DEVELOPMENT OF THE PLUG TRAY SEEDING SYSTEMVIA PNEUMATIC SERVO CONTROL

HAO-TING LIN

Department of Bio-Industrial Mechatronics Engineering, National Chung Hsing University, 145 Xingda Rd., South Dist., Taichung City 402, Taiwan
E-mail: haotlin@nchu.edu.tw

Abstract - This paper aims to develop the plug tray seeding system via pneumatic servo control. In the mechanism design, a rod-less pneumatic cylinder is selected as the actuator, equipped with a plug conveying platform combined with a needle seeding mechanism, and a soil perforating mechanism. The plug tray seeding system is designed by SOLIDWORKS. Mathematical models of the pneumatic servo system are established. The functional approximation method with sliding mode control is used to control the plug tray seeding system for pneumatic trajectory servo control. The real-time pneumatic control system is through MATLAB/SIMULINK to achieve automatic precise seeding for the soil cultivation. This study will offer a novel option for seedling operations contributing to the advancement of agricultural carbon reduction.

Keywords - Pneumatic Servo System, Plug Tray Seeding System, Trajectory Tracking Control.

I. INTRODUCTION

Recently, seeding industries play critical roles for transplanting plants in the field with well growths and high qualities such as seedling uniformities, low wastes of seeds and water, and high survival rates. A commonly used method for seedling is plug tray seeding.Seeds are placed in the cells of plug trays to culture. Traditionally, plug tray seeding had labor-intensive processes, involving manual seeding and transplanting. However, with the advancement of technology and automation in agriculture, automatic plug tray seeding machineshave been common in recent years.

Pneumatic actuators can be utilized to control the movement and positioning of the seeding mechanism, ensuring accurate and precise seeding in the cells of the plug tray. Pneumatic systems can also be used for the conveyor system that transports the plug trays, as well as for providing vacuum to the seeding mechanism. Several advantages can be brought by the integration of pneumatic systems in plug tray seeders. Firstly, pneumatic systems can reduce greenhouse gas emissions, thereby reducing reliance on fossil fuels. Secondly, pneumatic systems are known for their high efficiencies because they can convert electrical energy into compressed air with minimal energy loss to increase overall energy efficiencies in the seedling production process. Moreover, pneumatic systems are relatively clean and do not produce harmful emissions during seedling operations. Furthermore, integrations of pneumatic systems in plug tray seeders can also improve the overall performances and productivities of the seeding process. Fast and precise movement control can be provided by pneumatic actuators, allowing for accurate seeding, which can result in higher seedling qualities and uniformities. Recent studies have focused on automatic seeding machinessuch as precise seeding, monitoring systems, and automation through machine vision. In 2011, Xia et al. [1] proposed a new type of pneumatic plate-type vegetable seederdesigned with a detailed machine control system and pneumatic switch system based on kinematic simulation and analysis. The experimental results showed that singleseeding rates and missing seeding rates wereaffected by seeding speeds, suction hole diameters and relative pressures. In 2013, Sriwongras and Dostal [2] developed a plug tray seeder consisting a seed hopper, a seed dispenser, a seed release unit, a soil compression unit, and a depth control unit. Papaya seeds were tested by this seeder with a seeding rate of 79%, 7.88 times faster than manual seeding. In 2016, EL-Ghobashy et al. [3] developed a precision vacuum plug tray seeder and tested two types of plug trays, four vacuum pressures, and four suction hole diameters. In 2021, Xia et al. [4] used a row of fiber optic sensors to construct a photoelectric measurement system for the automatic pneumatic roller-type seeder. The evaluation of ten vegetable seed varieties showed that shapes of seeds can affect singleseeding rates and multi-seeding rates. In 2022, Zhang et al. [5] designed a precision seeder with an airblowing vibration to improve the problem of wholemachine vibration and reduced seeding rate caused by high-frequency and largeamplitude vibration of the seeder. The internal fluid motions in the seed supply tray were analyzed using FLUENT, and structure parameters of the supply tray were optimized. A mathematical regression models were established through orthogonal experiments to analyze the relationship between the intake pressure, vibration frequency, vibration amplitude, and seeding performance. In 2023, Yan et al. [6] proposed a machine vision-based tomato plug tray information perception method for detecting missing seeding and empty plug tray cells. Based on the YOLOv5x network model, positions of tomato seeds and coordinates of the edge of the hole were compared to detect missing seeding cells.The plug tray conveyor

and the seed suction needle were controlled to conduct row-by-row reseeding.

