Original Article

Hybrid Fuzzy PID Controller for Intelligent Tractor Steering Control

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Abstract - This article proposes an automatic Fuzzy PID hybrid steering control algorithm for a four-wheel tractor steering system. The proposed PID control mimics a tractor's manual steering movement characteristics, while a fuzzy logic algorithm is combined to optimize the autopilot parameter setting the PID value. The fuzzy inference engine is built on a rule base, so optimization of the fuzzy rule base is achieved by using a few parameters. The simulation results show that this algorithm can intelligently follow the given reference value and produce a small overshoot value with good resistance. As validation, this hybrid algorithm was tested using a four-wheel tractor with rear-wheel drive. The field test results show that the hybrid Fuzzy PID algorithm can well control the steering on autopilot.

Keywords - Hybrid control, Fuzzy, Pid, Steering control, Intelligent tractor.

1. Introduction

When applied to a tractor, a mobile robot's complexity combines several technologies, such as embedded systems, artificial intelligence, and communication protocols [1]–[3]. One of the essential parts of a mobile robot tractor is the control of the steering system because it is necessary to determine the direction in reaching some specific location [4]. In order to create a steering system that can move automatically, a controller is needed that plays an essential role in regulating the direction of the tractor movement. Stability and steering control became one of the main problems in automatic tractor control, given several setpoints of target parameters to drive the tractor automatically and track a given path [4], [5]. Several studies have been conducted to control mobile robots in recent years. The most popular control method used in robotics is PID (Proportional Derivative Integral) because PID has good stability but is not always have high accuracy. To overcome this, additional logic is needed to fine-tune the PID with fuzzy logic controls.

In recent decades, several studies regarding autonomous vehicles have used fuzzy logic control due to satisfactory results in almost all areas. One well-known fuzzy ability is to handle incorrect information between zero and one in knowledge-based approach heuristic rules, fuzzy-interpolative control, and flexible non-linear control [6]. In this article, the fuzzy-PID approach of the controller was proposed to regulate the steering of a four-wheeled tractor with an Ackerman drive. We propose a fuzzy-PID controller with two inputs (error (e) and delta error/ delta time (de/dt)) and three outputs (Kp, Ki, Kd). When an error occurs in the system, the fuzzy controller will perform parameter tuning against the PID controller.

Based on the results of the first simulation that has been carried out, it can be seen that the fuzzy-PID hybrid controller can produce stable movements in achieving the steering control angle setpoint target. The second simulation combines the hybrid fuzzy-PID steering control with the Purepursuit algorithm and shows stable and satisfactory results in achieving the target setpoint. The hybrid fuzzy-PID controller is the right choice for control applications based on path planning for robots that move with the Ackerman concept because of its fast reaction, high stability, and good tracking precision. The simulation results were then validated with field trials on four-wheeled tractors.

2. Materials and Methods

2.1. Tractor Configuration

In this paper, a four-wheel tractor configuration with Ackermann drive is used. The design tractor is equipped with two rear wheels as the pusher and two front wheels as the steering wheel. The Ackerman steering model as a tractor drive consists of a four-wheel chassis with the same axle. Kinematic Ackermann creates vehicle models such as cars that use Ackermann steering. This model represents a vehicle with two axles separated by a wheelbase. Figure 1 shows the tractor used in this study.
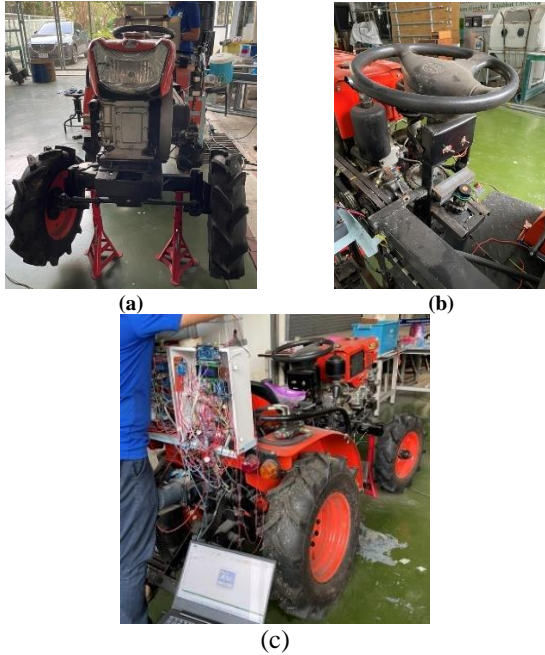
Fig. 1 Front and side view of the four-wheeled tractor with front steering. (a) Front View. (b) Steering. (c) Controller Box.
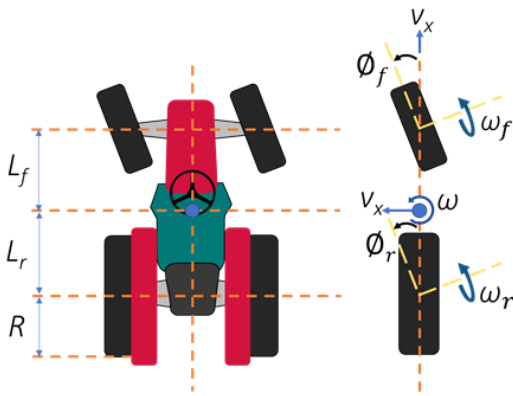

Fig. 2 Model of the four-wheeled tractor with front steering

2.2. Four-Wheel Tractor Model with Front Steering
This tractor has four wheels, of which two front wheels as steering and two rear wheels a self-controllable drive (Figure 2). The assumption used in this tractor steering system is the Ackerman model (two-wheel system) so that the system can be simplified, commonly known as the bicycle model.

2.3. Kinematic Model
The Ackermann Kinematic Model has several parameters as initial input, but it is important to note two main parameters: the Vehicle speed range and Maximum steering angle. Both parameters limit tractor motion. The lower limit of the Vehicle speed range parameter is set to -inf, and the upper limit is set to inf, so the vehicle speed can be any real value you specify. The maximum steering angle

is set to pi/4, so there is a maximum turning radius the vehicle can reach.

