	10
Nc	2
Q(i)	0.5813
R(i)	0.172
Umin	0
Umax	255
Ymin	0
Ymax	Infinity
Δumin	-100
Δumax	100

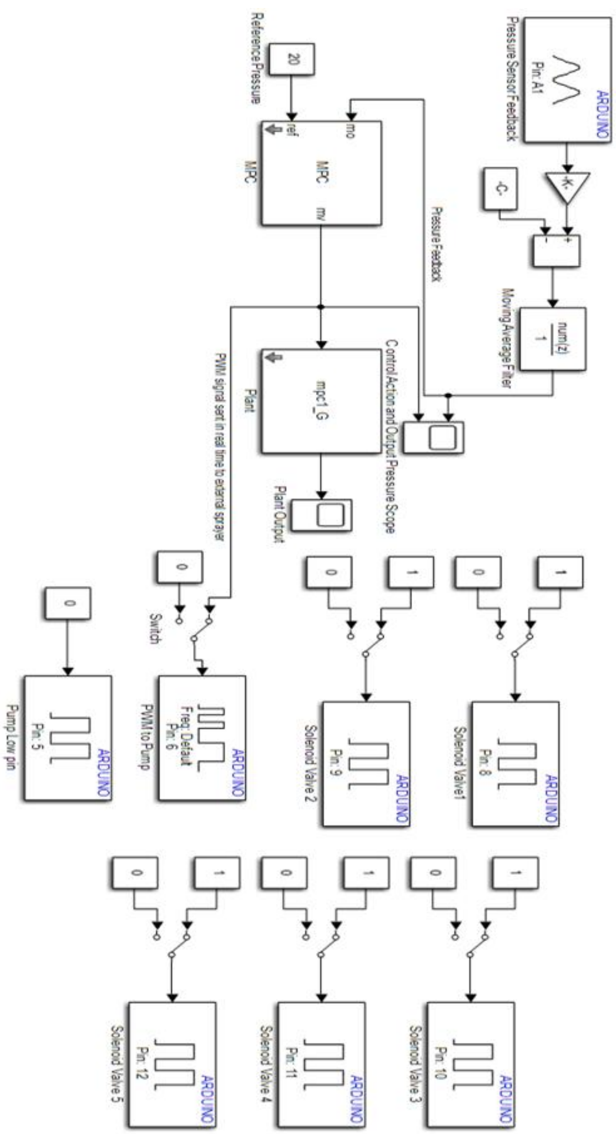

FIGURE 8: Simulink model predictive control integrated circuit Arduino mega 2560.

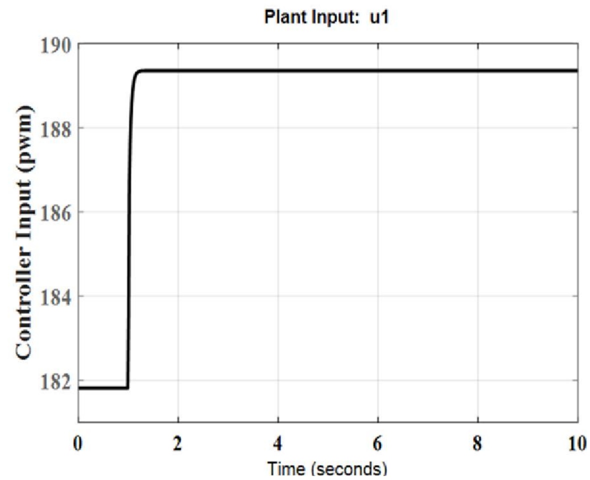

FIGURE 9: Controller input in PWM against Time

The objective function is minimized via optimization, and the state variables are estimated using a linear Kalman filter [12]. Figure 6 depicts the controller's input, and Figure 9 displays the matching output. The captivating realm of Model Predictive Control (MPC) beckons, and the journey unfolds in the mystic land of MATLAB Simulink. Here, every computation unravels in its full splendor, and the air pulsates with the rhythmic beats of the Arduino hardware support package, establishing a seamless communication channel between Simulink and the Atmel 2560 microcontroller, effectively controlling the pressure system. The analog sensor values, ranging from 0 to 1023, add to the excitement, and their transformation into pressure values from 0 psi to 80 psi creates an ethereal aura of enchantment. The formula that underpins this mystical transformation is $P = 0.087A - 0.867$, an alchemic spell that transcends the boundaries of the physical realm.