In 1998, Bobrow and McDonell [7] investigated the modeling and control of lightweight and inexpensive pneumatic robots, considering the nonlinear dynamic characteristics of pneumatic systems such as servo valve flow characteristics and thermodynamic properties of compressed air in cylinders. The experimental results showed that performances of the developed pneumatic actuators can be comparable to that of electric actuators, avoiding expensive cost of electric motors in controlling robots. In 2003, Zorlu et al. [8] focused on experimental modeling of pneumatic systems, recording piston position and chamber pressure data to create input-output data for model identification. In 2011, Meng et al. [9] developed a rod-less pneumatic cylinder controlled by a proportional directional valve, and studied the valve dynamics to describe the frictional force of cylinder seals. The proposed system model was verified by comparing the open-loop with step responses of experiments and simulations. In 2017, Danilishin et al. [10] proposed mathematical modeling, optimized pneumatic system configuration, operating mode, compressor unit optimization, and equipmentfor improving the efficiency of pneumatic systems. A multivariate mathematical model of the pneumatic system was established, which could be effectively applied to complex pneumatic systems. In 2019, Shi et al. [11] proposed a power evaluation and measurement method for pneumatic systems, analyzing power distribution in the pneumatic system. By analyzing the pneumatic efficiency of typical compressors and pneumatic components, the applicability of the proposed method was verified and the foundation for optimizing and energy-efficient design of pneumatic systems was laid. In 2021, Risma et al. [12] suggested that the simplicity and lower long-term cost of pneumatic systems make them a better choice for constructing agricultural robots. The pneumatic robotic arm for food sorting system was developed that can be used to detect and separate grapes from other agricultural products. In 2021, Navas et al. [13] studied the application of soft technology in the handling of delicate objects and developed a pneumatic soft gripper, which was experimentally verified for its adaptability to dual-arm robot systems used for precision agriculture tasks. In 2021, Wang et al. [14] proposed a new type of isobaric compressed air storage device by introducing compressed gas energy storage and nonlinear cam transformation mechanism. Mathematical models of typical pneumatic systems under different control modes were established, and parameter analysis was also conducted. This new type of isobaric compressed air storage device had good constant pressure characteristics and energy-saving performance. In 2023, Wei et al. [15] studied the application of pneumatic brake systems in vehicles, analyzed the dynamic performance of each component, including electrical, electromagnetic, mechanical, and fluid performance. The distributed model was proposed to describe the behavior of compressible gas in pipes and control strategies were designed. In 2023, Dhavalikar et al. [16] pointed out that the low cost of pneumatic actuators makes them more popular than electric and hydraulic actuators. However, the position of double-acting single-rod cylinders is difficult to predict and control because the forces on both sides are unequal. Therefore, estimating the response time and stopping accuracy is essential for achieving correct positioning.

II. DESIGN AND ESTABLISHMENT OF THE PLUG TRAY SEEDING SYSTEM VIA THE PNEUMATIC SYSTEM

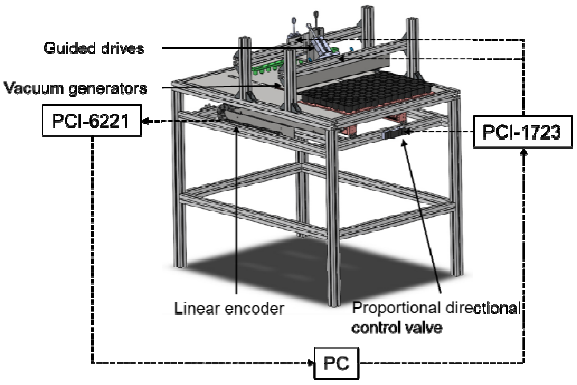


Figure 1: Layout of the plug tray seeding system via the pneumatic system.