The inputs to this simulation are Front and rear wheel speeds $[\omega_f; \omega_r]$ as shown in Equation 4 (rad/s), and Front and rear steer angles $[\phi_f; \phi_r]$ in Equation 5 (rad). While the output of the simulation is linear velocities v_X and v_y (Equations 1 and 2), in m/s and angular velocity ω (Equation 3), in rad/s. Below is a basic calculation of forward kinematics [7]–[10].

$$v_X = \frac{R}{2}\left(\omega_f \cos\phi_f + \omega_r \cos\phi_r\right) \tag{1}$$

$$v_Y = \frac{R}{2}\left(\omega_f \sin\phi_f + \omega_r \sin\phi_r\right) \tag{2}$$

$$\omega = \frac{R}{L_f + L_r}\left(\omega_f \sin\phi_f - \omega_r \sin\phi_r\right) \tag{3}$$

The inverse kinematics model of the tractor is shown in the following calculation with the front steering condition. The assumption used is that the rear wheel cannot be steered. The input of the inverse kinematic is the forward velocity v_X and angular velocity ω [7].

$$\omega_f = \frac{v_X}{R\cos\phi_f}, \qquad \omega_r = \frac{v_X}{R} \tag{4}$$

$$\phi_f = \mathrm{atan}\left(\frac{\omega(L_f + L_r)}{v_X}\right), \phi_r = 0 \tag{5}$$

3. Results and Discussion
3.1. Mechanical and Electrical Design
In this research, the tractor's steering system has been designed to measure the steering angle by installing an optical encoder-type incremental encoder on the steering gear set; this type of encoder has the advantage that it is easy to buy and cheap in Thailand. Designing for autonomous tractor drive steering wheel by using compass navigation. The modules include the steering wheel, front wheel, and Main Controller Unit (MCU). The system was designed by using an electrically controlled steering DC motor, as shown in Figure 3. The mechanical design and implementation for steering control can be seen in Figure 4.

3.2. Design the Fuzzy PID Controller
The Hybrid theory control by using a fuzzy and PID controller is shown in Figure 5. The block diagram of an adjustable fuzzy PID control system deviation *e* between target and feedback error and the *e* difference between the deviations of the current moment the quantity is used as the output variable of the two-dimensional fuzzy controller controlling the actuator operation to achieve the purpose of tracing the path [11]–[15]. The control algorithm is essential for controlling the steering system. The research aims for a Hybrid Fuzzy PID control system to be applied for driving the tractor steering.
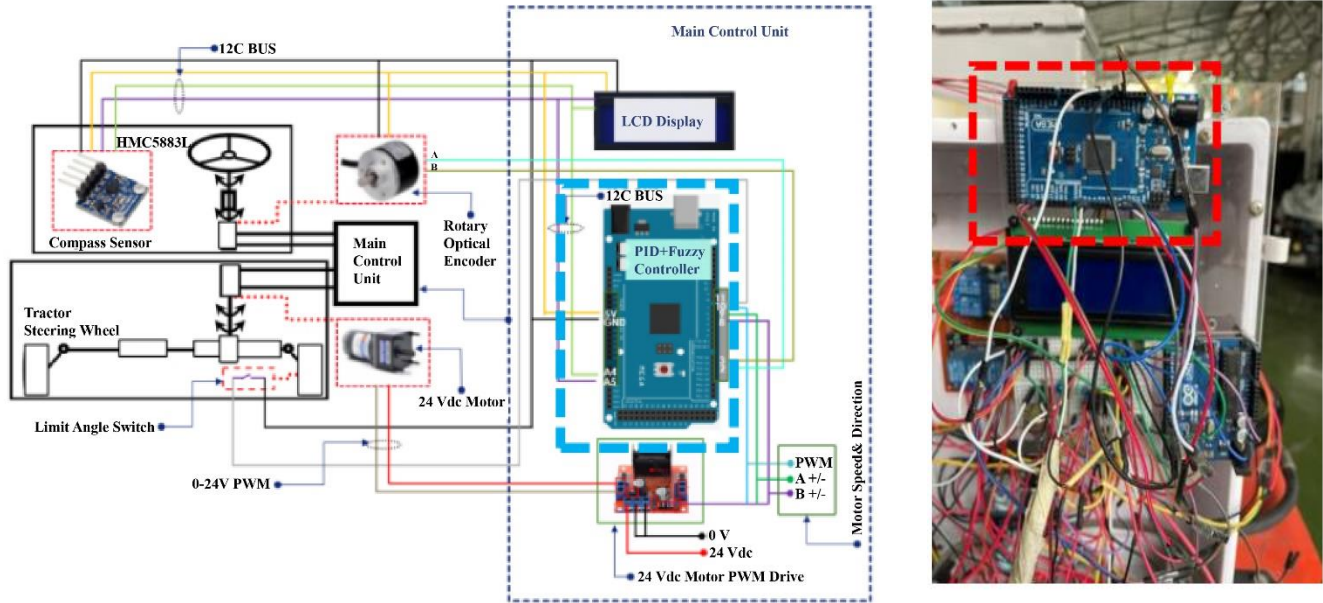
(a)

(b)

Fig. 3 Electrical Component Design and Implementation. (a) Wiring Diagram. (b) Implementation.

