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Design of Self-tuning Fuzzy PID Controllers for Position Tracking Control of Autonomous Agricultural Tractor

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ABSTRACT

As tractors have played an important role in improving agricultural productivity, enhancing the efficiency of tractor has become of interest in recent years. In this study, a design of self-tuning fuzzy PID tracking control for a tractor is proposed. The steering control is performed on the front wheels, whereas the tractor is rear-wheel drive. Efficiency of the proposed self-tuning fuzzy PID controllers is compared to the results from the conventional PID controller testing at different trajectory scenarios under the specified accuracy of GPS and acceleration of the tractor. The experimental results show that the proposed self-tuning control exhibits better performance than the conventional PID technique in terms of the fast response of the steering wheels, and the small distance and heading angle errors.

Keywords: PID controller, self-tuning fuzzy PID controller, tractor, trajectory

INTRODUCTION

Thai agriculture needs a new approach so as to "work less but accomplish more". A tractor is one of labor-saving devices that could help Thai farmers to achieve this objective. The modification of a tractor into an autonomous driverless vehicle is one of innovations which researchers have been currently working on. Several studies have concentrated on the design and test of controllers used in an autonomous driverless tractors.

Huynh et al. (2012), for example, utilized the nonlinear PI and the GPS sensor

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for trajectory control of a driverless tractor-trailer with accuracy of tracking. In a recent study on the design of an autonomous tractor by Kayacan et al. (2015), a fuzzy logic controller worked in parallel with a type-2 fuzzy neural network was applied to control the position while moving on prescribed trajectory. Ruangurai et al. (2015) adapted the PID controller to model the tracking system of the tractor, and in the same year, Moon et al. (2013) developed a path tracking model from kinematic and dynamic equations considering wheel slipping while moving by means of the PID controller.

It is obvious that controller selection is important for designers to achieve better efficiency of the navigation system of the autonomous tractor. The PID controller is one of the widely used controllers thanks to its functional simplicity. The PID controller consists of three term combination. “P” is proportional to the actual value of the error and “I” is integral controller generally used to decrease the steady state error while “D” is derivative controller which causes the output to decrease if the process variable is increasing rapidly.

Apart from being used to control the motion of the tractor, the PID controller has been widely employed by researchers to effectively control other systems. A position control scheme for a radio telescope (antenna) was presented using the PID controller designed in MATLAB Simulink environment in the presence of wind disturbance in the system model (Zaber et al., 2015). Basnayake et al. (2017) concluded that the geometric PID controller could ensure the stability of the Segway type mobile robot, constrained under no slip condition. A PID controller designed for Automatic Voltage Regulator systems was proposed using Simulink in MATLAB to compare PID with P, PI and PD controllers (Ratanaworahirunkun et al., 2013). Despite being widely used as a practical and simple controller with easy tunability, the PID controller has its own limitations with respect to the system stability control due to its linearity as the behavior of most systems is nonlinear and time varying. It cannot offer a good dynamic performance while wide range of parameters is considered.

In recent years, fuzzy logic based controllers, which have better performance in terms of its heuristic nature associated with simplicity and effectiveness for both linear and nonlinear systems, have been proposed in many studies. The fuzzy logic is used to address the vague events or situations. The significance of fuzzy logic controllers is its logical reasoning or ability to make decisions with human-like logical thinking and solving complex problems. The fuzzy logic controller consists of the three main processes. First, the process of converting classical data into membership functions (MFs) which is called the Fuzzification. Then Fuzzy Inference which is the process of combining membership functions with the control rules to derive the fuzzy output. The final process is Defuzzification which provides a real number as an output.

Recently, fuzzy logic controllers have been utilized in several studies. The design of a mobile robot to track the desired target and to avoid obstacles using the fuzzy logic controller was presented (Handayani et al., 2017). Allou et al. (2017) proposed the design of the path tracking controller based on fuzzy logic to control the speed and the steering angle of a four-wheel drive electric vehicle to follow the desired trajectory.

To integrate the advantages of PID and fuzzy logic based controllers, both are applied together to successfully increase the efficiency of control systems. This approach is also known as the self-tuning fuzzy PID technique. Regarding its working principle, Awouda and Mergani (2017) stated that the fuzzy auto-tuning of PID controller was to find the fuzzy logic relationships between three parameters of PID with error and change of error, calculate error and change of error in cycle in the operation of control system and adjust parameter of PID (K_p, K_i, K_d) on-line according to the fuzzy logic control principle. Pan and Zhou (2017) presented an adaptive fuzzy PID controller for maintaining vehicle yaw stability in different road conditions. Heikkinen et al. (2017) utilized a self-tuning fuzzy PID controller to control an autonomous differential drive mobile robot. In their paper, Su et al. (2016) developed a dynamic model using Lagrange method to the on-ball balancing mobile robot and a fuzzy self-adjusting PID controller was proposed to control the robot's balance.

