FUZZY DYNAMIC SURFACE CONTROL FOR 4-DOF PLATFORM IN CAR DRIVING SIMULATORS

THIẾT KẾ BỘ ĐIỀU KHIỂN MẶT ĐỘNG - MỜ CHO ROBOT SONG SONG 4 BẬC TỰ DO ỨNG DỤNG TRONG HỆ THỐNG MÔ PHỎNG LÁI XE

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ABSTRACT

In this paper, a control method using dynamic surface control (DSC) combined with fuzzy law is proposed for a four degrees of freedom car driving simulator. The DSC technique simplified the backstepping design by overcoming the problem of "explosion of complexity". By incorporating the fuzzy law into this technique, the control parameters are tuned in to be more flexible and appropriate in each period. The system's stability is proven to satisfy the Lyapunov theorem. The simulation results show the effectiveness and efficiency of the method.

Keywords: *Dynamic Surface Control; Fuzzy law; Lyapunov theorem; driving simulator; 4DOF robot.*

TÓM TẮT

Trong bài báo này, phương pháp điều khiển mặt động (DSC) kết hợp cùng luật mờ (fuzzy) được đề xuất để điều khiển hệ thống robot 4 bậc tự do sử dụng trong mô phỏng lái xe. Kỹ thuật DSC đã cải thiện những vấn đề ở điều khiển Backstepping thường dùng, trong đó đặc biệt là vấn đề "explosion of complexity". Bằng cách áp dụng luật mờ vào thiết kế này, các thông số điều khiển được tự động chỉnh định sao cho phù hợp với mỗi thời điểm. Tính ổn định của hệ thống đã được chứng minh thỏa mãn tiêu chuẩn ổn định Lyapunov. Kết quả mô phỏng cho thấy tính hiệu quả của phương pháp điều khiển.

Từ khóa: *Điều khiển mặt động; điều khiển mờ; luật Lyapunov; mô phỏng lái xe; 4DOF robot.*

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1. INTRODUCTION

In many industrial fields, simulation models such as aircraft driving practice model, driving simulation, checking automobile tires are playing an important role and creating tremendous strides. Especially, in the automotive industry, driving simulators offer a perfect tool to evaluate the potential influence on driving performance when applying new in-vehicle technology. In order to obtain the proper immersion sensation for the driver in the virtual reality environment, this paper focuses on developing the robotic platform constructed based on the parallel structure [1]. One of the most popular models is the 6 degrees of freedom (6DOF) model with high precision and far reach [2]. However, this research proposed a smaller and more affordable model of the four degrees of freedom (4DOF) robotic platform, which reducing the cost and unnecessary complexity in control while still maintaining the powerful and fast responsive qualities. The model is constructed with the movements that are translation along the OZ axis and rotation along OX, OY and OZ axes.

For the control method, numerous control approaches have been studied and proposed to achieve the acceptable control qualities as in [3 - 5]. One of the most common method which draws lots of attention by many researchers is the use of Backstepping control to satisfy the requirement of motion [6]. Nevertheless, according to [7], the drawback of the backstepping technique is the problem of "explosion of complexity" or "explosion of terms" when the model has more parameters and degrees of freedom, which made it extremely difficult to implement in practice. Dynamic surface control (DSC) as in [7, 8] was, therefore, developed as an alternative to backstepping approach. With the ability to overcome the problem encountered when using a first-order filter so that the relative degree of the output can be controlled. It is shown that these low pass filters allow a design where the model is not differentiated, thus ending the complexity arising in other methods, making DSC more possible to carry out in practice. Moreover, the DSC approach, being simpler to implement, can still guarantee boundedness of tracking error semi globally, when the non-linearities in the system are non-Lipschitz.

In this research, DSC technique is applied in designing the control system for the platform without any driver or object and the mass of the driver or the object placed on the platform will be considered as the disturbances. However, in fact, the mass of the objects can vary over a large range. And therefore, the surface coefficients must be chosen to maintain tracking qualities in the presence of disturbances. In addition, since the disturbance as defined in this problem can be massive, this approach requires the input control signals to be huge as well and the saturation phenomenon is generated. Despite the ability of coping with disturbance of the DSC design, this drawback in the "explosion" of input signal reduces the qualities of the system tremendously. And especially, makes it less possible to implement in practice. To overcome this problem, a controller based on dynamic surface technique with the aggregation of fuzzy logic is proposed. In many other studies, the fuzzy logic systems have been often used to approximate the unknown nonlinear functions as in [9, 10] because of their universal approximation properties [11] or input saturation as in [12, 13]. In this case, the fuzzy logic part will act as a feedforward controller that determine the feedforward control signals added to the input control signal from the DSC part. When the tracking errors increase, the feedforward control signals will be chosen as big enough to maintain tracking process, enhancing the system quality. The combination of DSC and Fuzzy here has increased the "adaptability" of the system. The method thoroughly solved the problem of controlling the system at the presence of disturbances in a wide range, with a feasible control signal.