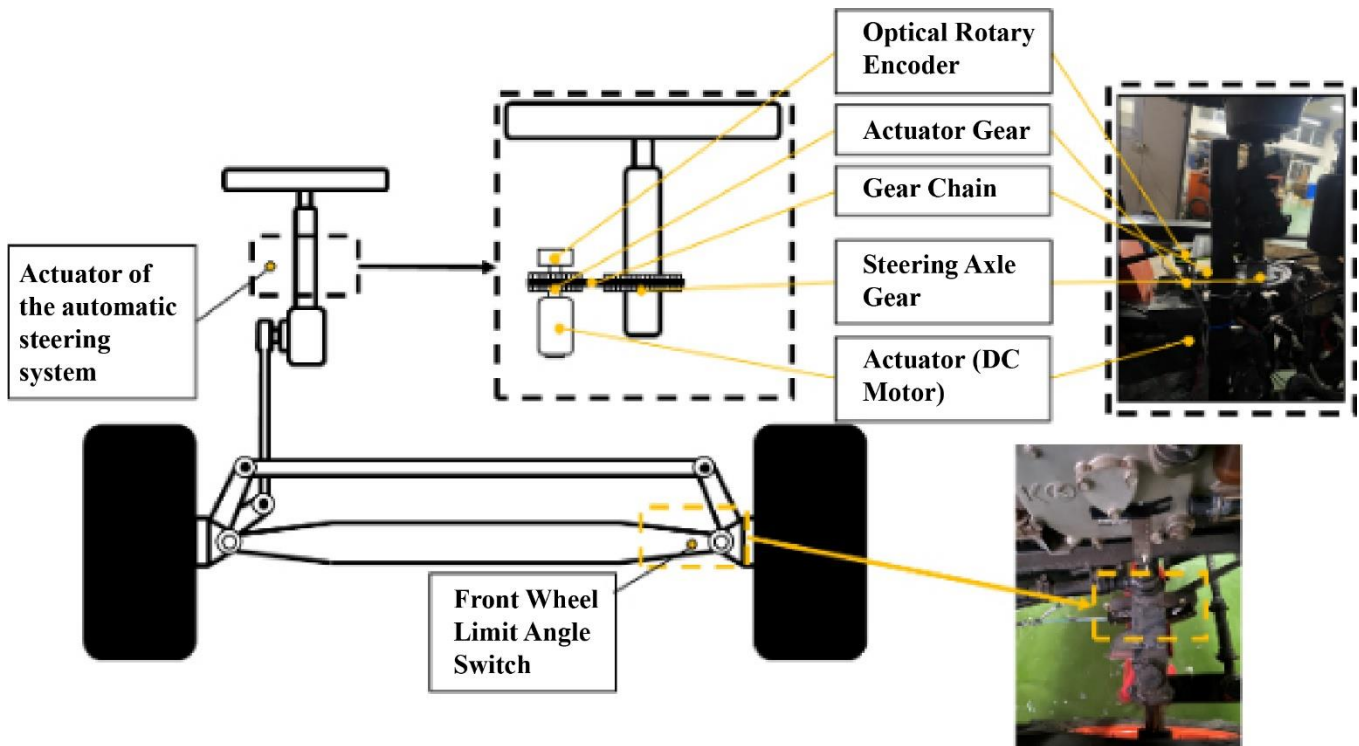**Fig. 4 Mechanical Design for Tractor Steering Control.**

The parameters Kp, Ki, and Kd, are tuning real-time by the calculation output by the fuzzy controller and changes to the PID parameters control. As a set value/target, the degree of azimuth value obtained from the compass sensor is used. Figure 5 describes the final closed-loop control fuzzy-PID system design.
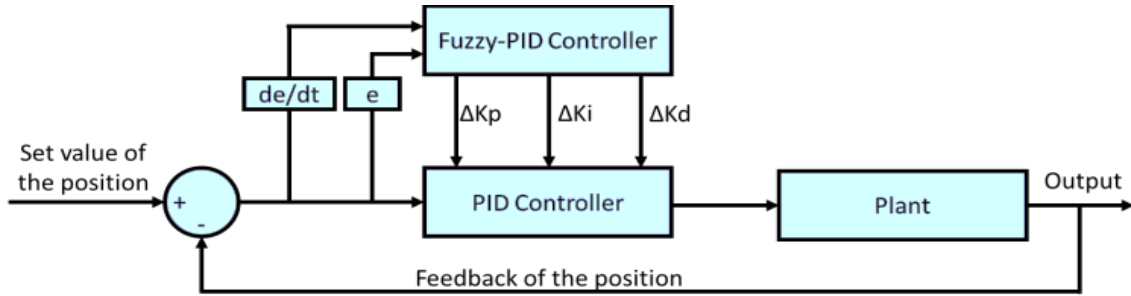
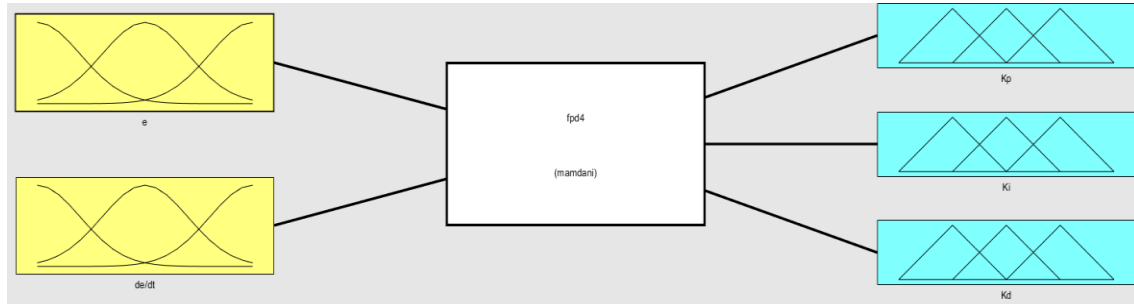Fig. 5 The Fuzzy-PID controller of the tractor

