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Trajectory Tracking Control Design for an Autonomous Tractor Using Fuzzy PID Controller

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Abstract The design of a position control system of an autonomous tractor using self-tuning fuzzy PID controller was studied. The design is developed by simulating the tractor movement using the dynamic model of front-wheel steering and rear-wheel driving. The tractor trajectory in Cartesian coordinate system is also created. The aim of the design was to control a tractor to track a specified path automatically. The design tasks was firstly set up an equation of tractor trajectory and to simulate the tractor movement using MATLAB/ Simulink, and to design the tractor controller using self-tuning fuzzy PID controller. Finally, the position control system was also designed. The results of simulation experiment showed that the self-tuning fuzzy PID controller was able to control the tractor to track the desired path. The maximum position error between the path designed and the tractor path was at 1.02 meter. The comparison with time, the maximum position error was 2.89 meter, because the tractor was slower than the path movement designed.

Keywords: Autonomous tractor, Dynamic mode, PID fuzzy controller, Trajectory

Introduction

Located on the fertile floodplain and having tropical monsoon climate, ideally suited to wet-rice cultivation, Thailand is predominantly an agricultural country. It is widely known as the rice bowl of Southeast Asia. In the past, agricultural sector in Thailand was labour intensive and produced limited products. However, in recent years, considerable efforts have been made to automate agricultural machinery to help increase the output and the quality of the products. Tractors play an important role in Thai agriculture. They perform many tasks such as soil preparation, fertilization and transportation of agricultural products. Moreover, they help increase operating efficiency and reduce labour costs (National Researeh council of Thailand, 2016).

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Therefore, there is a need for the development of an efficient agricultural tractor. Modern technology makes it possible for the introduction of an autonomous tractor. In this paper, an autonomous tractor which is able to track a desired path is studied.

According to autonomous vehicle development, a wide variety of different algorithms is used for autonomic drive. PID control is the most common control algorithm used in industry. The popularity of PID controllers can be attributed to their linearity and functional simplicity. Moreover, they can reduce errors to minimum in many kinds of control system models. However, when PID controllers are applied with nonlinear system models, they always give poor performance. PID control can yield less the ideal results in situations where the target value changes (Capitan, 2012).

Apart from PID, fuzzy logic is an algorithm that is also widely used as an autonomous vehicle controller because it possesses lots of prominent advantages such as an ability in self-decision making with human-like logical thinking (if-then) and an ability in ambiguous situation definition. A significance of fuzzy application is its reasoning or value specification. Generally, it is applied mostly with complex problems (Suwaphan, 2015). Mohammed Faisal *et al*, have used fuzzy logic to control a mobile robot to relocate (transport) objects and avoid obstacles. It is found that the navigation and obstacle avoidance using fuzzy logic can work (Faisal *et al.*, 2013). Yanan Zhao and Emmanuel G. Collins, Jr. have also used fuzzy logic to control a vehicle to park, automatically, in various kinds of tight spaces. Their simulation experiment shows that fuzzy logic can control autonomous vehicle to park in tight spaces effectively (Zhao *et al.*, 2003).

Moreover, PID and fuzzy logic are widely applied together to increase the efficiency of vehicle control. Aekaluk Supmanee and Tavida Maneewan (2007) have used a fuzzy PID controller as steering control to control the tuning of helicopter blades. The experimental result shows that the controller can control the tuning of helicopter–blades effectively because it can adjust the values of variables more precisely.Nurbaiti Wahid and Nurhaffizah Hassan (2012) have designed a self-tuning fuzzy PID controller for simulating aircraft pitch control. It is found that the self-tuning fuzzy PID controller can control the pitch angle of the aircraft. The study of M.Santhakumar and T. Asokan (2010) pertains to an experiment on trajectory tracking of autonomous underwater vehicle. They have compared the efficiency of gain value determination to three types of PID: 1) Ziegler-Nichols method (ZN) 2) Taguchi's tuning method (TM) and 3) self-tuning fuzzy PID controller. It is found that the fuzzy PID controller is the best in terms of tracking performance and robustness even in the presence of disturbances.

In this study the PID-fuzzy controller is applied in the simulation experiment to control a tractor to track the desired path by itself. With benefits of these two controllers, a more effective autonomous tractor is expected.

Materials and methods

To simulate the tractor movement, there are four major parts which are essential for the design of position control system. They are mathematical model, trajectory, Fuzzy PID control and position control system. The details of each part are as follows (Connor, 1996).

Mathematical Model

The mathematical model of a tractor can be divided into two parts: kinematic and dynamic models.