In this work, the self-tuning fuzzy PID controller is utilized for the motion of the tractor because the controller is able to tune gain value by itself according to a variety of areas where a tractor drive. An old tractor was modified into an autonomous driverless vehicle. The hydraulic system of this two-rear wheel drive tractor is electronically controlled. The steering system uses an AC Servo Motor. A GPS receiver and IMU sensor are used to locate the current position and direction of the tractor as an input of the self-tuning fuzzy PID controller which regulates speed and steer system of the tractor while moving along different prescribed trajectories. It is expected that our design will serve as a significant step towards the prototype of an autonomous tractor with inexpensive GPS guidance system and IMU sensor. In addition, the proposed control system is simple while providing satisfactory outcomes.

Theory of PID Controller

A PID controller is a feedback control system that minimizes the difference of the output and set point by adjusting three parameters: K_i ,K_d and K_d . The block diagram of the PID controller is shown in Figure 1.

Figure 1 shows the block diagram of the PID controller that consists of three subblocks : proportional, integral, and derivative terms. The summation of the outputs of all term is represented by $u(t)$ which is the output of the PID controller. The error function $e(t)$ is the difference between the output and the set point. The PID model can be expressed in the following equation.

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t) \qquad (1)$$

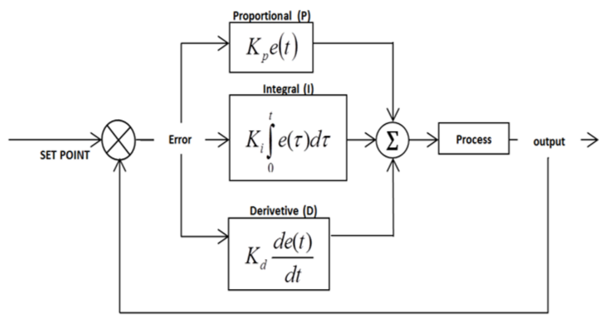

Figure 1. Block diagram of the PID controller

Theory of Self-tuning Fuzzy PID Controller

The self-tuning fuzzy PID controller employs the combination of PID and fuzzy algorithms. The Fuzzy controller is responsible for adjusting the PID gains to optimize the output. The block diagram of the self-tuning fuzzy PID controller is illustrated in Figure 2.

In Figure 2, the self-tuning fuzzy PID controller receives the inputs e and $\dot{e}$ to perform the fuzzification that transforms numerical inputs into language variable to identify the membership function as shown in Figure 3.

In Figure 3, functions of language variable consist of NB, NM, NS, Z, PS, PM, and PB which are identified by the input e. For instance, if e is within 15°, the status will be PS, and if K_i is within -6 m, the status will be NM. The status of ตัวแปรเชิงภาษา is evaluated by the process of Fuzzy Inference based on the fuzzy conditions where the condition (IF, THEN) is used to provide the output from the corresponding input and the conditions (AND, OR) are used for multiple inputs. Membership function rule is shown in Table 1.

From Table 1, the outputs of PID gains K_p, K_i, K_d can be obtained. For example, if K_p is PS and K_i is NM, K_p = Z, K_i = P, and K_d = Z will be obtained. The outputs from the membership function rule is consequently processed by the defuzzification that transforms them into actual quantity used to tune the system gains. Let μ_n be the output from the fuzzification and, y_n be the degree of membership. The defuzzification can be performed using (2).

$$Y_{(K_i, K_p, K_d)} = \frac{\Sigma \mu_n y_n}{\Sigma \mu_n} \qquad (2)$$

Where $Y_{(K_p, K_i, K_d)}$ is the numerical variable that vary from time to time. This outcome to tune the gains K_p, K_i, and K_d of the PID controller in (1) is used.