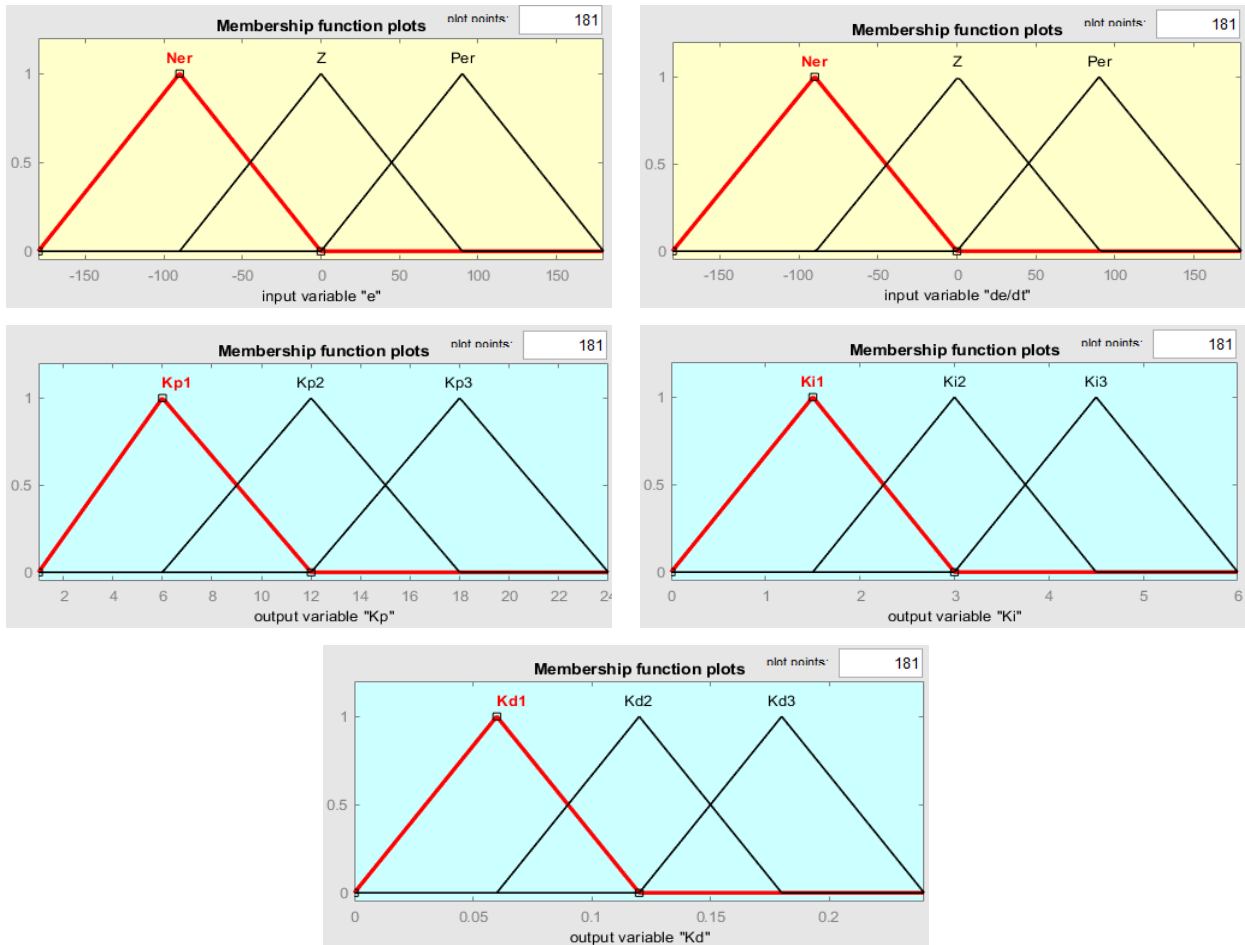Fig. 6 Structure of fuzzy controller

Fig. 7 Membership function of input and output

The developed fuzzy controller manages the PID controller's input value based on the compass sensor's target setpoint. Fuzzy logic is a theory widely used in academic studies of controllable robots [16]–[19]. The fuzzy control system has three basic structural blocks: fuzzification, inference machine, and defuzzification.

Fuzzification is an initial stage in fuzzy control that makes changes to each real value of inputs and outputs into a membership function. Furthermore, fuzzy inference is carried out to combine the facts of the rule-based fuzzification needed in the fuzzy reasoning process. The fuzzy inference has various applications depending on the form of membership function. One form of fuzzy is IF antecedents⟩, THEN conclusions⟩, and rules based on predefined input and output variables. The last part is defuzzification, which changes a subset of the output calculated by the inference engine.

This study used the Mamdani fuzzy inference system [20]–[23]. Figure 6 shows the Fuzzy-PID controller structure with two inputs in the form of error (e) and delta error/delta time (de/dt). Triangular membership function used on fuzzification block. The variable e dan de/dt is defined by three triangular membership functions: negative error (Ner), zero (Z), and positive error (Per). For Kp, Ki, and Kd, each is defined by three triangular membership functions, as shown in Figure 7.

The input from the tractor steering system (fuzzy logic control) is based on real conditions in the form of an angular value generated from the compass sensor. The fuzzy rule base is defined after the detailed process of membership functions is performed. In Figure 8, you can see the fuzzy rules used in this study.
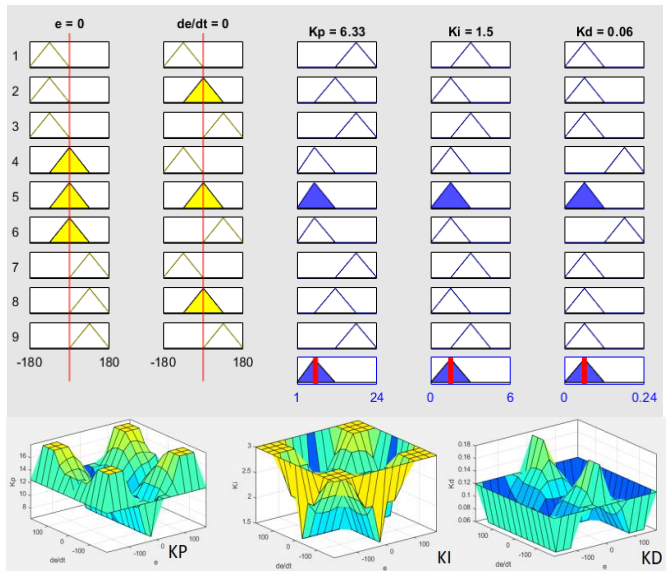

Fig. 8 The Fuzzy rules for Kp/Ki/Kd

Before field trials, it is necessary to test through simulations to obtain tractor movement using a hybrid Fuzzy-PID controller. The first test scenario is applied by providing an input value of 45°. Meanwhile, in the second simulation scenario, we use the waypoint concept with a pure pursuit [24]–[26] as an additional control system, as shown in Figure 9.

3.3. Simulation

Kinematic models and control designs that have been made are then implemented in Simulink using several interconnected block diagrams. Table 1 shows the DC Motor specification. Figure 10 shows the block diagram of the first scenario simulation with the parameters shown in Table 2. The first scenario is used to see the performance of the Fuzzy-PID design. The transfer function of the DC motor used can be seen in Equation 6. At the same time, the steering model used in the tractor is described in the transfer function of Equation 7.

$$G_{dcmotor}(s) = \frac{0.12}{0.04s + 1.1} \tag{6}$$

$$G_{motoroutput}(s) = \frac{1}{0.0012s + 0.0002} \tag{7}$$

Table 1. DC Motor Specifications

DC motor	W	V	A	N.M	RPM	rad/s
ZYTD-80SRZ-9F1	90	24	3.75	0.429	2000	209

Table 2. Parameters Value for First Scenario Simulation

Parameters		Value	Parameters		Value
FPID Angle Setpoint/ Target	:	45 °	Maximum Steering Angle	:	pi/4 rad
Vehicle Speed Range	:	0.25 m/s	Initial State	:	[0,0,0,0]
Wheel Base	:	1 m			

In Figure 11, the movement results form a circle with a 45 ° steering angle as the target setpoint. The graph shows the rise time value of 0.068s, a fast time to reach the setpoint even though there is an overshoot of 0.11 degrees (tolerable). In addition, the peak time achieved is 0.11 seconds with a setting time of 7 seconds. From this graph, the fuzzy PID design can reach the target setpoint to be implemented on the tractor. Before being implemented in the field trial, we simulated the second scenario by adding a pure pursuit control waypoint navigation system.