A PC-Based environment is adopted in this study for real-time control, as shown in Figure 1. The control signals generated by MATLAB/SIMULINK are transmitted to the proportional directional control valve through the DAQ card (PCI-1723), driving the rod-less pneumatic cylinder. The displacement of the rod-less pneumatic cylinder is captured by the linear encoder and fed back to MATLAB/SIMULINK through the counter card (PCI-6221). The real-time error is obtained by comparing the reference trajectory. By designing the controller appropriately and continuously correcting the tracking error, the plug tray carrying platform can accurately reach the designated positions. MATLAB/SIMULINK is also used for real-time control of the soil drilling mechanism, seed suction mechanism, and needle seeding mechanism. Through coordination with the plug tray position, automatic precise seeding is achieved. The performance of the seeding system is evaluated by measuring the single-seeding, multi-seeding, and missed-seeding rates. Germination rate is also compared to ensure that the seeding system does not cause seed damage. To validate the performance of the controller, metrics such as root mean square error (RMSE) and the sum of input voltages will be used for objective evaluation. Detailed information regarding the plug tray seeding system via the pneumatic system is provided in Table

1. Overall, the hardware architecture and the control system in the PC-Based environment contribute to the successful establishment and operation of the plug tray seeding system via the pneumatic system.

Component	Specification
Rod-less pneumatic cylinder	Piston diameter: 18mm
	Stroke: 700mm
Auxiliary cylinder	Stroke: 700mm
Proportional directional control valve	Valve function: 5/3 way
	Input voltage: 0-10V
Guided drive	Piston diameter: 12mm
	Stroke: 50mm
Solenoid valve	Valve function: 5/2 way
Vacuum generator	Valve function: 2/2 way
Linear encoder	Range: 700mm
	Resolution: 1μm
DAQ card	16-bit, 8-ch analog output PCI card with 16-ch digital I/O
Counter card	4-ch 32-bit counter with 20MHz maximum source frequency
Needle	Inside diameter: 0.51mm
	Outside diameter: 0.82mm
	Length: 30mm
Plug tray	104 cells, 42mm for cell diameter

Table 1 - Specifications of the plug tray seeding system via thepneumatic system

The plug tray seeding system consists of a plug tray carrying platform, a soil drilling mechanism, a seed suction mechanism, a needle seeding mechanism, and a seed grove. Also, a rod-less pneumatic cylinder, an auxiliary cylinder, a proportional directional control valve, guided drivers, solenoid valves, vacuum generators, and a linear encoder are set up for the pneumatic servo control system. As a result,the plug tray seeding system with the pneumatic servo control system can combine to achieve automatic seeding process.Figure 2shows the plug tray seeding system via the pneumatic system.

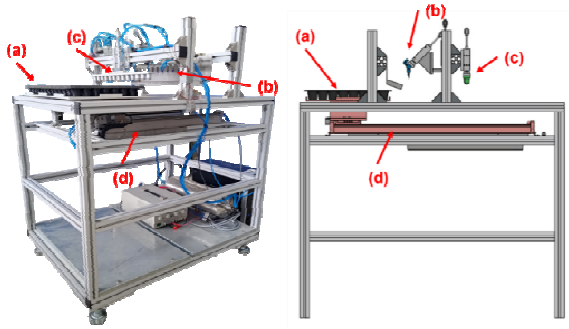


Figure 2: A diagram of the plug tray seeding system via the pneumatic system. (a) A plug tray and a plug tray carrying platform. (b) A needle seeding mechanism and a seed suction mechanism. (c) A soil drilling mechanism. (d) A rod-less pneumatic cylinder.

III. MATHEMATICAL MODEL AND CONTROLLER

To yield accurate mathematic models, this study firstly investigate rod-less pneumatic system mathematical models. The dynamics of a rod-less pneumatic system can be mainly divided into two parts: the pneumatic servo valve and the pneumatic cylinder. In the pneumatic servo valve, the opening area of the pneumatic valve orifice is controlled by input command signal. And air flow is affected through the pneumatic servo valve. As air flows into and out of the cylinder, pressure differences between pneumatic cylinder chambers will cause motions of the cylinder piston. We assume that the valve's dynamic behavior can be expressed using a zero order model as

$$A_o(t) = Ku(t) \quad (1)$$

where $A_o(t)$ is the open area of the pneumatic valve, K represents the open area-voltage gain, and u(t) is the control input of a pneumatic servo valve. Mass flow rate equations for pneumatic cylinder chambers can be written as follows