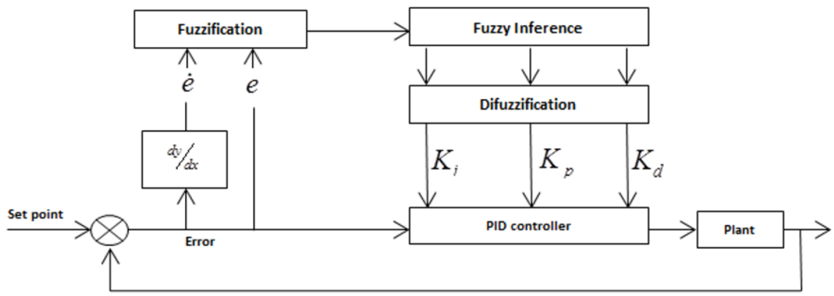

Figure 2. Self-tuning fuzzy PID controller

Table 1
Membership function rule

è	*e*	NB	NM	NS	ZE	PS	PM	PB
	Kp							
	Ki							
	Kd							
NB		P	Z	N	N	N	Z	P
		N	P	P	N	P	P	N
		P	N	N	N	N	Z	P
NM		P	P	Z	Z	Z	P	P
		N	Z	P	P	P	Z	N
		P	Z	Z	N	Z	Z	P
NS		P	P	Z	N	Z	P	P
		N	N	Z	P	Z	N	N
		P	P	Z	N	Z	P	P
ZE		P	P	P	Z	P	P	P
		N	N	N	Z	N	N	N
		P	P	P	Z	P	P	P
PS		P	P	Z	N	Z	P	P
		N	N	Z	P	Z	N	N
		P	P	Z	N	Z	P	P
PM		P	P	Z	N	Z	P	P
		N	Z	P	P	P	Z	N
		P	Z	Z	N	Z	Z	P
PB		P	Z	N	N	P	Z	P
		N	P	P	P	N	P	N
		P	Z	N	N	P	Z	P

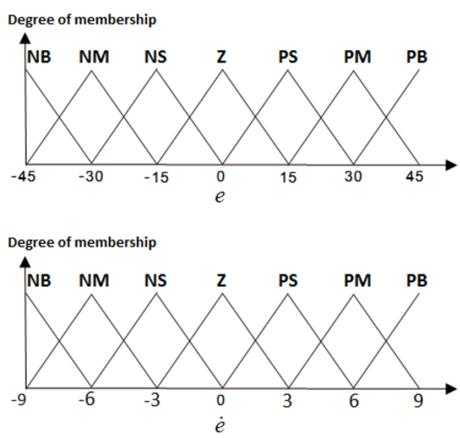

Figure 3. Fuzzification

METHODOLOGY

This work was divided into two parts including design and test steps. The first part consisted of plant and controller design for the autonomous driverless tractor. The second part of our work was to test for the efficiency of the proposed Self-tuning Fuzzy PID Controller for tracking.

Design of the Autonomous Driverless Tractor

The experimental hydraulic tractor has a maximum dimension of 110 x 180 x 130 cm. The diameters of front and rear wheels are 90 cm and 60 cm, respectively. The tractor uses a 15-horsepower gasoline engine to drive a hydraulic pump that generates pressure to be transmitted to the hydraulic motor for driving the rear wheels. The system has low maintenance costs and ease of use suitable for agricultural operation requiring high drawbar force. The directional control is operated through 1:80 ratio speed reducer gearbox to increase the motor rotating speed. The photograph of the designed tractor is given in Figure 4. The control system of the autonomous driverless tractor is created according to working diagram as shown in Figure 5.

The block diagram of the control system of the autonomous driverless tractor is shown in Figure 5. The target PC is installed on the tractor and the main PC is placed on the station. Both PCs communicate through WIFI by using Bullet M2 Point-to-Point Bridge transmission with 630 mW of output power (Horkaew, 2008). The target PC receives data from a GPS receiver through the serial port, which is used to locate the position of the tractor while moving. In this research, the Garmin GPS-72 receiver which has a radial error of no more than 5 meters in real time (Garmin Ltd., 2009) was used. The GPS works with a Pololu CHR-6dm IMU sensor, which is adapted for use with the tractor (Elecmaster, n.d.). The data is transmitted through the serial port to calculate the tractor attitude and