In this study, the group of authors focuses on constructing an adaptive controller for the car driving simulator model in the presence of unknown disturbances. This paper proposed a control method based on DSC technique combined with fuzzy law. To demonstrate the proposed design and illustrate the performance of the system, this paper is organized as follow: In Section 2, the mathematical model of the robotic platform is constructed. In Section 3, the proposed DSC controller combined with fuzzy law is given with the stability of the system proven. In Section 4, the simulation is conducted with numerous setups to verify the performance and the effectiveness of the proposed controller compared to the traditional DSC design. The results are then discussed. In Section 5, the conclusion is given.

2. MATHEMATICAL MODEL

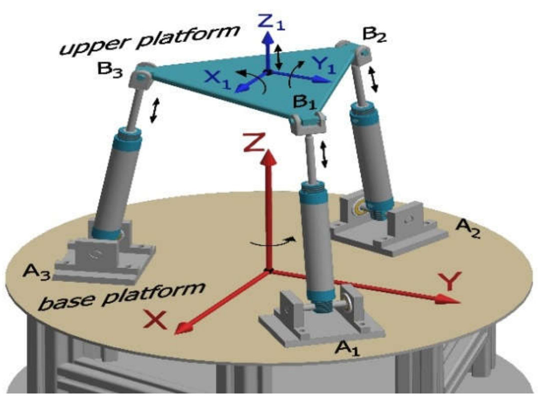

Figure 1. 4DOF car driving simulator system

Figure 1 shows the car driving simulator's mechanism model with the coordinates are chosen. The motion of the mobile pane is due to the movement of three pistons and the rotation of the rotating shaft attached below the fixed panel.

Using the Lagrange equations with multiplier for constrained systems, the algebraic-differential equations (DAE) of motion of car driving simulator can be written in the compact matrix form:

$$\bar{M}(x)\ddot{x} + \bar{C}(x,\dot{x})\dot{x} + \bar{g}(x) = \tau - \Phi_x^T\lambda \tag{1}$$

And $c_i(x) = 0, \quad i=\overline{1,3}$ (2)

$c_i(x)$ is a system of three geometric constraints $c_i = l_i - \|A_iB_i\|_2 \ (i = 1,2,3)$ where l_1 is an accurate length of the pistons and A_iB_i is a computational length. The configuration of the system is represented by a vector $x = \left[q^T, p^T\right]^T$ comprising of 4 active coordinates q, three passive coordinates $p = [p_z, \ \alpha, \ \beta]^T$, $\bar{M}(x)$ is the mass matrix with a size of 7x7, $\bar{C}(x,\dot{x})$ is the Coriolis and centrifugal matrix determined from the mass matrix, $\bar{g}(x)$ is generalized forces due to the potential energy and vector λ with size of 3x1 contains Lagrange multipliers.

In the Eq. (1) the Jacobian matrix is defined as follow

$$\Phi_x(x) = \frac{\partial c}{\partial x} = \begin{pmatrix} \frac{\partial c_1}{\partial q} & \frac{\partial c_1}{\partial p} \\ \frac{\partial c_2}{\partial q} & \frac{\partial c_2}{\partial p} \\ \frac{\partial c_3}{\partial q} & \frac{\partial c_3}{\partial p} \end{pmatrix} = [\Phi_a(x), \Phi_z(x)] \tag{3}$$

In order to eliminate the Lagrange multipliers in Eq. (1) and transform it to the form of minimal coordinates, the following relation is introduced:

$$\dot{x} = R(x)\dot{q} \tag{4}$$

With $R(x) = \begin{pmatrix} E_{3\times3} \\ -\Phi_z^{-1}\Phi_a \end{pmatrix}$ (5)

Noting that the matrix R(x) defined by (4) satisfies:

$$R^T\Phi_x^T = 0 \tag{6}$$

Multiply from link both sides of Eq. (1) with $R^T(x)$ undertaken into account of (6) yields:

$$M\ddot{q} + C\dot{q} + D = F \tag{7}$$

Where $M = R^T\bar{M}R, C = R^T\bar{M}\dot{R} + R^T\bar{C}R, D = R^T\bar{g}, F = R^T\tau$ (8)

The dynamic model of 4DOF Car Driving Simulator system is described by:

$$M\ddot{q} + C\dot{q} + D = F \tag{9}$$

Where $q = [l_1 \quad l_2 \quad l_3 \quad \gamma]^T$: l_1 is the length of the piston i (i = 1, 2, 3) and γ is the rotation angle around OZ axis.