1. Kinematic Model

The kinematic equation of a tractor is obtained from the calculation of kinematic equation of a car like robot (Luca A.D. *et al*., 1998) with front-wheel steering and rear-wheel driving. The equation is based on the hypothesis that the tractor wheels roll without slip as shown in Figure 1 where $q = [x \quad y \quad \theta \quad \phi]$ (state variable) and x, y = position on coordinate system, θ = tractor angle compared with x axis, ϕ = front wheel angle of the tractor, L is the distance between front wheels and rear ones, ω = angular velocity of rear wheel while v_1, v_2 are the velocity of rear wheel drive and the velocity of front wheel steering, respectively. The kinematic model can be written in a matrix form as (1)

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} \cos\theta \\ \sin\theta \\ \tan\phi/L \\ 0 \end{bmatrix} v_1 + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} v_2 \tag{1}$$

Due to the curvature of the tractor which is calculated via front wheel angle as (2)

$$\sigma = \frac{\tan\phi}{L} \tag{2}$$

The kinematic model can be rewritten in the new form as follows:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \\ \dot{\phi} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ \sigma & 0 \\ 0 & \dfrac{L}{1+L^2\sigma^2} \\ \dfrac{1}{a} & 0 \end{bmatrix} \begin{bmatrix} v_1 \\ \dot{\sigma}(t) \end{bmatrix} = \bar{J}(q,\bar{V}) \times \bar{V} \tag{3}$$

where $\dot{\sigma}$ is the velocity of the tractor running in curvature and $\bar{V} = [v_1 \quad \dot{\sigma}]^T$ is set.

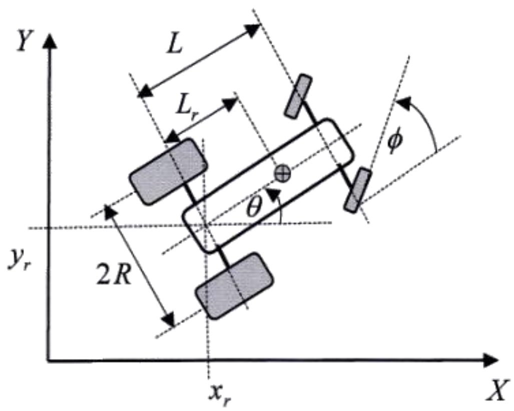

Figure 1. Position coordinate, angle, and various factors of a tractor

2. **Dynamic Model**

Regarding the simulation design of the tractor movement, its size, mass and weigh as well as kinetic and potential energy are considered.

Lagrange method is applied in order to set up an equation in form of tractor dynamic simulation as: (Yeh, C. Y. *et al*., 2009)

$$\frac{d}{dt}\left(\frac{\partial E}{\partial \dot{q}_i}\right) - \left(\frac{\partial E}{\partial q_i}\right) = Z(q)\cdot\tau \tag{4}$$

where $q_i = [x, y, \theta, \phi, \omega]^T$ and E is kinetic energy equation which can be written as (5)

$$E = \frac{1}{2}m\left(\dot{x}_r^2 + \dot{y}_r^2\right) + \frac{1}{2}I_\theta\dot{\theta}^2 + m_a\left(\dot{y}_r\cos\theta + \dot{x}_r\sin\theta\right)\dot{\theta} + 2I_w\dot{\theta}\dot{\phi} + I_w\dot{\phi}^2 + 4I_w\dot{\omega}^2 \quad (5)$$

where $m = \frac{1}{2}m_p + 2m_w$, $I_\theta = \frac{1}{2}m_pL_r^2 + 2m_wR^2 + 2I_w$, $m_a = m_pL_r + 2m_wL$

m_p = mass of the tractor, m_w = mass of the tractor wheel, I_w = moment of the inertia of the tractor wheel, I_θ = moment of the inertia of the tractor on z axis and x_r, y_r are linear velocities in Cartesian coordinates between the two rear wheels. After calculating various values to be substituted into Lagrange equation and rearranging its term, the dynamic equation of the tractor is derived as (6)

$$S(q)\ddot{q} + V(q,\dot{q})\dot{q} = Z(q)\tau \quad (6)$$

where $S(q)$ is an inertia matrix, $V(q,\dot{q})$ is a centripetal and coriolis matrix, $Z(q)$ is a transformation matrix, $\dot{q}$ is a velocity vector, $\ddot{q}$ is an acceleration vector and τ is an input torque vector. Various values are calculated to be substituted into Lagrange equation in a matrix form and the model equations of the tractor are obtained as (7) to (10) (Egerstedt. M. *et. al*., 1998)