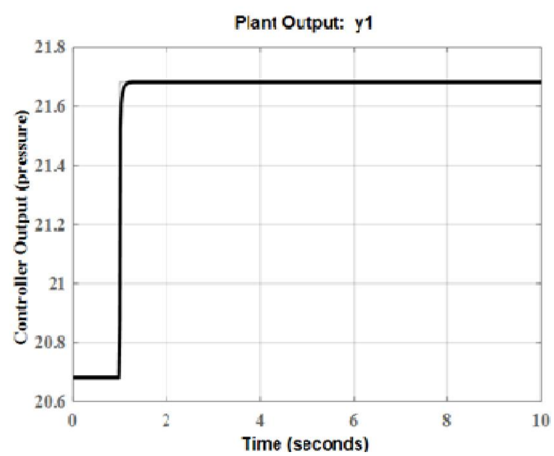

Figure 10: Controller output in PWM against Time

IV. EXPERIMENTATION & RESULTS

The results of an MPC simulation are depicted in Figure 10, where a pressure of 20 psi was used as the basis for the simulation. After the initial pressure has been brought under control and stabilized, the solenoid valves are cycled on and off at a rate of once every 3.5 seconds, which results in a disturbance pressure of 6 psi. The subsequent step, which occurs at the 6.5 second mark, is an increase in the output pressure from 20 to 26 psi. By modulating the control action u, the controller is able to maintain the output pressure within the expected horizon Np, as shown in the graph. This helps to confine the variations in the output pressure. By looking at Figure 11, we may determine that the results of the simulation and the real-time plant reaction are consistent with one another. The actual system needs a total of 0.65 seconds in order to reach the standard pressure of 20 psi. Following the deactivation of a solenoid valve, which causes a pressure spike of 6 psi, there is a period of 0.65 seconds during which there is no detectable peak, steady-state error, or oscillation in the pressure of the system.

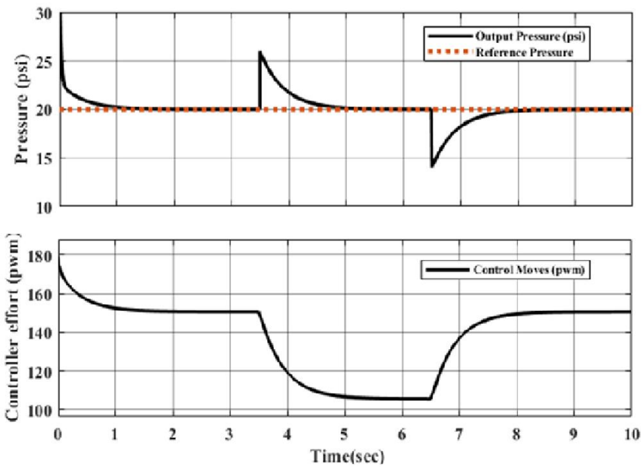

FIGURE 11: Simulation Result for Model Predictive Control

A comparison has been conducted between the newly developed Model Predictive Control (MPC) and the traditional Proportional-Integral-Derivative (PID) controller to assess their effectiveness in minimizing disturbances caused by the actuation of solenoid valves. The purpose of this comparison is to demonstrate the validity and efficiency of the MPC algorithm. Figure 12 illustrates the response of Model Predictive Control, while figure 13 illustrates the response of the PID controller, which reveals a buildup of pressure in the system when the solenoid valve is deactivated for 3.5 seconds. In an attempt to reduce system pressure, the controller works by decreasing the Pulse Width Modulation (PWM) signal, which subsequently lowers the pressure pump's voltage. On the other hand, the MPC controller showcases a rapid response time, minimal oscillation, and an absence of additional peaks, distinguishing itself from the PID controller's performance. Table II displays the parameters of Model Predictive controller and PID controller.

Table III presents the experimental pressure and flow data collected at a reference pressure of 20 psi by alternately activating and deactivating the solenoid valves. Although the control loop sustained a sampling rate of up to 10Hz, there was a 4-second time delay between the On and Off sequences of the solenoid valve numbers (SVNs). In an experimental environment, the responses of the MPC and PID controllers were evaluated and compared. A step reference pressure of 20 psi and various ON/OFF SVN sequences were employed as the disturbance signal.