Figure 4. Photograph of Hydraulic Tractor

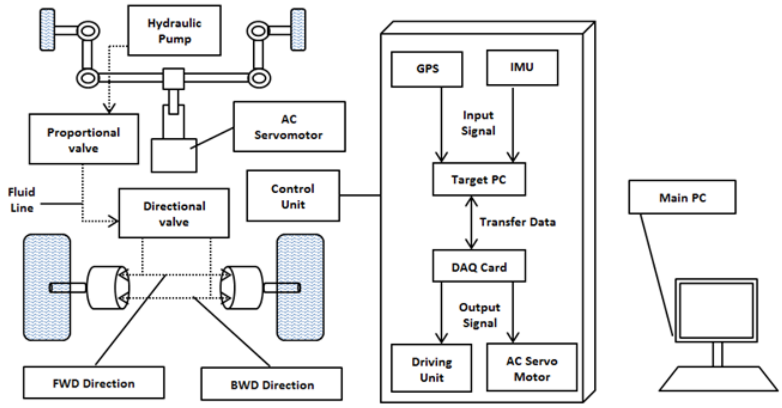

Figure 5. Working Diagram of Autonomous tractor

heading in relative to magnetic north. When the position and direction of the tractor is set, a control signal is processed and transmitted through the NI PCI-6221 data acquisition (DAQ) card which connects the equipment and sensors through the terminal block. The DAQ card reads and transmits electric signals, and these are retained in the target PC board attached to the tractor for measurement, analysis, and storage. The results are then displayed using LabVIEW software on main PC. The three signals used are: 1) Analog I/O for measuring the signals from the sensors and for generating analog signals, which are normally between -10V and +10V; 2) Digital I/O for acquiring and generating digital signals; and 3) Counter I/O for measuring the signals from the encoder or generating pulses to transmit signals to the equipment for controlling the steering system and the movement of the tractor (Chivapansri, 2013).

In addition, the steering system uses a 0.4 kW Panasonic MINAS A5II AC Servo Motor having high-precision positioning of the 1,048,576 pulses/rev (Panasonic Corporation, 2009). In this paper, the velocity mode was used to control the motor. It receives an analog input signal in the range of -10 V and +10 V for being a power source for direction control through a 1:80 ratio. A 4/3 directional control valve is used to control the forward and backward rotation of the wheels, and a proportional valve is used to control the speed of the wheels with a voltage in the range of 0-9 volts at 0-2 m/s.

Algorithm for Tractor Control

LabVIEW was used to process the data from/to the tractor. To control the motion of the vehicle, three important tasks, including identify the trajectory, formulating equations for the distance error and heading error, and designing the self-tuning fuzzy PID controller, are required. The diagram of the control algorithm is illustrated in Figure 6.

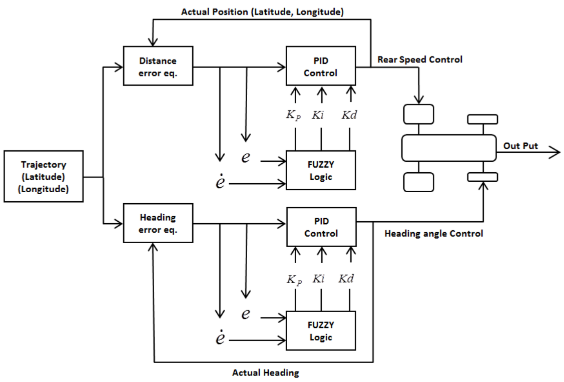

Figure 6. Diagram of the control algorithm

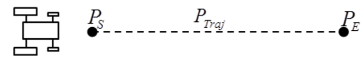

Figure 7. Straight line trajectory

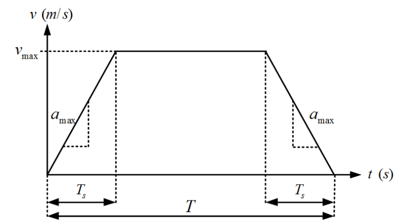

Figure 8. Trapezoidal velocity profile

From Figure 6, to begin with, the trajectories are generated to provide the data for identifying the instantaneous heading and distance errors. The error information is then sent to the self-tuning fuzzy PID controllers to calculate the output signals for controlling the speed and heading angle of the tractor.

Trajectory Identification. The motion of the tractor can be either straight or curved line. The trajectory is defined in the rectangular coordinate which will be discussed as follows (Luca, A. D., 2015; Upaphai et al., 2017).

Defining Straight-line Motion Model. Figure 7 shows the straight line trajectory (P_{Traj}) which can be obtained from

$$P_{Traj} = P_S + \sigma(P_E - P_S) \quad (3)$$

In (3), P_S is the starting position identified by (Latitude, Longitude), P_E is the ending point, and σ is the ratio of the position to trajectory length the can be obtained from (4)

$$\sigma = \frac{d}{l} \quad (4)$$

Where l is the straight line displacement of the motion and d is the time-dependent parameter that defines the velocity profile of the vehicle. In this study, the trapezoidal velocity profile as shown in Figure 8 is used to construct the trajectory.

d variable can be calculated using three equations according to its duration of time as follows:

$$d = \begin{cases} a_{\max}\left(\frac{t^2}{2}\right) & ; t \in [0, T_s] \\ v_{\max}t - \frac{v_{\max}^2}{2a_{\max}} & ; t \in [T_s, T - T_s] \\ -a_{\max}\left(\frac{(t-T)^2}{2}\right) + v_{\max}T - \frac{v_{\max}^2}{a_{\max}} & ; t \in [T - T_s, T] \end{cases} \quad (5)$$