$$S(q) = \begin{bmatrix} m & 0 & -m_a\sin\theta & 0 & 0 \\ 0 & m & m_a\cos\theta & 0 & 0 \\ -m_a\sin\theta & m_a\cos\theta & I_\theta & 2I_w & 0 \\ 0 & 0 & 2I_w & 2I_w & 0 \\ 0 & 0 & 0 & 0 & 8I_w \end{bmatrix} \quad (7)$$

$$V(q,\dot{q}) = \begin{bmatrix} 0 & 0 & -m_a\dot{\theta}\cos\theta & 0 & 0 \\ 0 & 0 & -m_a\dot{\theta}\sin\theta & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (8)$$

$$Z(q) = \begin{bmatrix} \cos\theta & \sin\theta & \rho\sin\phi\cos\phi & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}^T \tag{9}$$

Then, vector τ is set as equation (10)

$$\tau = \begin{bmatrix} \tau_v & \tau_\sigma \end{bmatrix}^T \tag{10}$$

τ_v, τ_σ are assigned as the torque-input of rear wheel driving and the torque-input of front wheel steering, respectively. The dynamic model (6) can be written in the simple form as tractor velocity ($\bar{V}$) which comes from the multiplication of dynamic equation and matrix of kinematic equation [$\bar{J}^T(q)$]. Therefore, the new dynamic model is obtained as follows:

$$\bar{S}(q)\cdot\dot{\bar{V}} + \bar{V}_m(q,\dot{q})\cdot\bar{V} = \bar{Z}(q)\cdot\tau \tag{11}$$

Where $\bar{S} = J^T SJ$, $\bar{V}_m = J^T SJ$ and $\bar{Z} = J^T Z$.

Equation (11) is conducted as matrix form as follow:

$$\bar{S}(q) = \begin{bmatrix} m + I_\theta\sigma^2 & \frac{2I_w L\sigma}{1+L^2\sigma^2} \\ \frac{2I_w L\sigma}{1+L^2\sigma^2} & \frac{2I_w L^2}{(1+L^2\sigma^2)^2} \end{bmatrix} \tag{12}$$

$$\bar{V}_m(q,\dot{q}) = \begin{bmatrix} I_\theta\sigma\dot{\sigma} & \frac{-4I_w L^3\sigma^2\dot{\sigma}}{\left(1+L^2\sigma^2\right)^2} \\ \frac{2I_w L\dot{\sigma}}{1+L^2\sigma^2} & \frac{-4I_w L^4\sigma\dot{\sigma}}{\left(1+L^2\sigma^2\right)^3} \end{bmatrix} \tag{13}$$

$$\bar{Z}(q) = \begin{bmatrix} \frac{1+2L^2\sigma^2}{1+L^2\sigma^2} & 0 \\ 0 & \frac{L}{1+L^2\sigma^2} \end{bmatrix} \tag{14}$$

The Creation of Trajectory

Normally, there are mainly two types of tractor movement. The first one is a straight line while plowing and the second one is a curve line while tuning. Thus, for this paper, the tractor trajectory with straight and curve line movements are created on the coordinate system. The equations of both types of the trajectory creation are as follows: (Luca A. D, 2015; R. Solea and U. Nunes, 2007)

1) Straight line trajectory

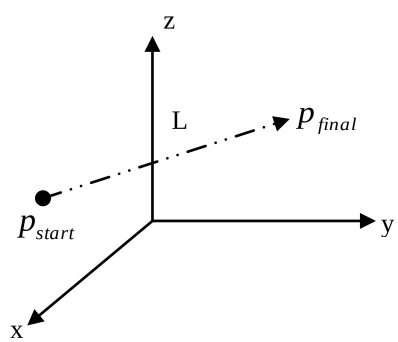

Figure 2. Straight line path

Figure 2 shows straight line trajectory of which the tractor drives in a straight line path. The starting point of the trajectory as p_{start} and the final one as p_{final} should be specified. The distance of the tractor movement from p_{start} to p_{final}, can be calculated as shown in equation (15) (Xu. Q *et al*., 2014)

$$L = p_{start} + s(p_{final} - p_{start}) \quad (15)$$

where parameter *s* is a fraction of the position and the distance of the tractor movement as shown in equation (16)

$$s = \frac{d}{l} \quad (16)$$

where l is the length of the straight line and *d* is the variable of time function which depends on the type of velocity profile of the tractor movement in a straight line as shown in Figure 3.

