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Design and implementation of DC linear actuator and stepper motor for remote control of the driverless tractor robot

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ABSTRACT

This research was to propose the DC linear actuators and a stepper motor as mechanical drive systems such as brake pedal, clutch pedal, forward-reverse gearshift, gear position selection, tail-lifting system to lift the chemical tank, and the speed selection system of power take-off (PTO). The DC linear actuators were used instead of the muscles, arms, and legs of the human being. The stepper motor was used to control the steering direction of a driverless tractor robot. The control was based on the programmable logic controller and radio remote control for the driverless tractor robots. Both MATLAB/Simulink simulation and experimental results were the validation and satisfactorily achieved. The test results of the driverless tractor robot in spraying water on a football field were satisfactory steering response and rapid braking.

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1. INTRODUCTION

At present, rural people in Thailand flock to work in industrial estates and cities more and more. The fewer people who work in the agriculture area have labor shortages and low productivity due to a lack of agricultural technology. The government encourages the introduction of innovations, robots, and technology into the agricultural robot tractor [1]-[3] sector to increase productivity, reduce labor, and avoid contact with toxic substances from various chemicals. The current agriculture in Thailand will be a large farm, vegetable garden, and a large field.

Workers spraying chemicals are at risk of toxic chemicals. It also takes time and very high wages. A new agricultural robot platform has been designed and developed [4], [5] so that it can be used to replace the workforce. For example, farmers in the United States, China, Japan, Spain, and Germany where labor shortages and production costs continue to rise.

This research can be supervised by a remote area using a low-cost DC actuator instead of the muscles, arms, and legs of the human being to control a driverless tractor robot. The driverless robotic tractors to be deployed will benefit farmers to work more conveniently and reduce work time, especially if agricultural chemicals are sprayed [6], [7] that are harmful to health if without wearable equipment to prevent toxic chemicals from spraying.

DC linear actuators [8], [9] are devices designed to operate horizontally and in a straight line. It can work horizontally without having to go through other transmission systems such as chains, sprockets, or other mechanisms. The DC linear actuators can be applied in a variety of applications such as conveyor systems, robot slide doors, moving objects, replacing pneumatic and hydraulic cylinders, physical work on patient beds, and many others as it will be applied. The internal structure of the DC linear actuator for controlling the operation is a DC motor that receives DC electric power. There are two types of movement directions, moving in and moving out. The electronic circuitry is generally used to control the incoming and outgoing motion, and the electronic circuitry used to control this depends on the accuracy and speed of the linear actuator's movement and its features.

Stepper motors [9]-[11] are electric motors driven by a pulse. The internal structure is composed of magnetic poles on the stator made of steel ring plates. There will be protruding ribs that come together in layers. Each protruding tooth is wrapped in a coil. When a current passes through the coil, an electromagnetic field is created. A stepper motor is a type of DC electric motor that is used to control direction and position for precision applications such as in computer numerically controlled (CNC) systems [12] and conveyor belts.

In this paper, the mathematical models of DC linear actuators and stepper motors using the MATLAB/Simulink program are used to simulate the operation to confirm the application of these electric motors. It is a mechanical control device of a driverless tractor control system that can be remotely [13] controlled by a radio transceiver working with a programmable logic controller.

2. RESEARCH METHOD

This paper is to design and implement of DC motor to control driverless tractor robots by using radio control. The DC motor is divided into two types, first type is used DC linear actuator [14], [15] for position control of the mechanism of the tractor. The second type is used stepper motor to control the steering system of the tractor.

2.1. The basics of the DC linear actuator

The schematic diagram of a DC linear actuator is consisting of a DC motor, a ball screw, and two gears, as shown in Figure 1. The block diagram of the DC linear actuator is shown in Figure 2. Figure 2, the DC motor is used to drive a ball screw [16]. The armature inductance of the motor was very small and neglected. The mathematical model of the DC motor [17] and the mechanism ball screw are derived in the equation as follows:

$$K_t K_e \dot{\theta}_1 = -R_a \tau_e + K_t u \quad (1)$$

$$J_m \dot{\theta}_1 + B\dot{\theta}_1 + K\theta_1 = \tau_e + KRx \quad (2)$$

$$J_m \dot{\theta}_1 + B\dot{\theta}_1 + K\theta_1 = \tau_e + KRx \quad (3)$$

$$M\ddot{x} + D\dot{x} + Kx + F_L = \frac{FRN_1}{N_2}\theta_1 \quad (4)$$

$$R = \frac{L}{2\pi} \quad (5)$$

$$\theta_2 = \frac{N_1}{N_2}\theta_1 \quad (6)$$

where u is the input voltage command, τ_e is output torque of the motor, K_t is the torque constant, R_a is the armature resistance, K_e is the electromotive force constant, B is the viscous damping coefficient of the motor shaft, J_m is the inertia of the rotor, R is the conversion ratio of linear to rotational motion, K is the equivalent stiffness of the ball screw, x is the displacement of linear actuator, θ_1 and θ_2 are the rotational angles of gear 1 and gear 2 respectively, τ_2 are the driving torque of gear 2, D is the viscous damper coefficient of load, F_L is the load disturbance, M is the mass of load, N_1 and N_2 are the numbers of teeth of gear 1 and gear 2 respectively, v is the velocity of ball screw, and L is the ball screw lead.

The DC linear actuator is low speed and high torque for driving the mechanical load. The transfer function of velocity feed drive systems between the voltage input command $U(s)$, and velocity of the ball screw $V(s)$ is represented as [18].

$$\frac{V(s)}{U(s)} = \frac{n_0}{s^3 + d_2 s^2 + d_1 s + d_0} \quad (7)$$

with

$$v(t) = x(\dot{t}) \quad (8)$$

$$n_0 = \frac{K_t R K N_1}{R_m J M N_2} \tag{9}$$

$$d_2 = \frac{R_m B M N_2 + R_m J D N_2 + K_t K_e M N_2}{R_m J M N_2} \tag{10}$$

$$d_1 = \frac{R_m B D N_2 + R_m D K N_2 + K_t K_e D N_2 + R_m J K N_2}{R_m J M N_2} \tag{11}$$

$$d_0 = \frac{R_m K D N_1 + R_m K B N_2 + K_t K_e K N_2}{R_m J M N_2} \tag{12}$$

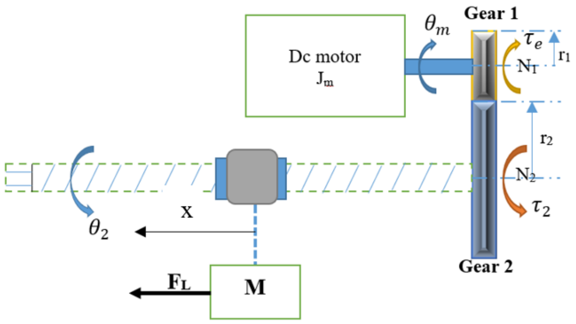


Figure 1. The schematic model of a dc linear actuator

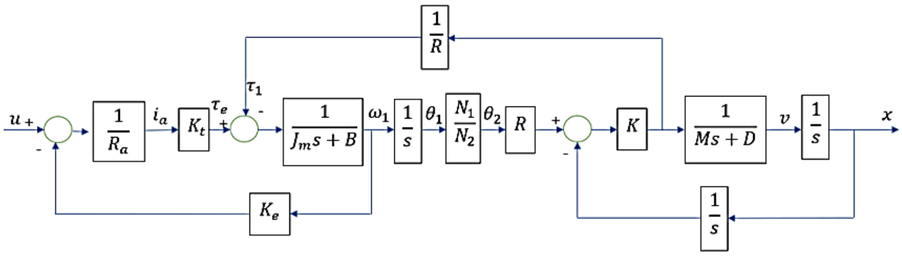


Figure 2. The block diagram of a DC linear actuator

2.2 Stepper motor of the steering system

The stepper motor is an electromechanical that converts the control signal from digital to analog output, enabling precise positioning control without signal feedback. It can operate in open-loop mode with no feedback part in position control. The mathematical models of the permanent magnet stepper motor are given in [19] as follows:

$$\frac{di_a}{dt} = \frac{u_a - R_a I_a + K_m \omega \sin(N\theta)}{L} \tag{13}$$

$$\frac{di_b}{dt} = \frac{u_b - R_b I_b + K_m \omega \cos(N\theta)}{L} \tag{14}$$