Pure pursuit control is applied to the second simulation scenario to get the results of the tractor movement based on the target coordinate points. Figure 12 shows the input poses and waypoints in the form of an array of coordinates [x,y; x_1,y_1;……;x_n,y_n], which is linked to the pure pursuit block diagram.
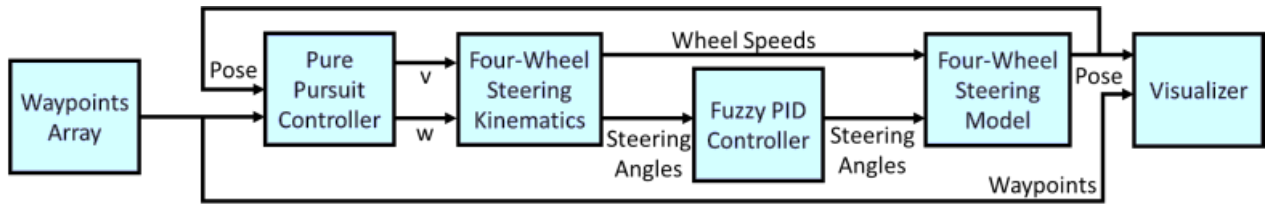
Fig. 9 The Pure Pursuit Fuzzy-PID controller for Tractor Waypoint Simulation
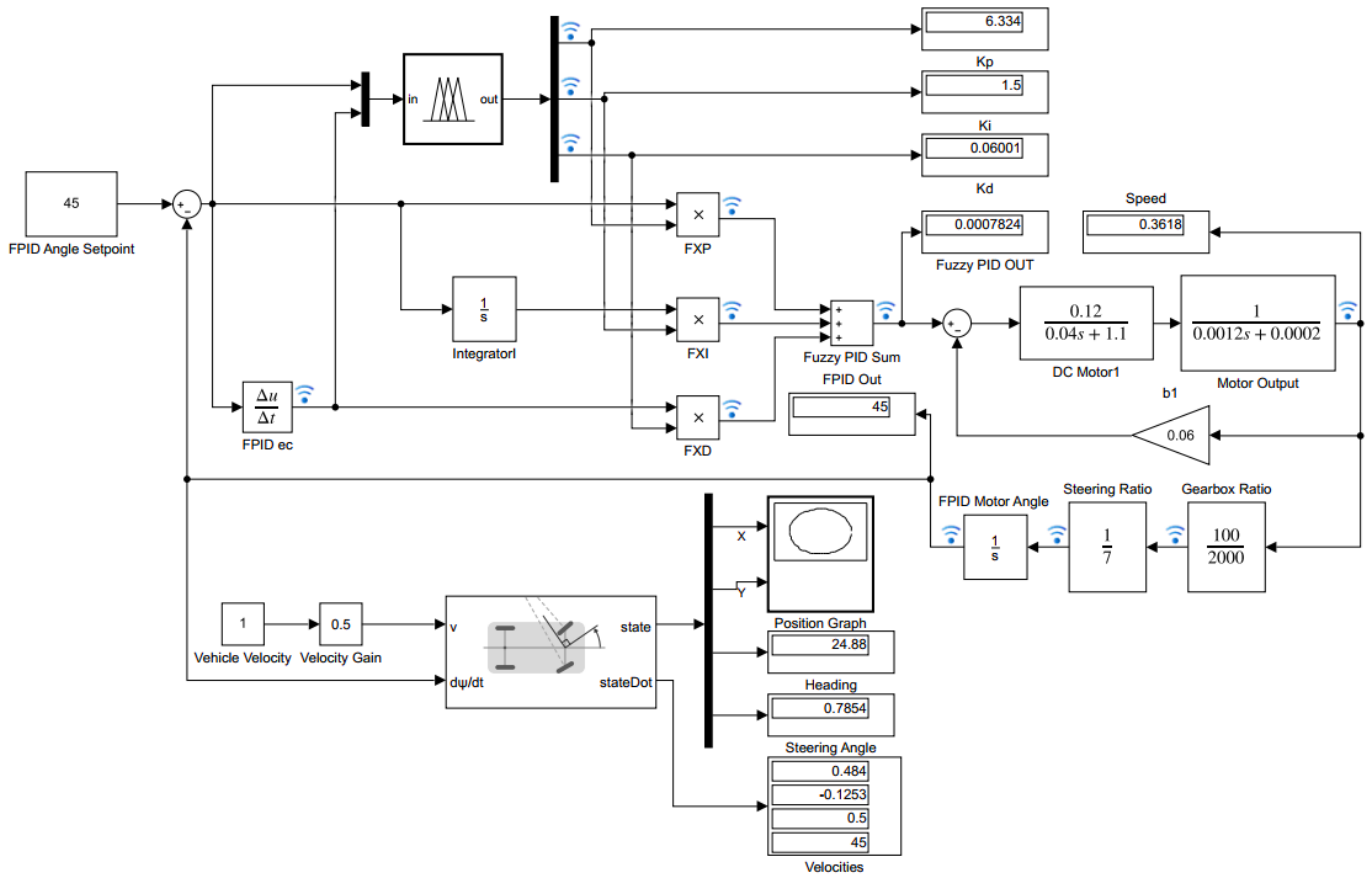