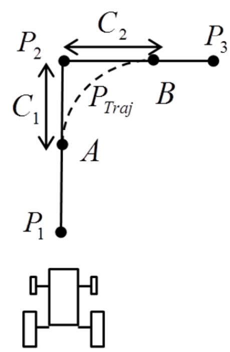

Figure 9. A curved line constructed from two straight lines

Where t and T are time and the time duration between P_S and P_E, respectively. v_{max} and P_1 is the maximum velocity (m/s) and acceleration (m/s²) of the tractor, respectively.

Figure 9 shows the construction of a curved line from two straight lines. The first straight line is between P_1 and P_2, and the second straight line is between P_2 and P_3. The dash-curved line in Figure 9 starts from A (Latitude, Longitude) and ends with curve line trajectory P_{Traj} that can be calculated using the following equation. (Luca, A.D., 2015; Upaphai et al., 2017)

$$P_{Traj} = A + V_1 m_{12} t + \frac{t^2}{2\Delta t}\left(V_2 m_{23} - V_1 m_{12}\right) \quad (6)$$

Where V_1 and V_2 are the velocity for the first and second straight lines, respectively. m_{12} and m_{23} are the directional vectors, and Δt is the time difference that can be obtained from the following equations.

$$m_{12} = \frac{P_2 - P_1}{\left\|P_2 - P_1\right\|} \quad (7)$$

$$m_{23} = \frac{P_3 - P_2}{\left\|P_3 - P_2\right\|} \quad (8)$$

$$\Delta t = \frac{2l_1}{V_1} \quad (9)$$

Defining the Equations of Distance and Heading Errors of the Tractor. The equations used to maintain the position of the tractor consists of the distance and heading error equations. The distance error from the trajectory is given by (10). On the other hand, the heading error, which is defined as the difference of the yaw angle from the trajectory, can be formulated in (11) (Upaphai et al., 2017; Phothongkum, 2016).

$$Distance\ error = \sqrt{(x_{ref} - x_{act})^2 + (y_{ref} - y_{act})^2} \tag{10}$$

$$Heading\ error = atan2((y_{ref} - y_{act}),(x_{ref} - x_{act})) - \theta_{act} \tag{11}$$

The reference position (x_{ref} , x_{act}) can be obtained from the defined trajectory model, whereas the actual position (x_{act} , y_{act}) and steering angle are provided by GPS and IMU. The outputs of (10) and (11) are consequently given to the self-tuning fuzzy PID controller to search for the optimal gains that result in the minimization of these error functions.

The Design of Self-tuning Fuzzy PID Controller. The Fuzzy PID controller is designed by applying LabVIEW program. The main controller consists of distance and heading control units. The block diagram of both units is illustrated in Figure 10.

The inputs for the self-tuning fuzzy PID controller in terms of the distance and heading errors and their derivative are represented by the matrices e and $\dot{e}$ in the above figure. These error functions are then given to the Fuzzy system in LabVIEW. In the fuzzification process, the seven variables are defined : NB, NM, NS, ZE, PS, PM, and PB, and construct the membership function of distance and Heading errors as demonstrated in Figure 3. For example, if the heading error of the tractor is 30° and the distance error is 3 m, the outcomes of language variable are PM and PS. These results are processed by the Fuzzy Inference which employed the defined membership functions as reported in Table 1. The Defuzzification provides the language variable of P,N,P and $y_{(K_p,K_i,K_d)}$ as given in (2). y_{K_p} is multiplied by e to obtain the proportional term to regulate the heading and distance errors of the tractor. y_{K_i} is multiplied by the integration of e to obtain the integral term to control the stead-state error, and y_{K_d} is multiplied by $\dot{e}$ to define the derivative term to control the overshoot in the tracking process.

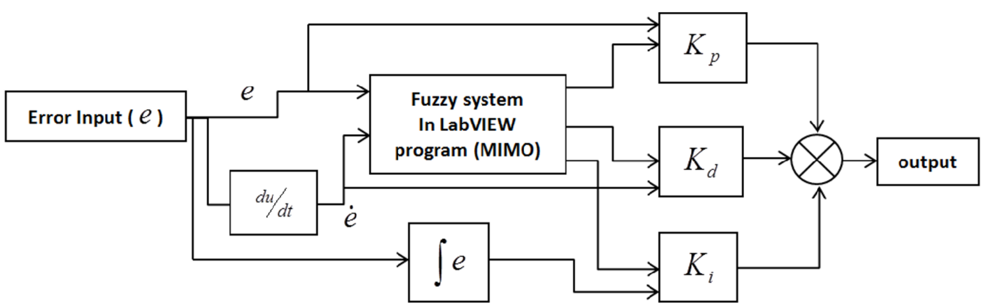

Figure 10. Block diagram of self-tuning fuzzy PID controller.