$$\frac{d\omega}{dt} = \frac{K_m I_b \cos(N\theta) - K_m I_a \sin(N\theta) - \beta\omega}{J_m} \tag{15}$$

$$\frac{d\theta}{dt} = \omega \tag{16}$$

where i_a, i_b and u_a, u_b are the currents and the voltages in phases A and B, respectively, I_a and I_b are the currents of winding A and B, respectively. ω is the angular velocity of the rotor, θ is the angular displacement of the shaft, R_a and L are the resistance and inductance of the phase windings, N is the of rotor teeth, K_m is the torque constant, J_m is the inertia of the rotor, and β is the viscous friction coefficient.

3. OVERVIEW OF THE PROPOSED SYSTEM

The system identification process is shown in Figure 3 as applied to the construction of the transfer function. The overall architecture of the system is proposed in Figure 3. The control system can be divided into two sides, the first side is the tractor robot side and the other side is the user side. The tractor robot side consists of the programmable logic controller. The converter 12 Vdc to 24 Vdc [20] is supply electrical voltage for a programmable logic controller. The programmable logic controller is responsible for controlling steering, brake pedal, clutch pedal, throttle engine speed, selecting of 1-2-3 gear position, reverser gear F-N-R position, lift the tail to lift the tank and spray equipment, and the power take-off (PTO). There are using a low-cost DC linear actuator instead of the muscles, arms, and legs of the human being to control a driverless tractor robot. The user side can select two modes of control by using the mode of a radio transmitter (FS-i6x) and radio receiver (FS-iA6B). The selecting channel of radio remote control such as the ch-1 control the robot to turn left and right direction, and the ch-2 is a controlled robot moving in a forward or backward direction. The steering control is controlled by a stepper motor. When the Arduino UNO receives a signal from the programmable logic controllers (PLC) as a counterclockwise or clockwise rotation command, the program will be processed to send the control signal to the DM542 control unit. To supply power to the stepper motor to run on command with position feedback with a limit switch.