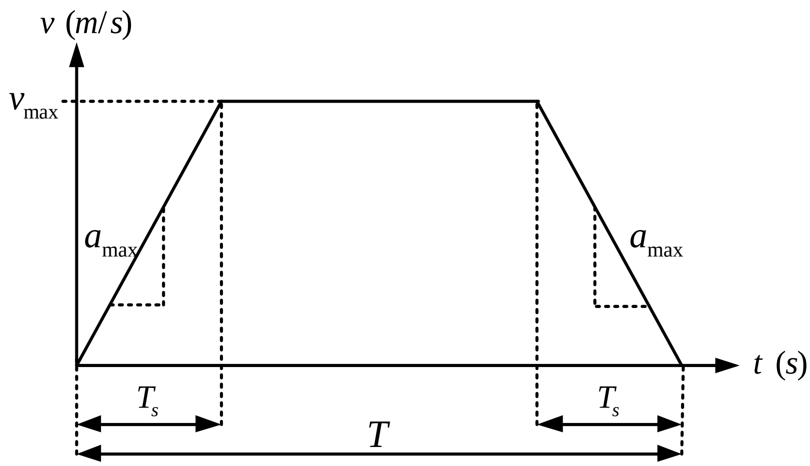

Figure 3. Velocity profile

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

$$d = \begin{cases} a_{\max}\left(\dfrac{t^2}{2}\right) & ; t \in [0, T_s] \\ v_{\max} t - \dfrac{v_{\max}^2}{2a_{\max}} & ; t \in [T_s, T - T_s] \\ -a_{\max}\left(\dfrac{(t-T)^2}{2}\right) + v_{\max} T - \dfrac{v_{\max}^2}{a_{\max}} & ; t \in [T - T_s, T] \end{cases} \tag{17}$$

where t and T are the time duration set and the real time of tractor movement from p_{start} to p_{final}, respectively, measured by seconds (s). With respect to $v_{\max}$, it is the maximum speed measured by m/s and $a_{\max}$ is the maximum acceleration measured by m/s^2, respectively.

2) Curve line trajectory

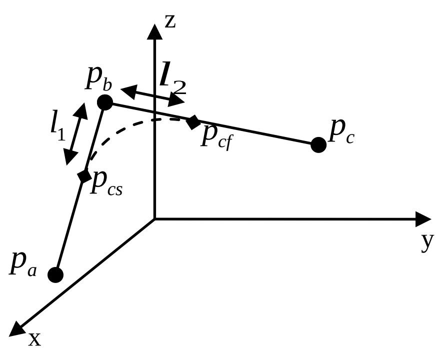

Figure 4. Curve line path

A curve line is set by connecting two straight lines together as shown in Figure 4. The first line is between p_a and p_b points, and the second one is between the two points of p_b and p_c. The curve line obtained (dashed line) starts at p_{cs} point (on the first line) and ends at p_{cf} point (on the second line). The trajectory curvature can be calculated as shown in equation (18).

$$P(t) = p_{cs} + V_1 n_{12} t + \frac{t^2}{2\Delta t}\left(V_2 n_{23} - V_1 n_{12}\right) \qquad (18)$$

where V_1 and V_2 are the speed of the tractor while running along the first and the second lines, respectively. n_{12} and n_{23} are unit vectors and Δt is time difference which can be calculated as shown in equations (19) to (21)

$$n_{12} = \frac{p_b - p_a}{\left\| p_b - p_a \right\|} \qquad (19)$$

$$n_{23} = \frac{p_c - p_b}{\left\| p_c - p_b \right\|} \qquad (20)$$

$$\Delta t = \frac{2 l_1}{V_1} \qquad (21)$$

Design of Self Tuning Fuzzy PID

The Fuzzy PID controller is designed by applying MATLAB program. The controller is divided into two functions: distance and heading controls which have a similar diagram of works. Both functions are presented in Figure 5.

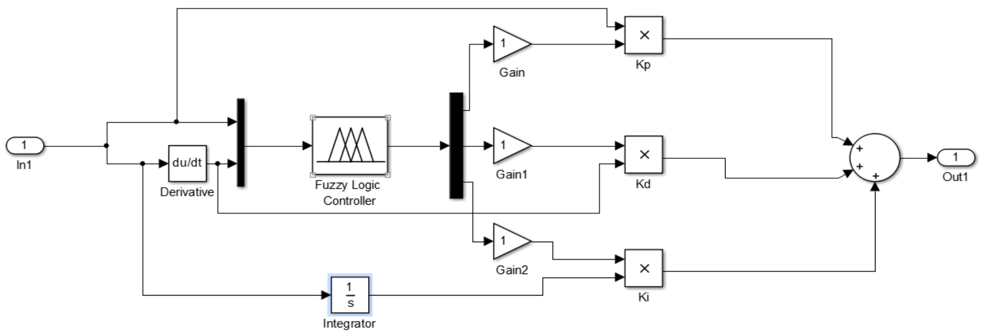

Figure 5. Diagram of Fuzzy PID controller

As Figure 5 shows, the Fuzzy PID controller obtains input values which are error *(e)* and error of the change rate ($\dot{e}$). Then, the input values are set under the fuzzy rules (if, and, then) for adjusting k_p, k_i and k_d . (Dey. C. *et al*., 2012; Jin. J. *et al*., 2013; Thailand industry. 2013; S. Junjaramanitch. 2015).