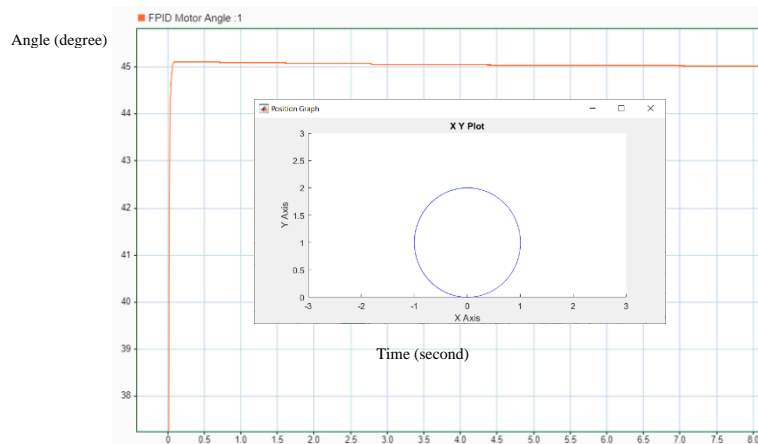**Fig. 10 Block diagram of fuzzy-PID control using MATLAB/ Simulink**

Fig. 11 First simulation scenario result

Furthermore, the output of the Purepursuit block in the form of linear and angular velocity becomes the input for the four-wheel steering inverse kinematics block. The result of the wheel speed calculation becomes the input for the four-

wheel steering model, while the steering angle becomes the input for the Hybrid Fuzzy PID. The tractor location and orientation were mapped and visualized from these two values, as shown in Figure 13.
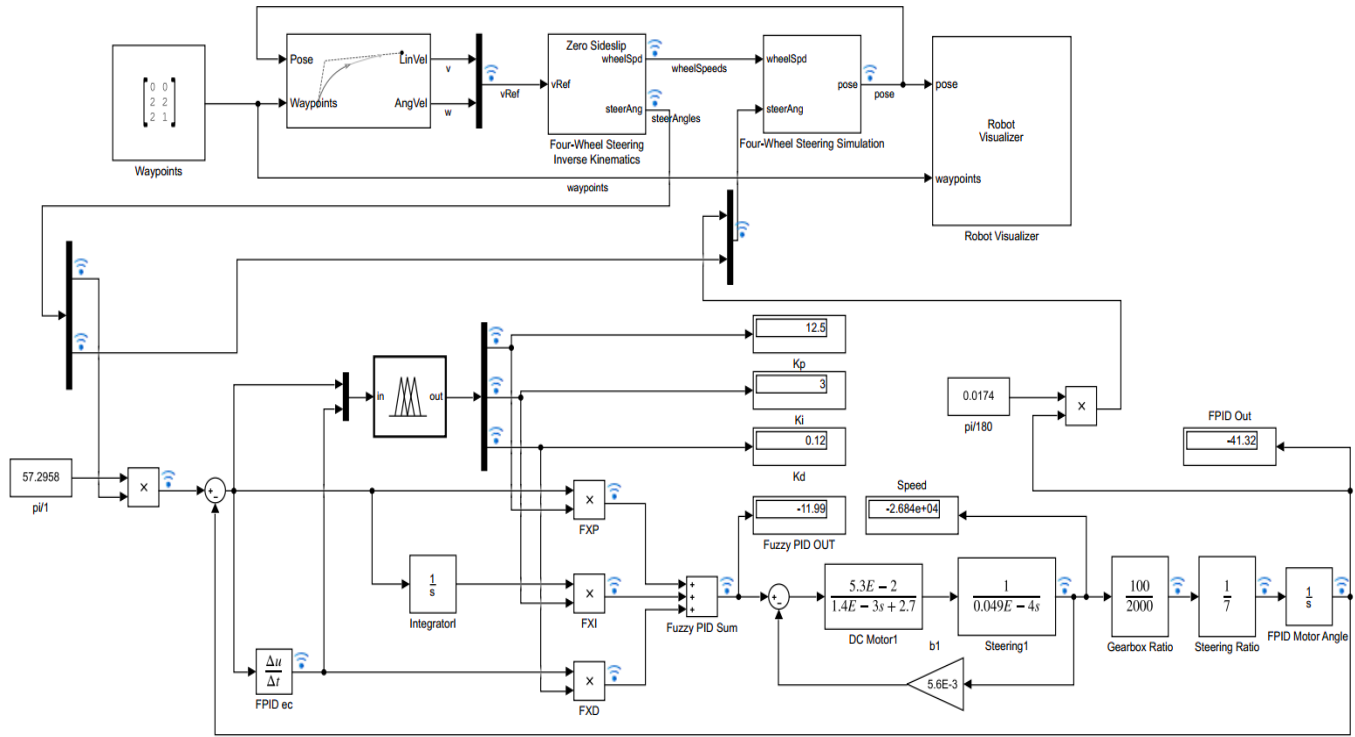