$$\dot{m}(t) = \frac{C_d C_0 A_0(t) P_u(t) \tilde{f}\left(\frac{P_d(t)}{P_u(t)}\right)}{\sqrt{T_u}} \quad (2)$$

$$\hat{f}\left(P_a(t), P_s(t), P_e(t)\right) = \begin{cases} \frac{P_s(t)\tilde{f}\left(\frac{P_a(t)}{P_s(t)}\right)}{\sqrt{T_s}} & \text{A is a driving chamber} \\ \frac{P_a(t)\tilde{f}\left(\frac{P_e(t)}{P_a(t)}\right)}{\sqrt{T_a}} & \text{B is a driving chamber} \end{cases} \quad (3)$$

$$\hat{f}\left(P_b(t), P_s(t), P_e(t)\right) = \begin{cases} \frac{P_s(t)\tilde{f}\left(\frac{P_b(t)}{P_s(t)}\right)}{\sqrt{T_s}} & \text{B is a driving chamber} \\ \frac{P_b(t)\tilde{f}\left(\frac{P_e(t)}{P_b(t)}\right)}{\sqrt{T_b}} & \text{A is a driving chamber} \end{cases} \quad (4)$$

where $\dot{m}(t)$ is mass flow rate, $C_d = 0.8$ is the displacement coefficient, C_0 is the flow rate parameter, $P_u(t)$ is up-stream pressure, $P_d(t)$ is down-stream pressure, $P_S(t) = 6 \times 10^5$ Pa is supplied pressure, $P_e(t) = 1 \times 10^5$ Pa is external pressure, $P_a(t)$ and $P_b(t)$ are chamber pressures. Assuming no temperature dependency, $T_s = T_a = T_b = 293$ K are supplied air temperature and temperatures of chambers A and B.

Assuming an adiabatic process, fluid continuity equations are shown as

$$\dot{m}_a(t) = \frac{\dot{P}_a(t)V_a(t)}{kRT_s} + \frac{\dot{V}_a(t)P_a(t)}{RT_s} \quad (5)$$

$$\dot{m}_b(t) = \frac{\dot{P}_b(t)V_b(t)}{kRT_s} + \frac{\dot{V}_b(t)P_b(t)}{RT_s} \quad (6)$$

where $\dot{m}_a(t)$ and $\dot{m}_b(t)$ are mass flow rate of chambers A and B, k=1.4 is the thermal constant, R= 287 J/(kg·K) is the ideal gas constant, $V_a(t)$ and $V_b(t)$ are chamber volumes A and B. Applying Newton's second law of motion to rod-less pneumatic cylinder's mass, we get

$$\left(AP_a(t) - AP_b(t)\right)\mathrm{sgn}\left(x(t)\right) - K_f\dot{x}(t) - K_c\left(x(t)\right)S\left(\dot{x}(t), P_a(t), P_b(t)\right) - Mg = M\ddot{x}(t) \quad (7)$$

where K_f is the coefficient of viscosity, and K_c is the Coulomb's friction coefficient. M is the mass of the rod-less pneumatic cylinder piston (kg).

From Eq. (1)-Eq. (7), the mathematical model of the rod-less pneumatic system can be expressed as a fourth-order model basically including the pneumatic servo valve system and the pneumatic actuator system. Its equation is expressed as follows:

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \\ \dot{x}_3(t) \\ \dot{x}_4(t) \end{bmatrix} = \begin{bmatrix} x_2(t) \\ \frac{(Ax_3(t) - Ax_4(t))\mathrm{sgn}(x_1(t)) - K_f x_2(t) - K_c(x_1(t))S(x_2(t), x_3(t), x_4(t))}{M} \\ \frac{-kx_2(t)x_3(t)}{x_1(t)+\Delta} + \frac{kRTC_dC_0wu(t)\hat{f}(x_3(t), P_S(t), P_e(t))}{A(x_1(t)+\Delta)} \\ \frac{kx_2(t)x_4(t)}{l-x_1(t)-\Delta} + \frac{kRTC_dC_0wu(t)\hat{f}(x_4(t), P_S(t), P_e(t))}{A(l-x_1(t)-\Delta)} \end{bmatrix} \quad (8)$$

Δ is an equivalent extra length to the cylinder, l is the total travel distance of the rod-less pneumatic cylinder. Additionally, x_1 is the amount of rod-less pneumatic cylinder piston movement, x_2 is the rod-less pneumatic cylinder piston movement speed, x_3 is the pressure of rod-less pneumatic cylinder Chamber A, x_4 is the pressure of rod-less pneumatic cylinder Chamber B.