1) Fuzzication

The input information of fuzzy sets (e and $\dot{e}$) is modified in a form of various membership functions. Then, the inputs are integrated and substituted by using language variable of seven functions. They are NB, NM, NS, ZE, PS, PM, and PB. The input of membership function is shown in Figure 6 and the output set is shown in Figure 7, respectively.

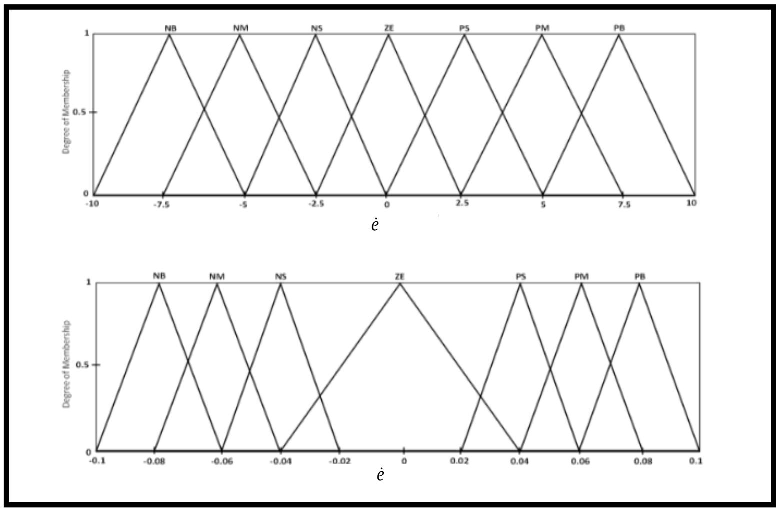

Figure 6. Input of membership function

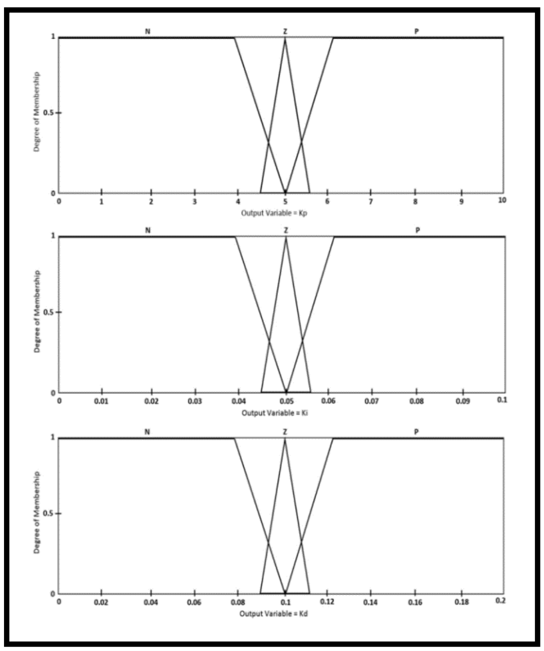

Figure 7. Output of membership function

2) Fuzzy Inference System

This process is to create a condition of membership function by using Fuzzy Rule Base (shown in Table 1) as a model in the "If, and, Then" condition.

Table 1. Membership function rule

$\dot{e}$	e **Kp** **Ki** **Kd**	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
		P	Z	N	N	N	Z	P
NB		N	P	P	N	P	P	N
		P	Z	N	N	N	Z	P
		P	P	Z	Z	Z	P	P
NM		N	Z	P	P	P	Z	N
		P	Z	Z	N	Z	Z	P
		P	P	Z	N	Z	P	P
NS		N	N	Z	P	Z	N	N
		P	P	Z	N	Z	P	P
		P	P	P	Z	P	P	P
ZE		N	N	N	Z	N	N	N
		P	P	P	Z	P	P	P
		P	P	Z	N	Z	P	P
PS		N	N	Z	P	Z	N	N
		P	P	Z	N	Z	P	P
		P	P	Z	N	Z	P	P
PM		N	Z	P	P	P	Z	N
		P	Z	Z	N	Z	Z	P
		P	Z	N	N	P	Z	P
PB		N	P	P	P	N	P	N
		P	Z	N	N	P	Z	P

The format of the fuzzy reasoning in the above table is if the tractor error (e) is NB and the tractor error change rate ($\dot{e}$) is ZE then output k_p is P, k_i is N, and k_d is P.