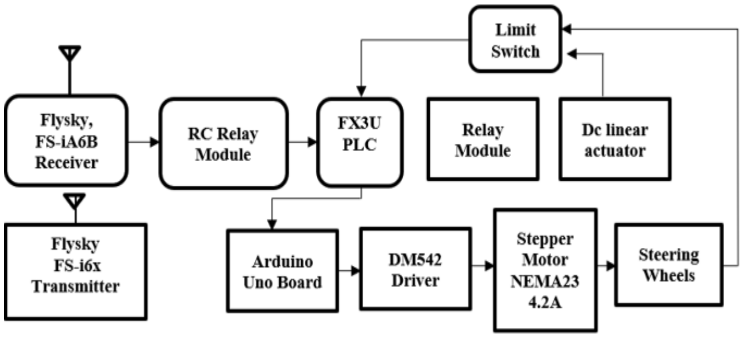


Figure 3. The block diagram of system architecture control

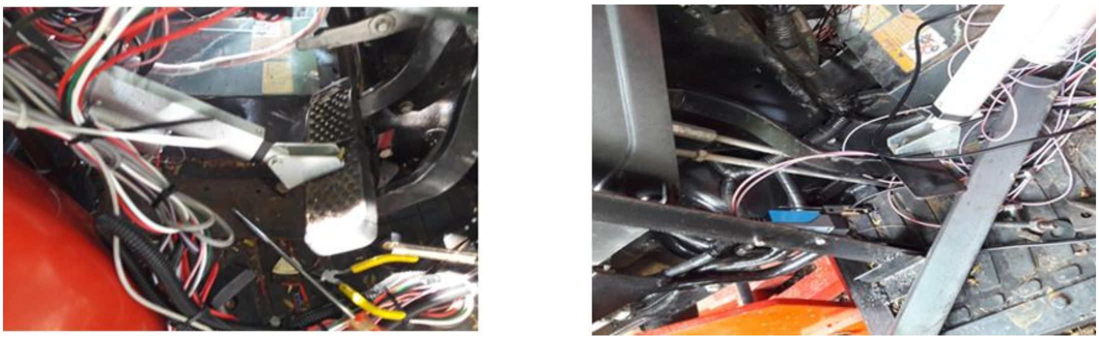
3.1. Installation hardware setup

Figure 4 shows the installation of the stepper motor to the steering of a tractor with worm gear ratio 8:1 coupling with a 24 mm socket wrench. The limit switch installations at the left and right of the core of the control wheels. Figure 5 shows the installed DC linear actuator for gear selecting the control and reverser gear with position sensors. Figure 6(a) shows the installation of the DC linear to the brake pedal, and Figure 6(b) shows the installation of the DC linear actuator for the clutch to pedal with the limit switch. Figure 6(a) shows the installation of the DC linear to the brake pedal, and Figure 6(b) shows the installation of the DC linear actuator for the clutch to pedal with the limit switch.

The mechanism control drive is used a programmable logic controller (FX3U-64MR) [21], [22] as shown in Figure 7(a). There is an input signal from various sensors, from a radio transmitter. The signal from the radio receiver [23] is connected to the RC relay unit that feeds the signal to the input of FX3U as shown in Figure 7(b).

Figure 4. Install of steering control by stepper motor drives with both of limit switch

Figure 5. Installing of DC linear actuator and sensors on gear selects



(a) (b)

Figure 6. Installing of DC linear actuator on (a) brake and (b) clutch pedal

(a) (b)

Figure 7. Installing of control part for (a) PLC FX3U and (b) FlyskyFS-i6x radio control and RC module

4. RESULTS AND DISCUSSION

4.1 Simulation results and descriptions of DC linear actuator

Based on the derived (1) to (12) Simulink model [24] of the Simscape library [25], [26] was built to solve the equation using the parameter values given in Table 1. Table 2 shows the specification of the DC linear actuator. The MATLAB/SIMULINK model block diagram on the Simscap library of dc linear actuator is shown in Figure 8. Running the system, by using parameters data in Table 1 and Table 2. The characteristic of the linear speed (lead screw) shows in Figure 9(a). The rotation speed shows in Figure 9(b). The motor current and worm gear speed are shown in Figure 9(c) and Figure 9(d), respectively. Figure 9(e) and Figure 9(f) are shown the motor torque and dc supply voltage, respectively.

As illustrated in Figure 9, the running of the simulation model based on the parameters in Table 1 and Table 2, the DC motor is assigned parameters to the equivalent circuit. The torsional friction was defined with a no-load speed of 30 mm/s. And achieve the simulation was the required value of 0.022 Nm. The maximum current is 3A and the maximum linear force is 750 N is confirmed.

Table 1. The parameters values of the simulation

Parameters	Notation	Value
Voltage input	u	12 V
Armature resistance	R_a	3 Ω
Viscous friction	D	1×10^{-8} Nm/rad/s
Inertia at the armature	J_m	0.00025 kgm^2
Motor back emf constant	K_e	0.0637 V/rpm
Motor torque constant	K_t	0.066 Nm/A
Screw lead	L	0.003 m/rev
Load Mass	M	75 kg
Screw Damping	C	0.0001 N/m/s
Screw stiffness	K	5×10^9 N/m

Table 2. Specification of DC linear actuator

Specification	Value	Unit
Weight	0.75	kg
Rating voltage	12	Vdc
Rating current	3	A
Thrust force (maximum)	750	N
Pulling force (maximum)	500	N
Speed	30	mm/sec
Duty cycle	25	%
Stroke	100	mm