$I_{px}, I_{py}, I_\gamma, m_2, m_{dc}$ and m_p are moment of inertia about axis x, axis y, axis z, the mass of pistons, the mass of motors on the cylinders and the mass of the mobile panels, respectively.

$F=\begin{bmatrix}F_1 & F_2 & F_3 & \tau_\gamma\end{bmatrix}^T$ is the control signal vector.

Matrices M, C and D are defined as follow ($g \approx 9.8\,(m/s^2)$ is the gravity acceleration):

$$M=\begin{bmatrix}\left(m_2+m_{dc}+\frac{m_p}{9}+\frac{I_{py}}{4a^2}\right) & \frac{m_p}{9} & \frac{m_p}{9} & 0\\ \frac{m_p}{9} & \left(m_2+m_{dc}+\frac{m_p}{9}+\frac{I_{px}}{12a^2}\right) & \frac{m_p}{9} & 0\\ \frac{m_p}{9} & \frac{m_p}{9} & \left(m_2+m_{dc}+\frac{m_p}{9}\right) & 0\\ 0 & 0 & 0 & I_\gamma\end{bmatrix}$$

$$C=\begin{bmatrix}\frac{15I_{py}\dot{l}_1^2}{4a^4} & 0 & 0 & 0\\ 0 & \frac{5I_{px}\dot{l}_2^2}{12a^4} & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\end{bmatrix}$$

$$D=\left(m_2+\frac{m_p}{3}\right)g\begin{bmatrix}1 & 1 & 1 & 0\end{bmatrix}^T x$$

3. FUZZY DYNAMIC SURFACE CONTROL

3.1. DSC controller for system serving bounded mass of object

This section focuses on steps to design the DSC controller for car driving simulation. The algorithm's aim is to lead the position of the car driving simulator to desired values and the controller is generated by the DSC technique.

The model can be rewritten as follows to facilitate the control design process

$$\begin{cases}\dot{x}_1 = x_2\\ \dot{x}_2 = M^{-1}u - M^{-1}(Cx_1 + D) + \Delta\phi(x)\end{cases} \tag{10}$$

where $x_1 = q$ and $\Delta\phi(x)$ is unknown bounded element and $\left|\Delta\phi(x)_i\right| \le \rho_i, i=\overline{1,4}$. Consider bounded mass of object as an one of components of $\Delta\phi(x)$. Defining tracking variables below:

$$e_1 = x_1 - x_d, e_2 = x_2 - x_{2d} \tag{11}$$

where x_d is the desired trajectory of the system. The idea is to use virtual control signal x_{2d} generated through Backstepping technique to have $e_1 \to 0$. Considering a Lyapunov candidate function:

$$V_1 = \frac{1}{2}e_1^Te_1 \tag{12}$$

Taking derivative of V_1 we get:

$$\dot{V}_1 = e_1^T\dot{e}_1 = x_2 - \dot{x}_d \tag{13}$$

Choose $x_{2d} = \dot{x}_d - k_1e_1$, therefore

$$\dot{V}_1 = -ke_1^{\,2} + e_1e_2 \tag{14}$$

By using DSC technique, hence the synthetic input x_{2d} is renamed as $\overline{x}_2 = \dot{x}_d - k_1e_1$ and $\overline{x}_2$ is pass through a first-order filter:

$$\tau\dot{x}_{2d} + x_{2d} = \overline{x}_2, \quad x_{2d}(0) = \overline{x}_2(0) \tag{15}$$

where τ is the filter time constant. Taking derivative of e_2 with respect to time, we obtain:

$$\dot{e}_2 = M^{-1}u - M^{-1}(Cx_1 + D) + \Delta\phi(x) - \dot{x}_{2d} \tag{16}$$