Evaluation of the Effectiveness of the Proposed Tracking System

The proposed self-tuning Fuzzy PID approach is evaluated by comparing to the conventional PID control. The results of straight-line motion and combined straight/curved lines (N-Shaped) from two techniques are assessed. To begin with, the PID controller that can take the linear input is used to manage the motion of the tractor. In this experiment, the controller gains on a trial and error basis are adjusted. After that the proposed self-tuning fuzzy PID controller is applied to take the nonlinear input in the tracking process. All results are reported in terms of the average heading and distances errors as given in (12) and (13).

$$\textit{Average heading error} = \frac{\sum_{i=1}^{n} D}{n_d} \qquad (12)$$

$$\textit{Average distance error} = \frac{\sum_{i=1}^{n} D}{n_d} \qquad (13)$$

In (12), and (13), n_h and n_d are the total number of heading error points and distance error points, respectively. $\Sigma + H$ and $\Sigma - H$ are the summations of the heading errors deviated to the right and left, respectively. ΣD is the summation of the distance errors.

The metrics in (12) and (13) are used to evaluate the comparative effectiveness of our approach with respect to the reference method. However, maintaining the same condition of the landscape and weather throughout the test is essential, since this can affect the functionality of the GPS.

RESULTS AND DISCUSSION

Experimental Results of the Straight Line Trajectory Tracking Control of the Tractor. In this experiment, the starting and ending points of the straight-line trajectory were set at (14.0371 latitude, 100.724 longitude) and (14.0372 latitude, 100.7243 longitude), respectively, as shown in Figure11. The maximum speed was set to 1 m/s.

To compared the effectiveness of the conventional PID and self-tuning fuzzy PID controllers, the gains of the PID control loop were set to Kp = 12, Ki = 0, and Kp = 0. The membership function rules of the self-tuning fuzzy PID controller were set as reported in Table 1. The experimental results are shown in Figures 12 to 14.

Figure 12 compares the results of the trajectory tracking of the tractor controlled by the conventional PID controller (red dashed line), self-tuning fuzzy PID controller (blue solid line), and the prescribed straight-line trajectory (black dotted line). From this figure, it can be noticed that the self-tuning fuzzy PID control provides a faster response to the steering wheel compared to the other. Therefore, the heading angle of the tractor (blue solid line) is relatively smoother. On the other hand, the maximum errors from the prescribed trajectory of both control systems are 2 m due to the error of GPS according to the specifications of the equipment, Garmin GPS-72, which has a radial real-time error less than 5 m.

Figure 13 compares the heading errors resulted from the conventional PID Controller (red dashed line) and self-tuning fuzzy PID controller (blue solid line). The conventional PID Control (red dashed line) provides the maximum heading errors of -18 degree and 25 degree, while the self-tuning fuzzy PID control (blue solid line) provides the maximum heading errors of -15 degree and 14 degree. The average heading errors from the conventional PID and self-tuning fuzzy PID controllers, are from -14.35 to 22.46 degree and from -11.82 to 10.66 degree, respectively. It can be clearly seen that the proposed self-tuning fuzzy PID control system has a faster response to the steering wheel, and has a smaller average heading error. Hence, the proposed automatic control system outperforms the conventional PID techniques.

Figure 14 shows the distance errors of the autonomous tractor controlled by the conventional PID controller (red dashed line) and self-tuning fuzzy PID controller (blue solid line). The distance errors from the conventional PID and self-tuning fuzzy PID controllers are 4-7m and 3-5.8m, respectively. In addition, the average distance errors from the conventional PID and self-tuning fuzzy PID controllers are 5.23 m and 4.41 m, respectively. It can be noticed that the self-tuning fuzzy PID controller gives better tracking performance compared to the results from the conventional PID. The proposed self-tuning fuzzy PID controller also provides more consistent speed as well as smaller average distance error.