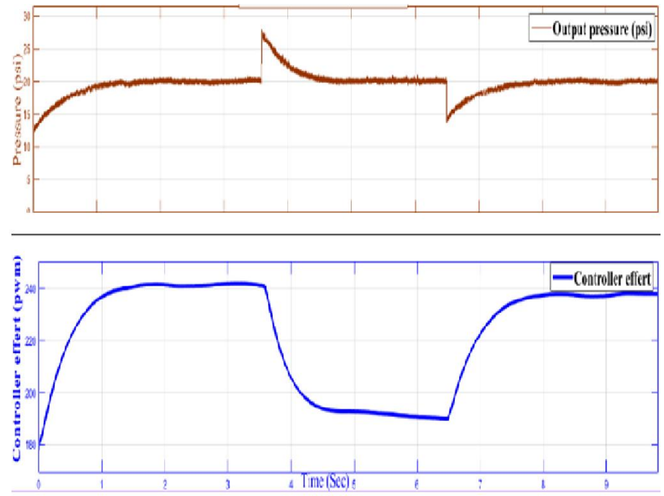

FIGURE 12: Controlling Pressure employing an Model Predictive Control in Real Time.

TABLE II
PERFORMANCE IN FLOW CONTROL BASED ON PRESSURE

Controller	Overshoot in Percentage	Rise time (Seconds)	Settling Time (Second)
Model Predictive Controller	0	0.8	1.2
Proportional Integral Derivative	0.4	0.2	1.5

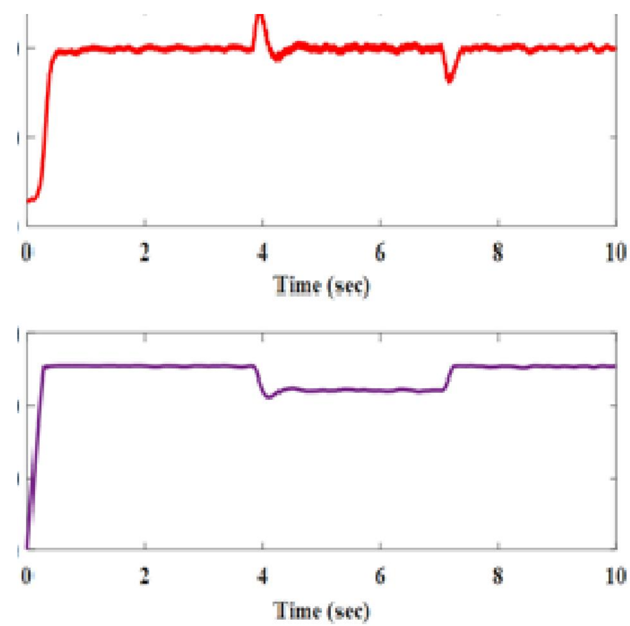

FIGURE 13: Controlling Pressure in Real Time with a PID Controller.

TABLE III
EFFECT OF PRESSURE ON FLOW

Active Nozzles	Active nozzles order					Pressure (psi)	Flow rate (L/m)
	n1	n2	n3	n4	n5		
1	0	1	0	1	0	20	1.983
2	1	1	0	0	1	20	3.015
3	0	1	1	1	1	20	3.216
4	1	1	1	1	1	20	4.542

Figure 14 depicts the results of a constant-angle test conducted after changing the number of active solenoid valve numbers.

Images capture the spray angle of a single nozzle while modifying the number of active solenoids (Nn=1, 2, 3, 4, 5). The nozzle spray angles remain consistent regardless of the value of n. This observation implies that, under a constant regulated pressure, the flow rate at each location remains unchanged, ensuring a uniform droplet size.