3) Defuzzication

After obtaining outputs from the Fuzzy Rules Base, defuzzication is applied in order to adapt the output for use.

Design of Movement Control System of the Tractor

There are two types of tractor movement control: distance and heading tractor. The loop control is also divided into two types. The equations for calculating the distance and the heading are as follows:

$$Distance = \sqrt{(x_{ref} - x_{cur})^2 + (y_{ref} - y_{cur})^2} \quad (22)$$

$$Heading = atan2((y_{ref} - y_{cur}),(x_{ref} - x_{cur})) - \theta_{cur} \quad (23)$$

where x_{ref} and y_{ref} are reference positions of tractor trajectory on x and y axis, respectively and x_{act}, y_{act} and θ_{act} are actual positions on Cartesian coordinates and the real time heading of the tractor, respectively. The distance error and the heading error are taken into account as an input of Fuzzy PID controller. Then, output signals of the Fuzzy PID controller are calculated as wheel driving velocity (v_1) and angular heading (v_2) which are input signals of tractor dynamic model. The diagram design of tractor movement control is shown in Figure 8.

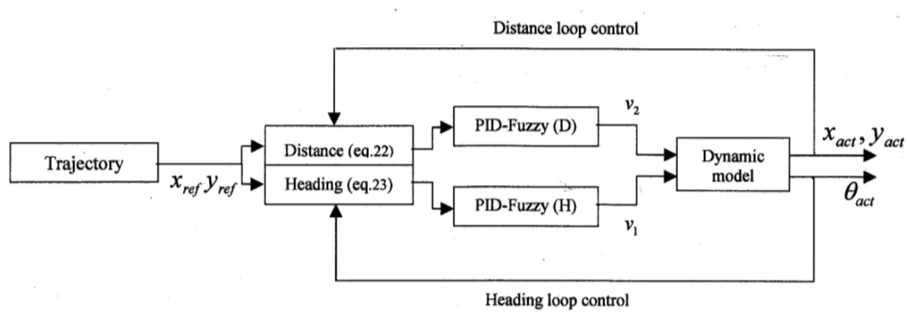

Figure 8. Diagram loop control

Results and Discussion

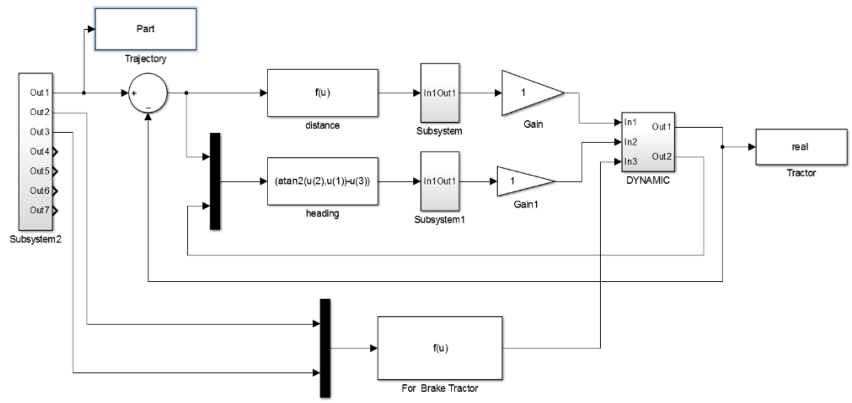

Figure 9. Simulation of dynamic model and controller via MATLAB/ Simulink Program

Figure 9 presents the simulation of dynamic model of the tractor movement by applying MATLAB/ Simulink and the design of Fuzzy PID control. The parameters in the dynamic equation of the tractor (eq.3) are shown in the following Table 2.

Table 2. Parameters of a tractor

parameter	Regular	Size	Unit
m_p	Mass of the tractor	595	kg
m_w	Mass of the tractor wheel	90	kg
I_w	Moment of the inertia of the tractor wheel	74.4	kg.m^2
I_θ	Moment of the inertia of the tractor	247.5	kg.m^2
L_r	Distance between the center of mass and the CG of the tractor	1.5	M
R	Distance between the pair of wheels	1	M
L	Distance between the front wheels and the rear wheels	2	M

The tractor trajectory is designed in a straight line as shown in Figure 10 and a curve line as shown in Figure 12 as well as the letter "N" shape which is the combination of the straight and the curve lines as shown in Figure 14. An initial condition of the simulation experiment is to define the tractor heading to y-axis at (0, 0) coordinate. The highest speed as 1 m/s and the highest acceleration as 1 m/s^2 is also identified.