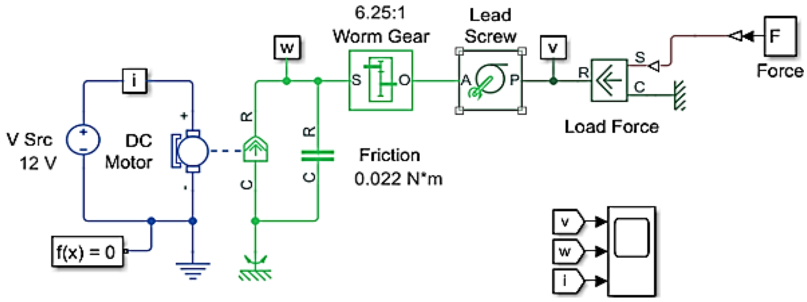
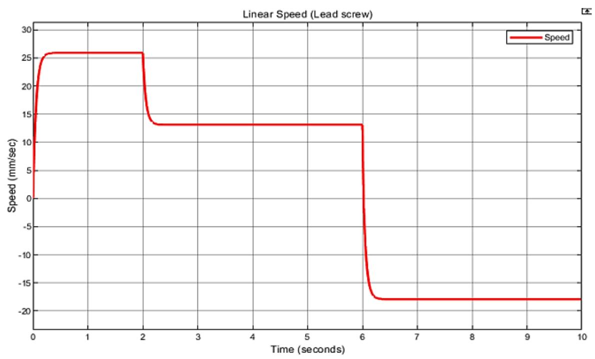
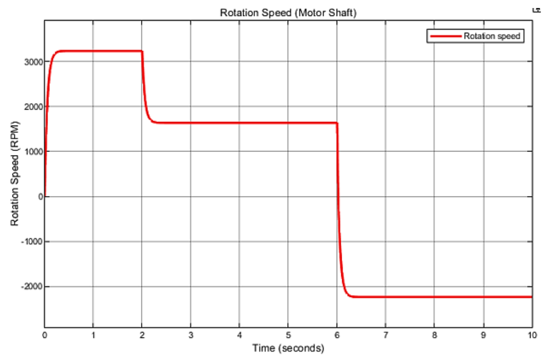


Figure 8. The MATLAB simulation circuit of the DC linear actuator control



(a)



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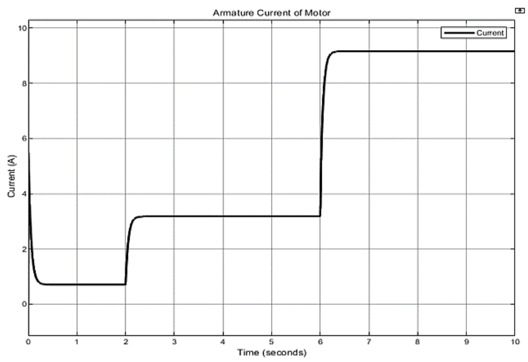
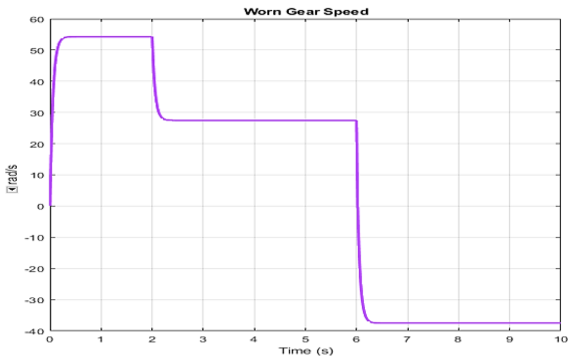


(c)



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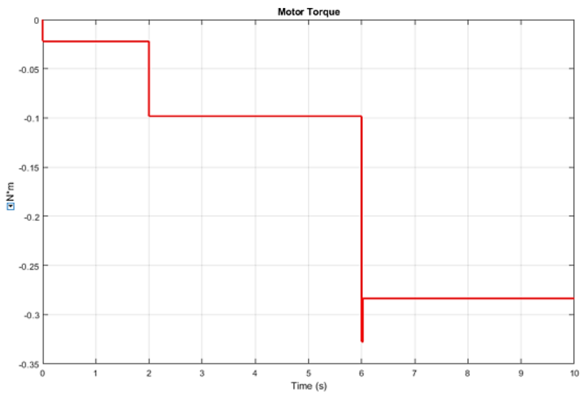

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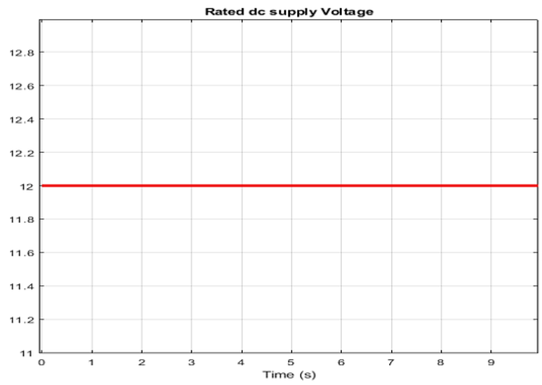