Figure 11. Straight line trajectory

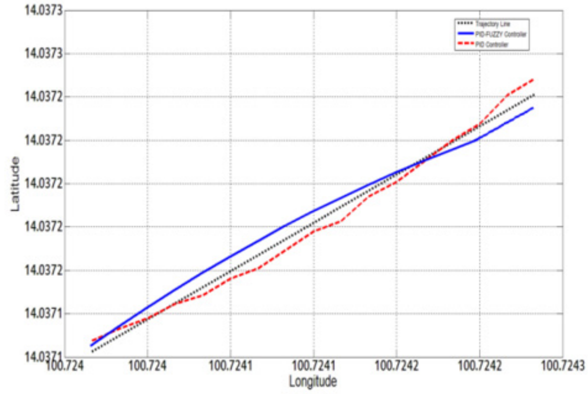

Figure 12. Experimental results of straight line trajectory tracking Control

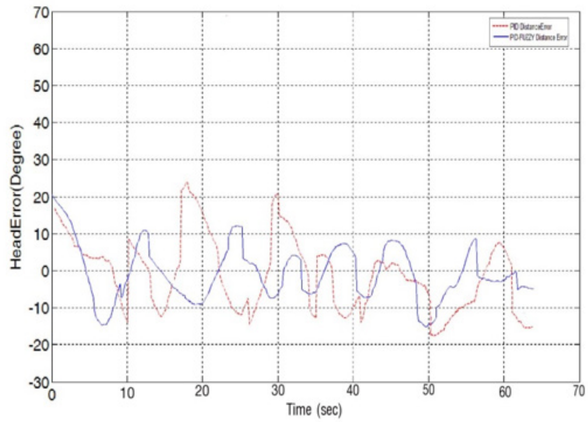

Figure 13. Heading error of the tractor

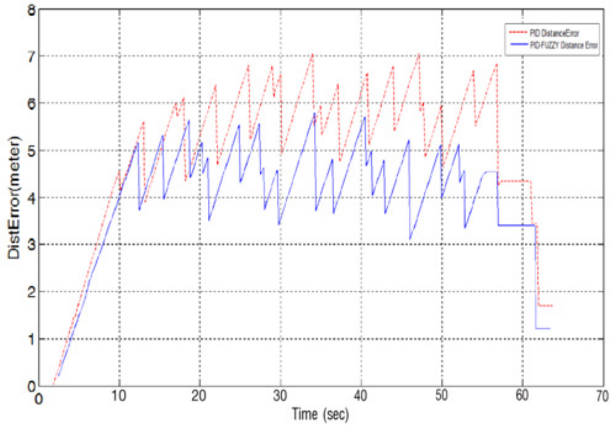

Figure 14. Distance error of the tractor

Figure 15. N-shaped trajectory

Experimental Results of The N-shaped Trajectory Tracking Control of The Tractor

The N-shaped trajectory that consists of both straight and curved lines was set with the same starting point, ending point, maximum speed, and controller gains as defined in the previous experiment. The comparisons of the results from the conventional PID and the proposed self-tuning fuzzy PID techniques are shown in Figures 16 to 18.

Figure 16 compares the results of the trajectory tracking of the tractor controlled by the conventional PID controller (red dashed line), self-tuning fuzzy PID controller (blue solid line), and the prescribed straight-line trajectory (black dotted line). From this figure, it can be noticed that the response of the conventional PID controller is so slow that it provides poor tracking performance along the first curve and the other compared the proposed automatic control technique. However, the moderate response of the acceleration of the vehicle may bring some amount of error to the system.

Figure 17 compares the heading errors resulted from the conventional PID controller (red dashed line) and self-tuning fuzzy PID controller (blue solid line). The conventional PID controller (red dashed line) provides the maximum heading errors of -48 degree and 35 degree, while the self-tuning fuzzy PID controller (blue solid line) provides the maximum heading errors of -10 degree and 20 degree. The average heading errors from theerrors from the conventional PID and self-tuning fuzzy PID controllers are 4.69 m and 4.64 m, respectively. It can be noticed that the self-tuning fuzzy PID controller gives better tracking performance compared to the results from the conventional PID. The proposed self-tuning fuzzy PID controller also provides more consistent speed as well as smaller average distance error. Hence, the proposed automatic control system outperforms the conventional PID techniques.

Figure 18 shows the distance errors of the autonomous tractor controlled by the conventional PID controller (red dashed line) and self-tuning fuzzy PID controller (blue solid line). The distance errors from the conventional PID and self-tuning fuzzy PID controllers are 0.9 - 9 m and 2 - 6.8 m, respectively. In addition, the average distance errors from the conventional PID and self-tuning fuzzy PID controllers are 4.69 m and 4.64 m, respectively. It can be noticed that the self-tuning fuzzy PID controller gives better tracking performance compared to the results from the conventional PID. The proposed self-tuning fuzzy PID controller also provides more consistent speed as well as smaller average distance error.