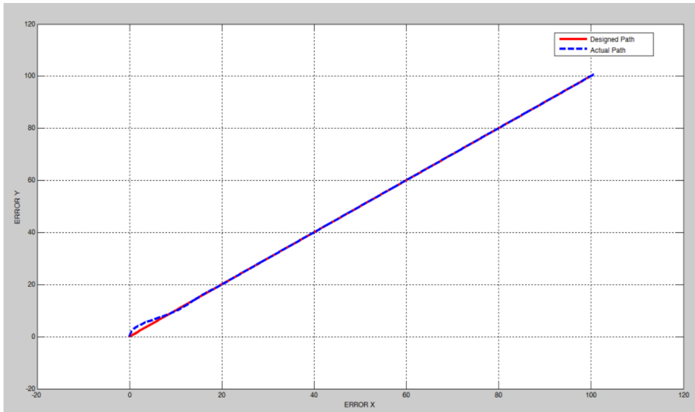

Figure 10. Straight line trajectory tracking control of the tractor

According to Figure 10, the tractor trajectory path (solid line) is set as a straight line with (0, 0) coordinate starting point and (100, 100) coordinate finishing one. It is found that the tractor is able to satisfactorily track the reference trajectory path. However, due to the tractor heading to Y axis, there is a slight error at the beginning of the path (dashed line).

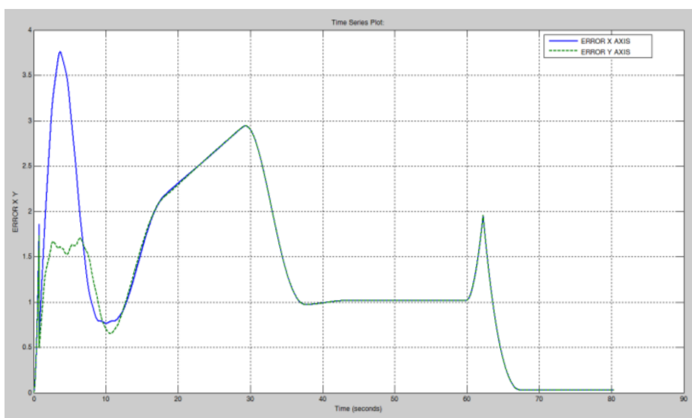

Figure 11. The errors of straight line trajectory tracking control of the tractor on X and Y axis

Figure 11 presents the errors of the straight line trajectory tracking control of the tractor on X and Y axis which are distances between the tractor and the reference trajectory. This means that the tractor moves slower than the trajectory. It is found that the highest errors of tractor trajectory tracking control on X and Y axis are 3.75 m at 3.67 second and 2.94 m at 29.4 second, respectively.

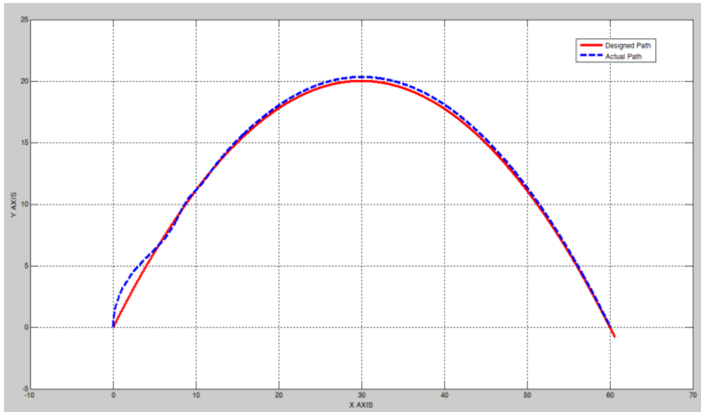

Figure 12. Curve line trajectory tracking control of the tractor

Figure 12 shows the curve line of the tractor trajectory path (solid line) of which starting point is set at (0, 0) coordinate, the middle point at (30, 20) coordinate and the finishing one at (60, 0) coordinate. It is found that the tractor is able to satisfactorily track the reference path. However, there is a slight error at the beginning of the path (dashed line) due to the tractor heading to Y axis defined.