Using the filter signal $\overline{x}_2$ instead of x_{2d}. Then the control input is obtained by:

$$u = M\left[-(Cx_1 + D) - k_2e_2 + \frac{\overline{x}_2 - x_{2d}}{\tau} - e_2\frac{\rho^2}{2\varepsilon}\right] \tag{17}$$

where ε is an arbitrary positive constant. Defining the filter error $\xi_2 = x_{2d} - \overline{x}_2$ and including the low-pass filter property in (15), the augmented closed-loop dynamics are:

$$\begin{aligned}&\dot{e}_1 = -k_1e_1 + e_2 + \xi_2,\\ &\dot{e}_2 = -k_2e_2 + \Delta\phi(x) - e_2\frac{\rho^2}{2\varepsilon},\\ &\dot{\xi}_2 = \frac{-\xi_2}{\tau} - \frac{d}{dt}(\dot{x}_d - ke_1) = \frac{-\xi_2}{\tau} + \sigma\end{aligned} \tag{18}$$

Where σ is nonlinear function. The Lyapunov candidate function is chosen as:

$$V = \frac{e_1^Te_1 + e_2^Te_2 + \xi_2^T\xi_2}{2} \tag{19}$$

The derivative of V is:

$$\begin{aligned}\dot{V} &= e_1^T\dot{e}_1 + e_2^T\dot{e}_2 + \xi_2^T\dot{\xi}_2\\ &= e_1^T(e_2 + \xi_2 - k_1e_1) + e_2^T\left(-k_2e_2 + \Delta\phi(x) - e_2\frac{\rho^2}{2\varepsilon}\right) + \xi_2^T\left(\frac{-\xi_2}{\tau} + \sigma\right)\\ &\le \frac{2e_1^Te_1 + e_2^Te_2 + \xi_2^T\xi_2}{2} - k_1e_1^Te_1 - k_2e_2^Te_2 + \varepsilon - \frac{\xi_2^T\xi_2}{\tau} + \frac{\xi_2^T\xi_2\sigma\sigma^T}{2\varepsilon}\end{aligned} \tag{20}$$

where the inequality come from Young's inequalities:

$$\frac{e_1^Te_1 + e_2^Te_2}{2} \ge e_1^Te_2, \quad \frac{e_1^Te_1 + \xi_2^T\xi_2}{2} \ge e_1^T\xi_2,$$

$$\frac{e_2^Te_2\rho^2}{2\varepsilon} + \frac{\varepsilon}{2} \ge e_2^T\rho \ge e_2^T\Delta\phi, \quad \frac{\xi_2^T\xi_2\sigma\sigma^T}{2\varepsilon} + \frac{\varepsilon}{2} \ge \xi_2^T\sigma$$

Consider the set:

$$B = \left\{z \,\middle|\, e_1^Te_1 + e_2^Te_2 + \xi_2^T\xi_2 \le 2p\right\} \tag{21}$$

$$z = \begin{bmatrix}e_{11} & e_{12} & e_{13} & e_{14} & e_{21} & e_{22} & e_{23} & e_{24} & \xi_{21} & \xi_{22} & \xi_{23} & \xi_{24}\end{bmatrix}^T, z\in\mathbb{R}^{12}, p>0$$

$$e_1 = x_1 - x_d = \begin{bmatrix}l_1 - l_{1d} & l_2 - l_{2d} & l_3 - l_{3d} & \gamma - \gamma_d\end{bmatrix}^T = \begin{bmatrix}e_{11} & e_{12} & e_{13} & e_{14}\end{bmatrix}^T$$

$$e_2 = \begin{bmatrix}e_{21} & e_{22} & e_{23} & e_{24}\end{bmatrix}^T, \xi_2 = \begin{bmatrix}\xi_{21} & \xi_{22} & \xi_{23} & \xi_{24}\end{bmatrix}^T$$

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which is compact and convex, then the elements of σ satisfy $\sigma_i \le K_i$ and $K = [K_1 \quad K_2 \quad K_3 \quad K_4]^T$.

On the set B we choose:

$$K_0 > \frac{\varepsilon}{p}, \text{ and } k_1 = 1 + K_0, k_2 = \frac{1}{2} + K_0,$$

$$\frac{1}{\tau} = \frac{1}{2} + \frac{K^T K}{2\varepsilon} + K_0 \quad (22)$$

The inequality (20) is written as:

$$\dot{V} \le -2K_0 V + \varepsilon - \left(1 - \frac{\sigma\sigma^T}{K^T K}\right)\frac{K^T K \xi_2^T \xi_2}{2\varepsilon} \quad (23)$$

Therefore $\dot{V} \le -2K_0 V + \varepsilon$. Because $K_0 > \frac{\varepsilon}{p}$ and $e_1^T e_1 + e_2^T e_2 + \xi_2^T \xi_2 \le 2p$, it is obvious that $\dot{V} < 0$. This guarantees asymptotical stability of system.