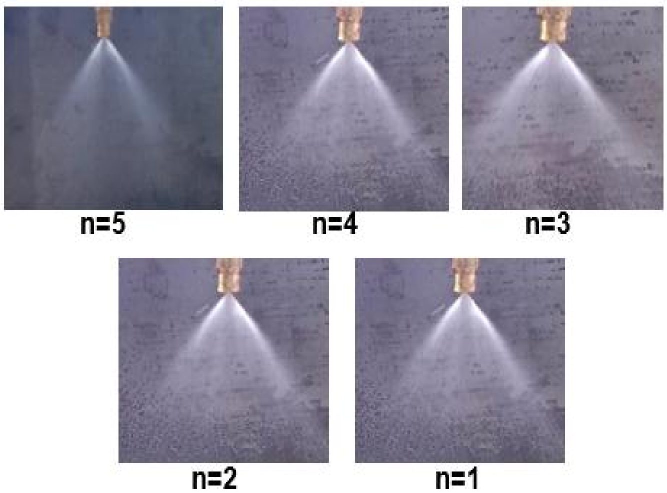

FIGURE 14: Pressure of 20 psi while testing at a constant angle

V. CONCLUSION & FUTURE WORK

The research findings that were presented in the research article proved that utilizing a different control approach in a sprayer that had a variable application rate led to more precise results. These findings were supplied to demonstrate that the research had been carried out. Even though the solenoid valves were cycled on and off in fast succession, it did not appear as though the spraying profile or droplet size were changed in any way. This study took precautions to ensure that the flow rate at each nozzle remained constant and that the pressure remained constant around an operational setpoint. An innovative control technique that is based on model predictive control is designed with the help of the empirical sprayer plant model in order to manage the required pressure level. Using the Arduino software package as a guide, the Arduino Mega 2560 is able to successfully implement the MPC scheme. The findings from the performance analysis were contrasted with the results of the simulation in order to highlight the benefits of the MPC strategy in comparison to the traditional PID control method. When compared to the PID, the MPC clearly has a considerably faster reaction time, which translates to less time spent in oscillation, settling, and overshoot. This could be visualized by comparing the MPC to the PID. A constant angle test was performed on each nozzle to ensure that the sprayer boom pressure and nozzle flow rates would remain consistent throughout the process. The total flow rate of the sprayer system adjusts itself according to the number of individual solenoid valves that are being used. In addition, it has been recommended that the flow rate in VRA should be regulated in reaction to the speed of the robot, while at the same time allowing the droplet size to stay the same. As a consequence of this, you would have the ability to spray your crops at the appropriate height.

REFERENCES

[1] B. S. Faiçal et al., “An adaptive approach for UAV-based pesticide spraying in dynamic environments,” Comput. Electron. Agric., vol. 138, pp. 210–223, 2017, doi: 10.1016/j.compag.2017.04.011.

[2] L. Wang et al., “Vision-based adaptive variable rate spraying approach for unmanned aerial vehicles,” Int. J. Agric. Biol. Eng., vol. 12, no. 3, pp. 18–26, 2019, doi: 10.25165/j.ijabe.20191203.4358.

[3] S. Wen, Q. Zhang, X. Yin, Y. Lan, J. Zhang, and Y. Ge, “Design of plant protection uav variable spray system based on neural networks,” Sensors (Switzerland), vol. 19, no. 5, 2019, doi: 10.3390/s19051112.

[4] G. Wang et al., “Field evaluation of spray drift and environmental impact using an agricultural unmanned aerial vehicle (UAV) sprayer,” Sci. Total Environ., vol. 737, p. 139793, 2020, doi: 10.1016/j.scitotenv.2020.139793.

[5] S. Hussain et al., “Spray uniformity testing of unmanned aerial spraying system for precise agro-chemical applications,” Pakistan J. Agric. Sci., vol. 56, no. 4, pp. 897–903, 2019, doi: 10.21162/PAKJAS/19.8594.

[6] P. Braekman, D. Foque, W. Messens, M. C. van Labeke, J. G. Pieters, and D. Nuyttens, “Effect of spray application technique on spray deposition in greenhouse strawberries and tomatoes,” Pest Manag. Sci., vol. 66, no. 2, pp. 203–212, 2010, doi: 10.1002/ps.1858.

[7] T. R. Butts, L. E. Butts, J. D. Luck, B. K. Fritz, W. C. Hoffmann, and G. R. Kruger, “Droplet size and nozzle tip pressure from a pulse-width modulation sprayer,” Biosyst. Eng., vol. 178, pp. 52–69, 2019, doi: 10.1016/j.biosystemseng.2018.11.004.

[8] Z. Zhang, X. Wang, Q. Lai, and Z. Zhang, “Review of Variable-Rate Sprayer Applications Based on Real- Time Sensor Technologies,” Autom. Agric. - Secur. Food Supplies Futur. Gener., 2018, doi: 10.5772/intechopen.73622.