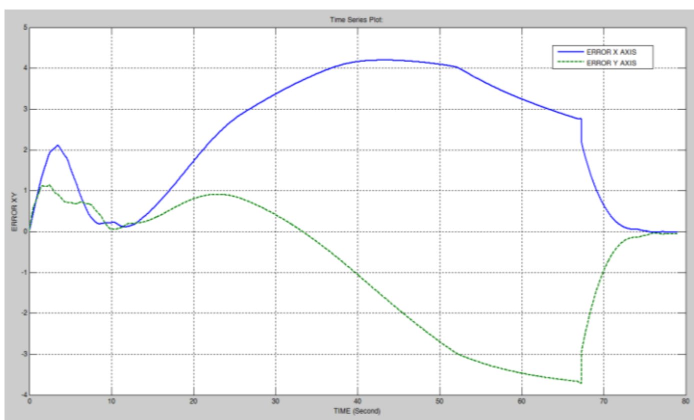

Figure 13. The errors of curve line trajectory tracking control of the tractor on X and Y axis

Figure 13 presents the errors of tractor driving in curve line trajectory on X and Y axis. The distances between the tractor and the reference trajectory are the errors. It is found that the highest errors of the tractor trajectory tracking control on X and Y axis are 4.19 at 42.9 second and -3.72 at 67.3 seconds, respectively.

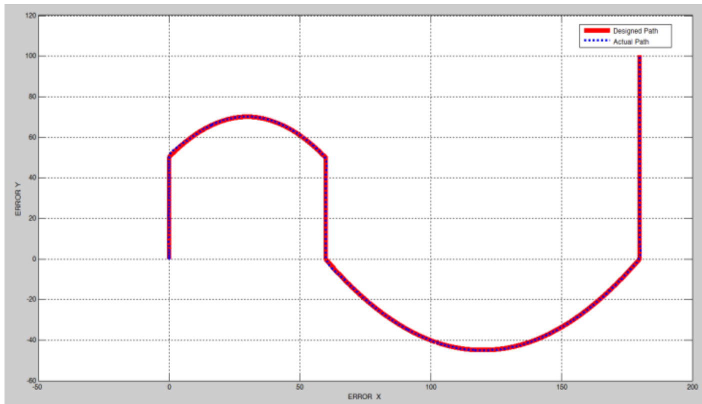

Figure 14. N shape trajectory tracking control of the tractor

Figure 14 presents the N shape of the tractor trajectory path (solid line) which consists of straight and curve lines with its starting point at (0, 0) coordinate and finishing one at (180, 100) coordinate. With respect to this kind of trajectory path, it is found that the tractor is able to completely track the reference trajectory all through the path.

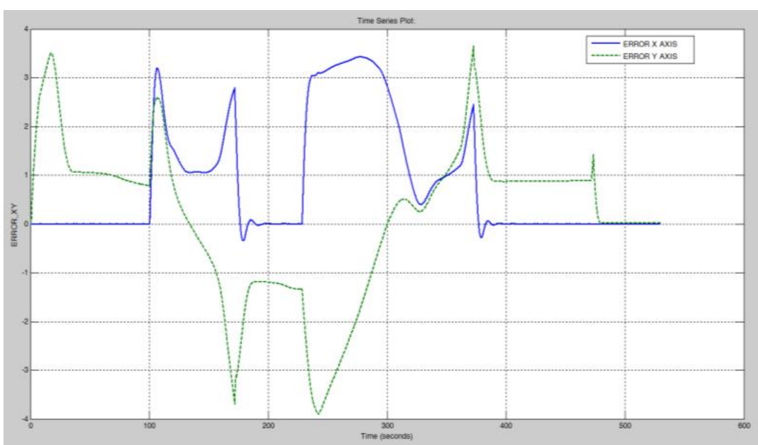

Figure 15. The errors of N shape trajectory tracking control of the tractor on X and Y axis

Figure 15 presents the errors of the N shape trajectory tracking control on X and Y axis. The distances between the tractor and the reference trajectory are the errors. It is found that the highest errors of the tractor trajectory tracking control on X and Y axis are 3.405 at 282.4 second and -3.905 at 242.1 seconds, respectively.

Conclusions

The paper presents the design of the position controller of an autonomous tractor and the creation of the tractor trajectory on a rectangular coordinate system. There are two types of the trajectory: straight and curve lines. The self-tuning fuzzy PID is used as a tractor controller with the distance and heading control loops. The tractor movement simulation using MATLAB/Simulink program is applied in the experiment. The tractor is set to drive along the trajectory of straight and curve lines connected together. It is found that the control system designed is able to control the tractor to move along the created trajectory. However, it is also found that when the tractor runs along the seam position between the straight and curve lines, the error occurred is much more than those of any other positions of the line path because the tractor movement is slower than the trajectory at that moment. This shows that the designed controller still has some restrictions as it cannot limit the errors occurred. Thus, to limit these restrictions, the development of a controller is needed. For instance, an adaptive controller with error limitations at a particular position is recommended.

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