3.2. Fuzzy controller aggregated to overcome large mass disturbance

The DSC controller above is designed to control car driving simulation system when the mass of object assigned in the mobile panels is considered as the disturbances. In the actuality, this system is used for the quantity of object with various mass. So, the surface coefficients must be chosen as the appropriate numbers to interfere disturbances. In this case, this must be big numbers, however the disadvantage of method are the input control signals will be huge and the saturation phenomenon is generated. Finally, the quality of system decreases dramatically.

To handle this problem, a controller-based DSC aggregated fuzzy logic is proposed. Fuzzy logic-based tracking errors will determine feedforward control signals that are added to input control signal. When the tracking errors are large, the feedforward control signals will be chosen as large enough to maintain tracking process We design 3 fuzzy models for tuning four control signals F. The fuzzy controller acts like the P component in PID controller. The input of fuzzy controller is difference between q_{out} and q_{ref}.

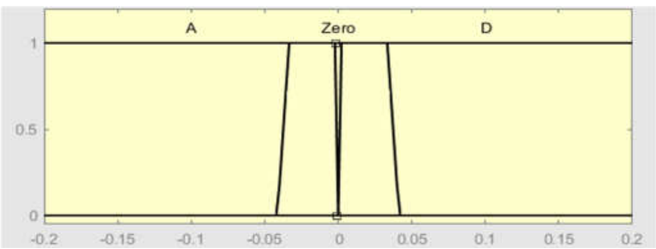
Consider the fuzzy model as follow:

R^1: If e is A_1 then $\underline{y} = \underline{\kappa}_1(x)$,

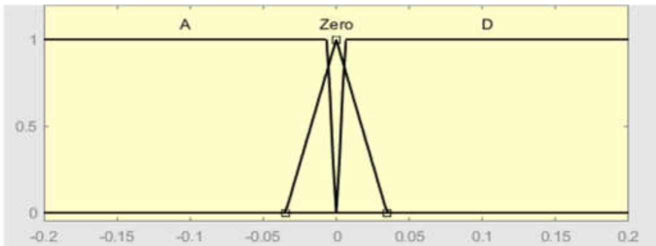
R^2: If e is A_2 then $\underline{y} = \underline{\kappa}_2(x)$,

R^3: If e is A_3 then $\underline{y} = \underline{\kappa}_3(x)$,

Where $\underline{e} = \underline{q}_{ref} - \underline{q}_{out}$. $A = [N \quad Z \quad P]$, $\underline{\kappa}_i(x)$ is linear function.



a)



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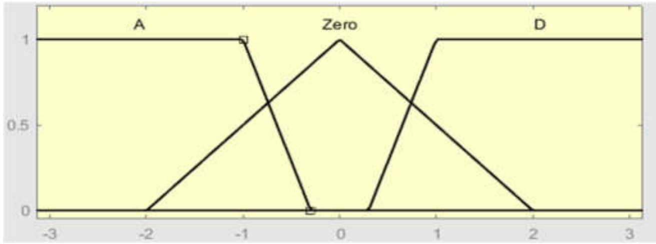


c)

Figure 2. Fuzzy input for F_1 (upper), F_2, F_3 (middle), F_4 (lower)

Table 1. Fuzzy law

$q_1 - q_{iref}$	F_i
N	P
Zero	Zero
P	N

Table 2. Output of the Fuzzy law

F_1	N	20x - 550
	Zero	-2000x
	P	-20x + 550
F_2, F_3	N	20x - 500
	Zero	-1000x
	P	-20x + 500
F_4	N	20x
	Zero	0.1x
	P	20x

Where F_i is the *i*th output of 4-members Sugeno fuzzy controller.