[9] F. Solanelles, A. Escolà, S. Planas, J. R. Rosell, F. Camp, and F. Gràcia, “An Electronic Control System for Pesticide Application Proportional to the Canopy Width of Tree Crops,” Biosyst. Eng., vol. 95, no. 4, pp. 473–481, 2006, doi: 10.1016/j.biosystemseng.2006.08.004.

[10] R. Berenstein, O. Ben Shahar, A. Shapiro, and Y. Edan, “Grape clusters and foliage detection algorithms for autonomous selective vineyard sprayer,” Intell. Serv. Robot., vol. 3, no. 4, pp. 233–243, 2010, doi: 10.1007/s11370-010-0078-z.

[11] H. V. Mercaldi, E. A. G. Peñaloza, R. A. Mariano, V. A. Oliveira, and P. E. Cruvinel, “Flow and Pressure Regulation for Agricultural Sprayers Using Solenoid Valves,” IFAC-PapersOnLine, vol. 50, no. 1, pp. 6607–6612, 2017, doi: 10.1016/j.ifacol.2017.08.693.

[12] S. Wen, Q. Zhang, J. Deng, Y. Lan, X. Yin, and J. Shan, “Design and experiment of a variable spray system for unmanned aerial vehicles based on PID and PWM control,” Appl. Sci., vol. 8, no. 12, 2018, doi: 10.3390/app8122482.

[13] J. Fu, C. Chen, R. Zhao, and L. Ren, “Accurate Variable Control System for Boom Sprayer Based on Auxiliary Antidrift System,” J. Sensors, vol. 2020, pp. 1–8, Jan. 2020, doi: 10.1155/2020/8037046.

[14] T. R. Butts, L. E. Butts, J. D. Luck, B. K. Fritz, W. C. Hoffmann, and G. R. Kruger, “ScienceDirect Droplet size and nozzle tip pressure from a pulse-width modulation sprayer,” Biosyst. Eng., vol. 178, pp. 52–69, 2018, doi: 10.1016/j.biosystemseng.2018.11.004.

[15] H. Zhu et al., “Development of a PWM Precision Spraying Controller for Unmanned Aerial Vehicles,” J. Bionic Eng., vol. 7, no. 3, pp. 276–283, 2010, doi: 10.1016/S1672-6529(10)60251-X.

[16] R. Gonzalez, A. Pawlowski, C. Rodriguez, J. L. Guzman, and J. Sanchez-Hermosilla, “Diseño e implementación de un sistema de control automático para un pulverizador móvil para aplicaciones,” Spanish J. Agric. Res., vol. 10, no. 4, pp. 939–949, Nov. 2012, doi: 10.5424/sjar/2012104-2797.

[17] J. Fu, C. Chen, R. Zhao, and L. Ren, “Accurate Variable Control System for Boom Sprayer Based on Auxiliary Antidrift System,” vol. 2020, 2020.

[18] L. Valousek and R. Jalovecky, “Use of the MATLAB® System Identification Toolbox® for the creation of specialized software for parameters identification,” in 2021 8th International Conference on Military Technologies, ICMT 2021 - Proceedings, Jun. 2021, vol. 27, no. 1, pp. 1–5, doi: 10.1109/ICMT52455.2021.9502786.

[19] M. J. Rabbani, K. Hussain, A.-R. Khan, and A. Ali, “Model Identification and Validation for a Heating System using MATLAB System Identification Toolbox,” IOP Conf. Ser. Mater. Sci. Eng., vol. 51, p. 012022, Dec. 2013, doi: 10.1088/1757-899X/51/1/012022.

[20] R. Gonzalez, A. Pawlowski, C. Rodriguez, J. L. Guzman, and J. Sanchez-Hermosilla, “Design and implementation of an automatic pressure-control

system for a mobile sprayer for greenhouse applications," Spanish J. Agric. Res., vol. 10, no. 4, p. 939, 2012, doi: 10.5424/sjar/2012104-2797.

[21] K. Burn, L. Maerte, and C. Cox, "A Matlab Toolbox for Teaching Modern System Identification Methods for Industrial Process Control," Int. J. Mech. Eng. Educ., vol. 38, no. 4, pp. 352–364, Oct. 2010, doi: 10.7227/IJMEE.38.4.7.