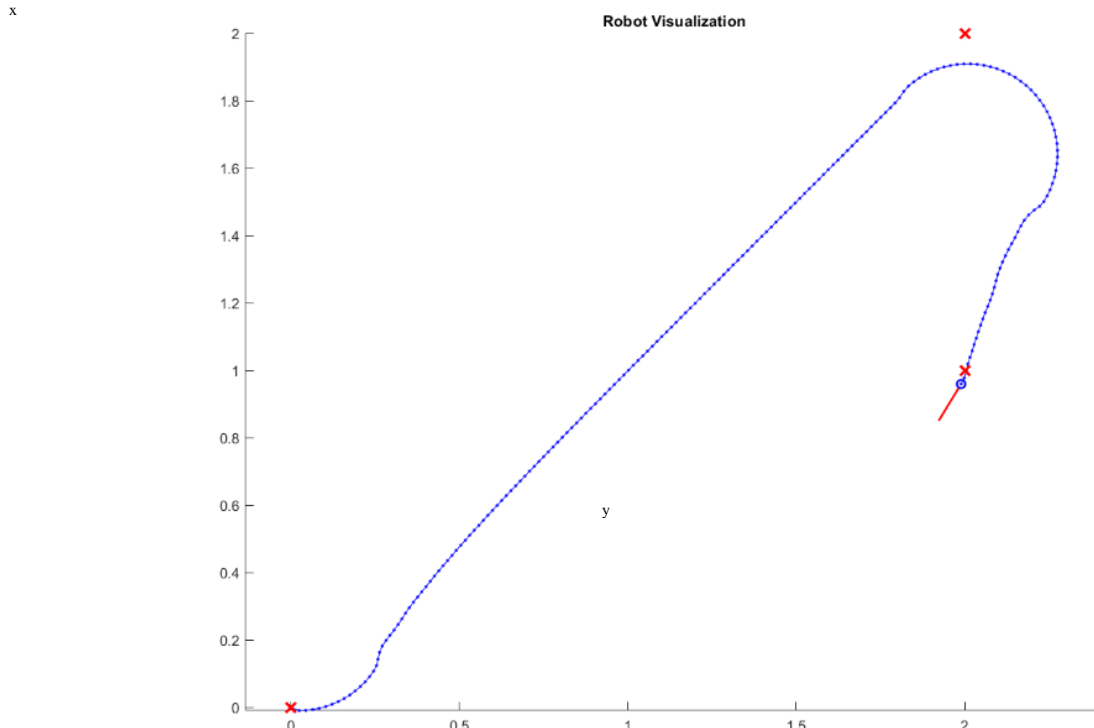**Fig. 12 Simulink block diagram of pure pursuit and fuzzy pid waypoint simulation**
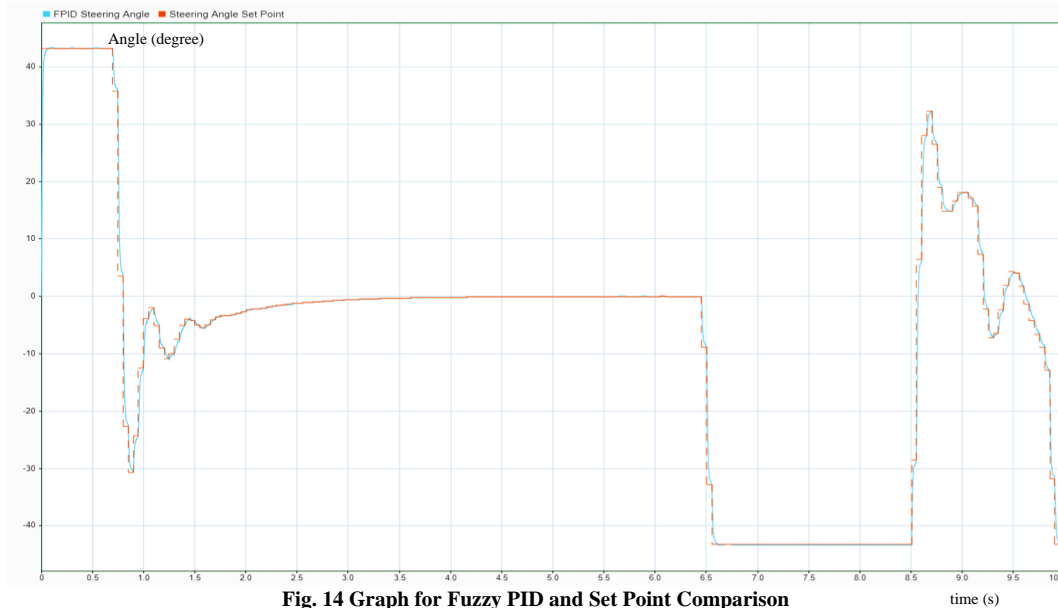

Fig. 13 Tractor waypoint simulation visualization

Fig. 14 Graph for Fuzzy PID and Set Point Comparison

time (s)

The graph shown in Figure 14 shows that the Hybrid Fuzzy PID controller can achieve the target setpoint smoothly. The negative value is the movement of the tractor turning left, while the positive value is the movement of the tractor turning right.

3.4. Experiment

Furthermore, we conducted a field test using a scenario to validate the simulation results, as shown in Figure 15. The path-tracking process starts from the initial mode, namely, the steering control unit is controlled by Kp1, Ki1, and Kd1 (constant) values without fuzzy influence to reset the wheel rotation. Steering to the starting point (move left) until the limit switch is touched (zero position). Next, the encoder sensor calculates the steering position starting from zero to turn the steering wheel (moves to the right) to the middle position. When the steering wheel is in the middle position, the navigation mode is activated so that the steering wheel moves automatically based on the compass sensor as a direction detector where the control unit with PID hybrid control theory and fuzzy logic determines the values of Kp2, Ki2, and Kd2.

The field test results are shown in Figure 16, where the target setpoint of the steering angle is a degree of the azimuth of 357 degrees. The start point of the wheel angle comes from the compass sensor readings. Initial steering mode starts from zero seconds which then turns the steering wheel towards the left until the limit switch is triggered at eight seconds. After that, the steering wheel is turned towards the right to reach the center of the wheel before finally being switched to compass navigation mode at fourteen seconds. After switching modes, Hybrid Fuzzy-PID is activated to reach the target setpoint.
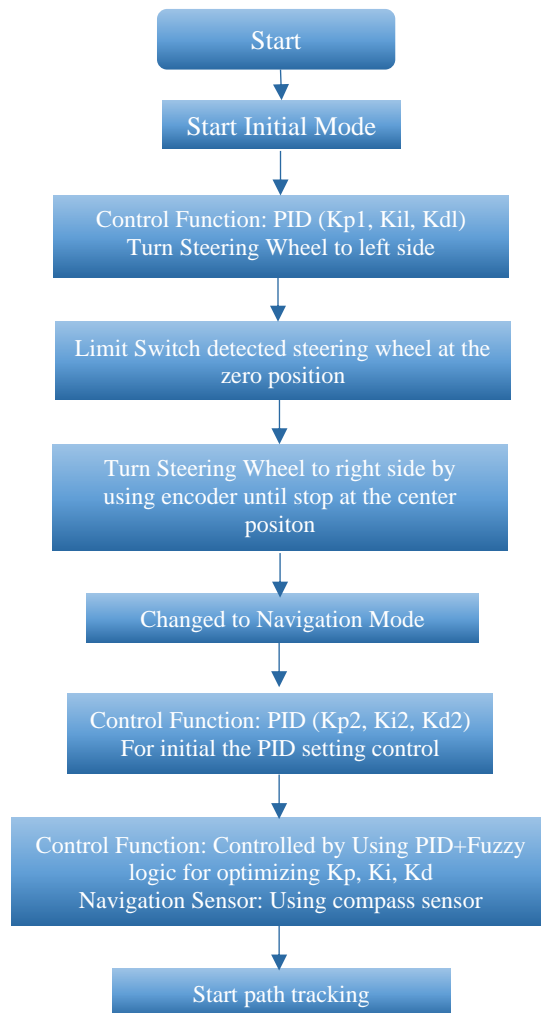