(f)

Figure 9. The simulation results in the cases of DC linear actuator (a) the linear speed (lead screw), (b) motor speed, (c) armature current, (d) worm gear speed, (e) motor torque, and (f) DC voltage supply

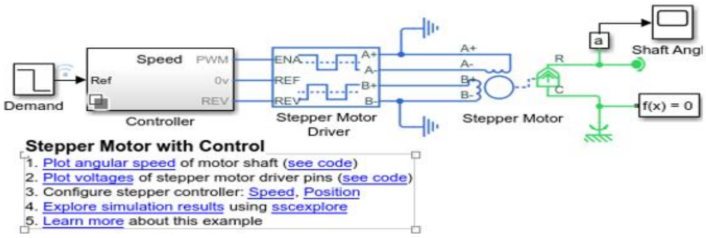
4.2. Simulation results and descriptions of stepper motor

The model in Figure 3 shows the stepper motor blocks and stepper motor driver together to implement a controlled stepper motor [27]. The model is provided two controller options: one to control the position and one to control the speed. In speed control mode, the input reference signal is used for the required number of steps per second. And in position control mode, the input reference signal is used as the number of steps given as a full 1.8-degree step size. The parameters used in the simulation are given in Table 3.

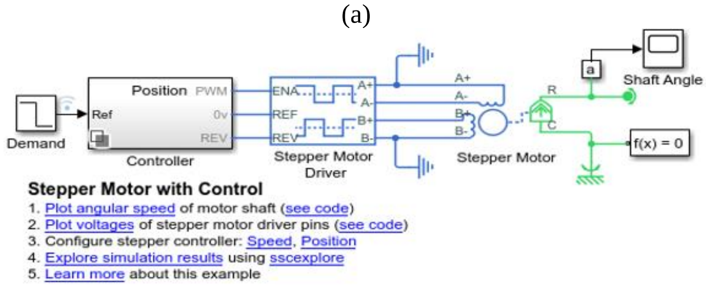
This stepper motor simulation studies step dynamics and slip when driving a mechanical load. Figure 10(a) shows the simulation of the stepper motor using the speed controller. Figure 10(b) is shown the simulation of the stepper motor using the position controller. As a result, the stepper motor control system module has been tuned to improve the performance of the stepper motor shown in Figure 11.

Table 3. Specification of stepper motor NEMA23

Parameters	Value	Unit
Current	4.2	A
Phase resistance	0.9	Ω
Phase inductance	3.8	mH
Inertia of motor	0.008	kgm^2
Step angle	1.8	deg
Torque constant	3	Nm



(a)



(b)

Figure 10. The simulation circuit of the stepper motor (a) speed controller test and (b) position controller test

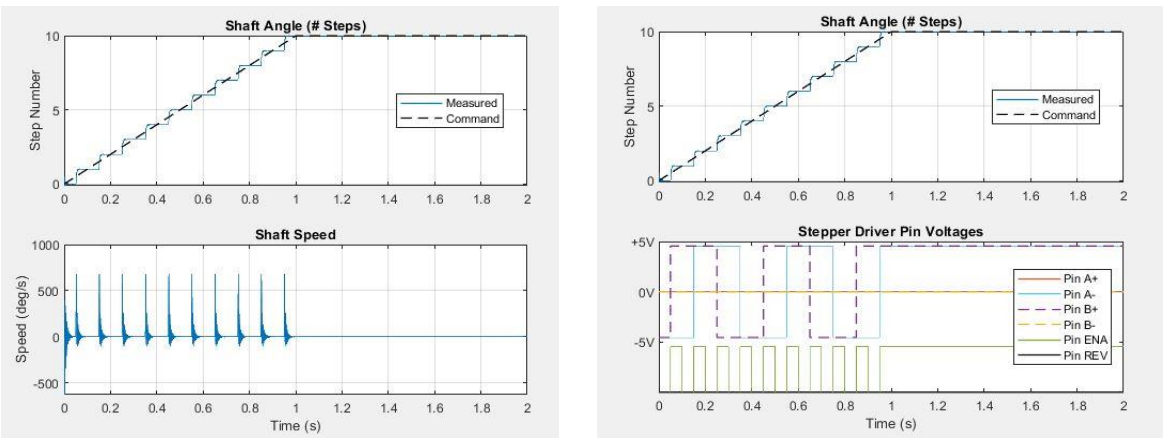


Figure 11. The simulation results of the stepper motor circuit from Figure 10(a)

As illustrated in Figure 11, shows, the plotting of speed control simulation results from the motor shaft angle graph is compared to the input command speed signal, resulting in the step-per-second speed control being accepted and the pulse train signal being converted to the stepper motor driver. When the shaft settles into the current step occur spikes on the angular velocity plot.