[22] V. K. Tewari, C. M. Pareek, G. Lal, L. K. Dhruw, and N. Singh, "Arti fi cial Intelligence in Agriculture Image processing based real-time variable-rate chemical spraying system for disease control in paddy crop," Artif. Intell. Agric., vol. 4, pp. 21–30, 2020, doi: 10.1016/j.aiia.2020.01.002.

[23] W. Deng, C. Zhao, L. Chen, and X. Wang, "proportion integration differentiation regulation co m m er us e on er al," vol. XLVII, 2016, doi: 10.4081/jae.2016.512.

[24] J. Huang, Y. Zhang, X. Su, and S. Tian, "Research of Variable Application Control System Based on Fuzzy Control," vol. 01013, pp. 10–12, 2018.

[25] J. E. Silva, H. Zhu, and J. P. A. R. Cunha, "Spray outputs from a variable-rate sprayer manipulated with PWM solenoid valves."

[26] F. P. Terra, G. H. d. Nascimento, G. A. Duarte, and P. L. J. Drews-Jr, "Autonomous Agricultural Sprayer using Machine Vision and Nozzle Control," J. Intell. Robot. Syst. Theory Appl., vol. 102, no. 2, 2021, doi: 10.1007/s10846-021-01361-x.

[27] W. Deng, C. Zhao, L. Chen, and X. Wang, "Constant pressure control for variable-rate spray using closed-loop proportion integration differentiation regulation," J. Agric. Eng., vol. 47, no. 3, pp. 148–156, 2016, doi: 10.4081/jae.2016.512.

[28] A. Sharda, T. Griffin, L. Haag, D. Mangus, J. Fulton, and J. Slocombe, "Pulse Width Modulated (PWM) Technology for Liquid Application," no. Figure 2, 2016.

[29] K. Von Bargen, G. E. Meyer, D. A. Mortensen, S. J. Merritt, and D. M. Woebbecke, "<title>Red/near-infrared reflectance sensor system for detecting plants</title>," Opt. Agric. For., vol. 1836, no. May 1993, pp. 231–238, 1993, doi: 10.1117/12.144032.

[30] P. J. Walklate, J. V. Cross, G. M. Richardson, R. A. Murray, and D. E. Baker, "Comparison of different spray volume deposition models using LIDAR measurements of apple orchards," Biosyst. Eng., vol. 82, no. 3, pp. 253–267, 2002, doi: 10.1006/bioe.2002.0082.

[31] D. K. Giles and J. A. Comino, "Droplet size and spray pattern characteristics of an electronic flow controller for spray nozzles," J. Agric. Eng. Res., vol. 47, no. C, pp. 249–267, 1990, doi: 10.1016/0021-8634(90)80045-V.

[32] K. L. Hughes and A. R. Frost, "A review of agricultural spray metering," J. Agric. Eng. Res., vol. 32, no. 3, pp. 197–207, Oct. 1985, doi: 10.1016/0021-8634(85)90080-0.

[33] Z. Khan et al., "Prevalence of insect pests on maize crop in District Mansehra, Khyber Pakhtunkhwa, Pakistan," Brazilian J. Biol., vol. 84, pp. 1–7, 2024, doi: 10.1590/1519-6984.259217.

[34] C. Michael, E. Gil, M. Gallart, and M. C. Stavrinides, "Influence of Spray Technology and Application Rate on Leaf Deposit and Ground Losses in Mountain Viticulture," Agriculture, vol. 10, no. 12, p. 615, Dec. 2020, doi: 10.3390/agriculture10120615.

[35] A. Alengebawy, S. T. Abdelkhalek, S. R. Qureshi, and M. Q. Wang, "Heavy metals and pesticides toxicity in agricultural soil and plants: Ecological risks and human health implications," Toxics, vol. 9, no. 3, pp. 1–34, 2021, doi: 10.3390/toxics9030042.

[36] A. McBratney, B. Whelan, T. Ancev, and J. Bouma, "Future directions of precision agriculture," Precis. Agric., vol. 6, no. 1, pp. 7–23, 2005, doi: 10.1007/s11119-005-0681-8.

[37] P. Singh et al., "Hyperspectral remote sensing in precision agriculture: Present status, challenges, and future trends," Hyperspectral Remote Sens. Theory Appl., vol. 10, pp. 121–146, 2020, doi: 10.1016/B978-0-08-102894-0.00009-7.