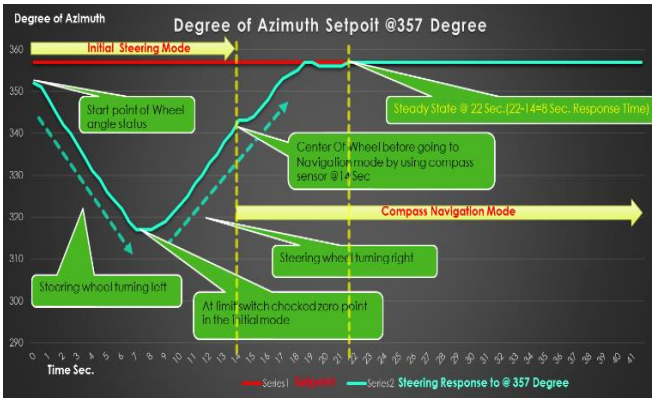**Fig. 15 Field Trial Experimental Scenario**

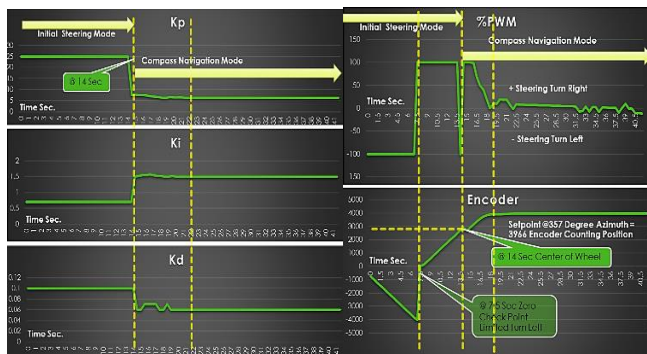**Fig. 16 Degree of Azimuth of Fuzzy PID Control (Initial Mode)**

Fig. 17 Fuzzy PID, PWM, and Encoder Value Record (Initial Mode)

Fig. 18 GPS Tracking Field Trial Result

Fig. 19 Wagon Installation on Tractor

Fig. 20 Second Trial GPS Tracking

The response time required is 8 seconds, with a difference of 1 second between the simulation (Figure 11) and the field test. Figure 17 shows changes in the values of Kp, Ki, Kd, PWM, and Encoder from time to time.

Furthermore, the steering control test on the tractor was carried out using a remote control. The test was carried out at the parking lot of the Industrial Technology Faculty, Valaya Alongkorn Rajabhat University. As shown, Figure 18 is the result of GPS tracking of a tractor controlled using a Radio Frequency (RF) remote; the red line shows the recorded track.
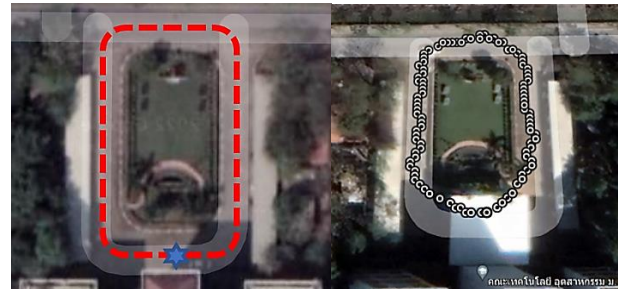
Modifications were made to the positioning of sensors and data recording devices based on the initial test results, as the vibration from the tractor's engine is so intense that it influences sensor readings. As shown in Figure 19, the sensors and data recording equipment were relocated to the tractor's rear by adding a small wagon. Figure 20 depicts the results of tracking the location of the tractor's movement.

During the second test, the parameter values P, I, and D in the fuzzy PID controller of the steering robot controller were obtained in real-time, as shown in the graph in Figure 21. A comparison between the angular and actual target setpoints was performed and is shown in Figure 22.
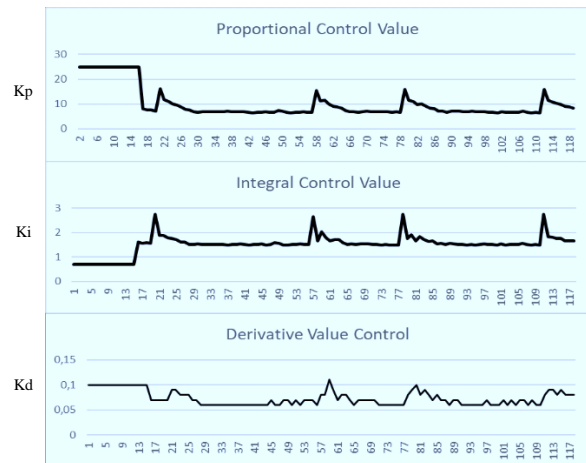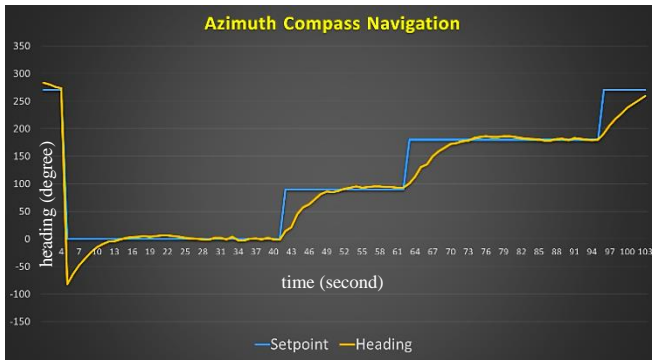

Fig. 21 Graph for PID Value

Fig. 22 Field Trial Graph for Fuzzy PID and Set Point (Compass) Comparison

4. Conclusion

This research proposes a Hybrid fuzzy PID-based tractor steering control based on goal parameters. The experimental findings demonstrate that the suggested algorithm effectively controls routes with cement pavement. Because of its quick response, high stability, and excellent tracking precision, a hybrid fuzzy-PID controller is an optimal choice for control applications based on robot waypoints utilizing the Ackerman principle. The presented algorithm has promising application prospects in agricultural working settings that are complex and harsh for agricultural machines.

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