To allow the plug tray seeding system via the pneumatic system to control locations and trajectories, $u(t)$ is control input adopted the adaptive sliding mode in function approximation to solve problems of nonlinearity, time change, and external interferences used in pneumatic systems.

$$u(t) = \frac{-\widehat{W}_F^T q_F(t) - \sum_{n=1}^{2} a_n e^{(n)} - p_{21}e - p_{22}\dot{e} + y_m^{(3)}(t) - \frac{s}{2\rho^2}}{\widehat{W}_g^T q_g(t)} \quad (9)$$

where $\widehat{W}_F^T$ and $\widehat{W}_g^T$ are the estimates, $q_F(t)$ and $q_g(t)$ are the orthogonal functions, e is the output error, s is the sliding surface, and ρ is the natural number. $y_m(t)$ is a given bounded reference objective, p_{2i} is elements.

IV. EXPERIMENT RESULTS AND DISCUSSIONS

This section presents the experimental results of trajectory tracking using the functional approximation method with sliding mode control for the plug tray seeding system. Figure 3 illustratesthe seeding trajectory for the plug tray seeding system.

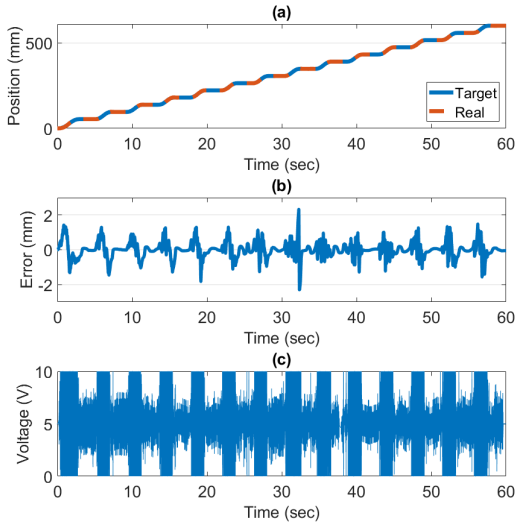


Figure 3: The experimental results of a seeding trajectory. (a) Trajectories of target and simulation. (b) Tracking errors. (c) Control signals.

To validate whether the seeding process using theplug tray seeding system affects seed growth, germination rates experiments were conducted.The experiments were performed using five different Brassicaceae crop seeds and the plug trays were placed in a good environment for cultivation. The plug trays were watered twice a day with 5 mL of water per cell. After six days, the germination rates were manually calculated. Table 2 displays the germination rate results, with three repetitions performed under the same conditions to calculate the average values. The experimental results demonstrate that the germination rates of all crop seeds exceeded 80%, surpassing the nominal germination rates. The germination rates achieved through theplug tray seeding system were comparable to those obtained through manual seeding, indicating that theplug tray seeding system does not adversely affect seed growth. These results confirm the effectiveness of theplug tray seeding system in achieving high germination

rates and provide evidence that theplug tray seeding systemis capable of supporting healthy seed growth.

Type of seed	Seeding rate(%)	Germination rate (%)
Brassica rapa subsp. pekinensis	96.79	94.23
Brassica rapa subsp. chinensis	99.36	83.01
Brassica parachinensis	98.08	95.83
Brassica oleracea var. botrytis	97.12	87.18
Brassica oleracea var. capitata	99.04	91.35

Table 2 - Experiment results of germination rate

V. CONCLUSION

In this study, the plug tray seeding system via pneumatic servo controlwas developed for precise and efficient seeding in agricultural automation. The design and components of the plug tray seeding system via pneumatic servo control were introduced, mainly composed of rod-less pneumatic cylinder and servo system. The dynamic models of the pneumatic system were presented to provide the foundation for designing effective control strategies. The experiments demonstrated high singleseeding rates and low missing seeding rates forthe plug tray seeding system via pneumatic servo control. Also, the germination experiments showed well results. Overall, the plug tray seeding system via pneumatic servo control successfully developed and evaluated for precise seeding.

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