As illustrated in Figure 12, shows, the plotting of position control simulation results from the motor shaft angle graph is compared to the input command position signal, resulting in the step-per-second position control being accepted and the pulse train signal being converted to the stepper motor driver. When the shaft settles into the current step occur spikes on the angular velocity plot.

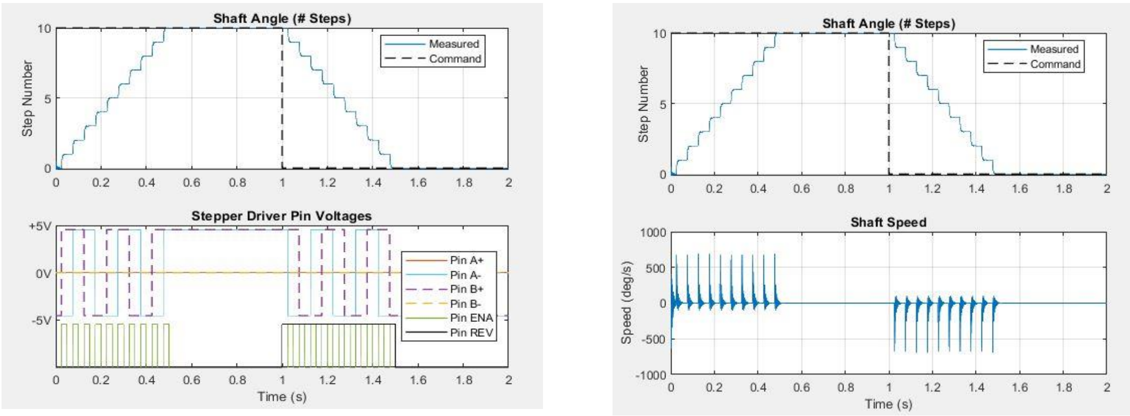


Figure 12. The simulation results of the stepper motor circuit from Figure 10(b)

4.3. Results of testing control on filed

The results of testing the operation of a driverless tractor robot for spraying chemicals on the football field. The driverless tractor robot can be remotely controlled using digital technology as the radio signal. The video signal is a real-time show on mobile phones for use in long-distance agricultural spraying applications. The test results on the road and field at Rajamangala University of Technology Isan Khon Kaen are shown in Figure 13.

Figure 13. Test results of driverless tractor robot on-road and football field

5. CONCLUSION

In this research, a stepper motor was used to drive the steering wheel of a 39 hp tractor by connecting the motor shaft to the steering shaft to steer in the desired direction through a vision at a distance or through a camera. The demonstration by applying the MATLAB program to test the operation in the laboratory and bring the test results to real use in the field. The user will send a radio signal in the distance to control the robot's operation as a direction control by looking through the camera for steering, forward, or backward control. The programmable logic control system receives commands from a radio transmitter. It can respond and work well at a distance of up to 2 kilometers. The steering test results have a good response speed. The test operates DC linear motors that operate mechanisms in tractor controls such as clutch pedal, brake pedal, gear selector, tail lift, PTO, forward and reverse gears, and wireless radio control for throttle system through a programmable logic controller. The test results of piloting an unmanned robotic tractor spraying chemicals on a football field can work fine. The reason to use the permanent magnet stepper motor and DC linear actuator that can be done at a low cost, and it works fine for use in the agriculture sector in the 4.0 era. It is satisfying to maneuver the robot by using a radio transmitter at a distance to control. Most farmers who already have tractors can add equipment as proposed in this research for transforming traditional tractors into state-of-the-art driverless tractor robots for spraying dangerous chemicals in rice fields or large farms.

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