In summary, the average values of heading and distance errors for the straight line and N-shaped cases, resulted from the conventional PID controller and the proposed self-tuning fuzzy PID approach, are reported in Table 2.

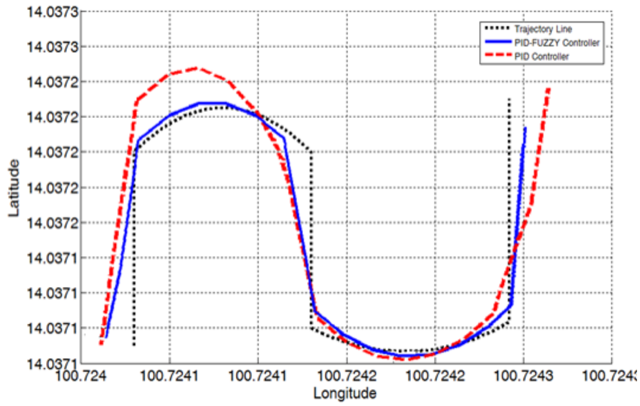

Figure 16. Experimental results of the N-shaped trajectory tracking control of the tractor

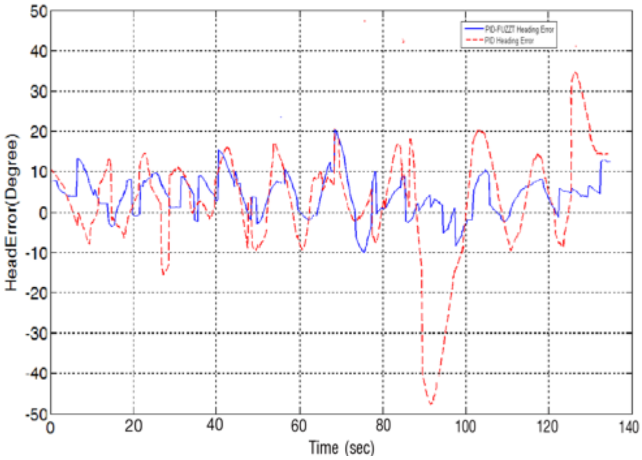

Figure 17. Heading error of the tractor

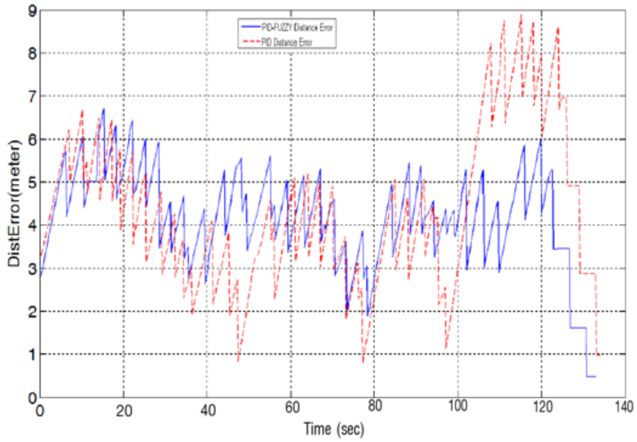

Figure 18. Distance error of the tractor

Table 2

Tracking control results of the conventional PID controller and the proposed self-tuning fuzzy PID controller

	Case of error	PID controller	Self-tuning fuzzy PID controller
	Heading error	-18 to 25 deg	-15 to 14 deg
Straight line	Distance error	4 to 7 m	3 to 5.8 m
trajectory	Ave. heading error	-14.35 to 22.46 deg	-11.82 to 10.66 deg
	Ave. distance error	5.23 m	4.91 m
	Heading error	-48 to 35 deg	-10 to 20 deg
N-Shaped	Distance error	0 to 9 m	2 to 6.8 m
trajectory	Ave. heading error	-11.73 to 8.92 deg	-3.13 to 6.27 deg
	Ave. distance error	4.69 m	4.64 m

CONCLUSIONS

This article presented a design of self-tuning fuzzy PID tracking control for a tractor. The efficiency of the proposed controller is compared to that of the conventional PID controller. From the experimental results, the proposed self-tuning fuzzy PID approach shows the high efficiency. In particular, the faster response of steering wheel from the self-tuning fuzzy PID controller leads to relatively small errors. The performance of the design is limited by the specifications of the tractor's drive system and the accuracy of the GPS used in this work. It is belived that the proposed design technique can be well applied to any high performance/precision systems to perform better tracking control.

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