The preceding Fuzzy model is specified as follow:

R^1: If e is negative then $F_1 = 20x - 550, F_2 = 20x - 500, F_3 = 20x - 500, F_4 = 20x$,

R^2: If e is zero then $F_1 = -2000x, F_2 = -1000x, F_3 = -1000x, F_4 = 0.1x$,

R^3: If e is zero then $F_1 = -20x + 550, F_2 = -20x + 500, F_3 = -1000x, F_4 = 20x$,

The block diagram of control strategy is below:

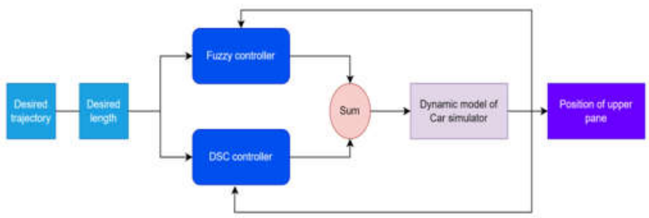


Figure 3. Block diagram

4. SIMULATION RESULTS AND DISCUSSION

In this section, the performance of the controller is illustrated and evaluated through the MATLAB/Simulink environment in which the system is assumed to be experienced external impacts of the system operators. Besides, system parameters are $m_p = 30$kg; $m_1 = 0.5$kg; $m_2 = 10$kg; and $m_{dc} = 3$kg. The cotroller parameters are chosen as $\tau = 0.09$, $k_1 = 4$. The simulation scenario is that the weight of person slightly varies around 900N.

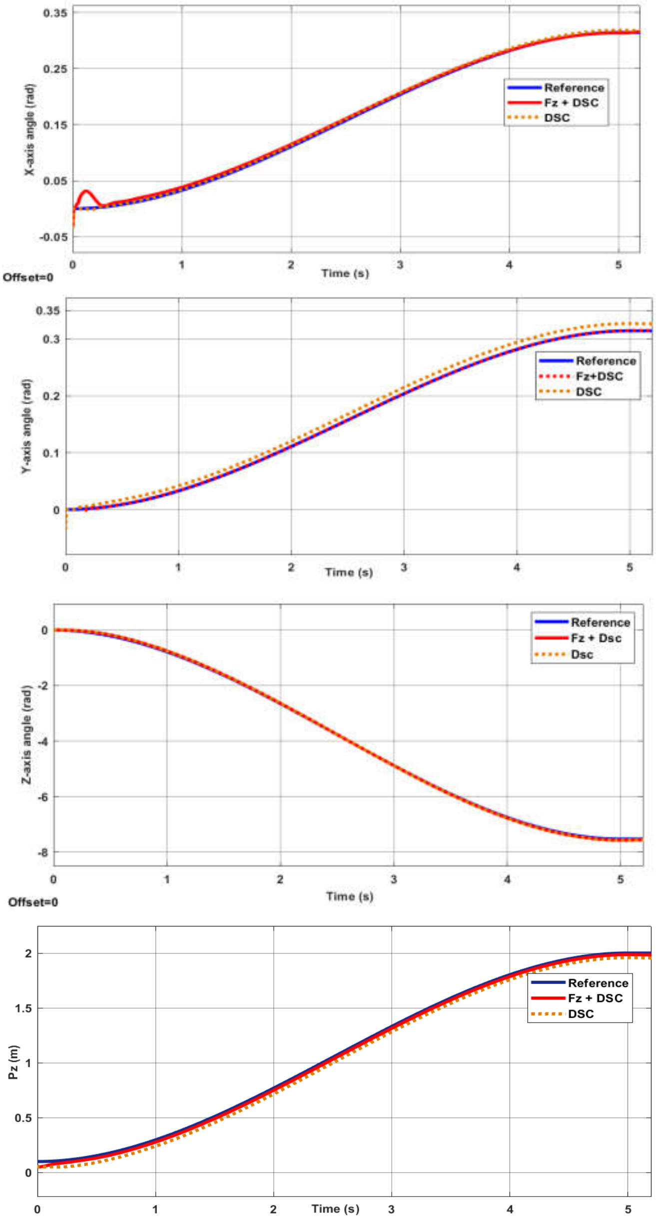


Figure 4. Trajectories of α, β, γ and P_z

The results are shown in a comparison between the conventional Dynamics Surface Control (DSC) and proposed controller (DSC aggregated with Fuzzy Law). Due to the presence of disturbance (the weight of person sitting on CDS), the DSC controller performs inaccurate outputs, especially in Figure 4, there is a static error in y-axis rotation tracking. On the other hand, the proposed method shows the higher quality when tracking so closely to reference signals. Figure 5 and 6 demonstrating the tracking error of DSC and proposed controller insists our comments. The tracking error of DSC controller is damping but always greater than 0.02. Besides, from 5^{th} second, the error seems increasing while the DSC and Fuzzy controller help quick stable with very small error. In general, Fuzzy-DSC controller shows higher accuracy and quick stability than the DSC controller, thus enhance the overall quality of the system. According to these figures, the proposed controller designed by integrating Fuzzy Law into the DSC method can ensure the stability and tracking performance for the system.

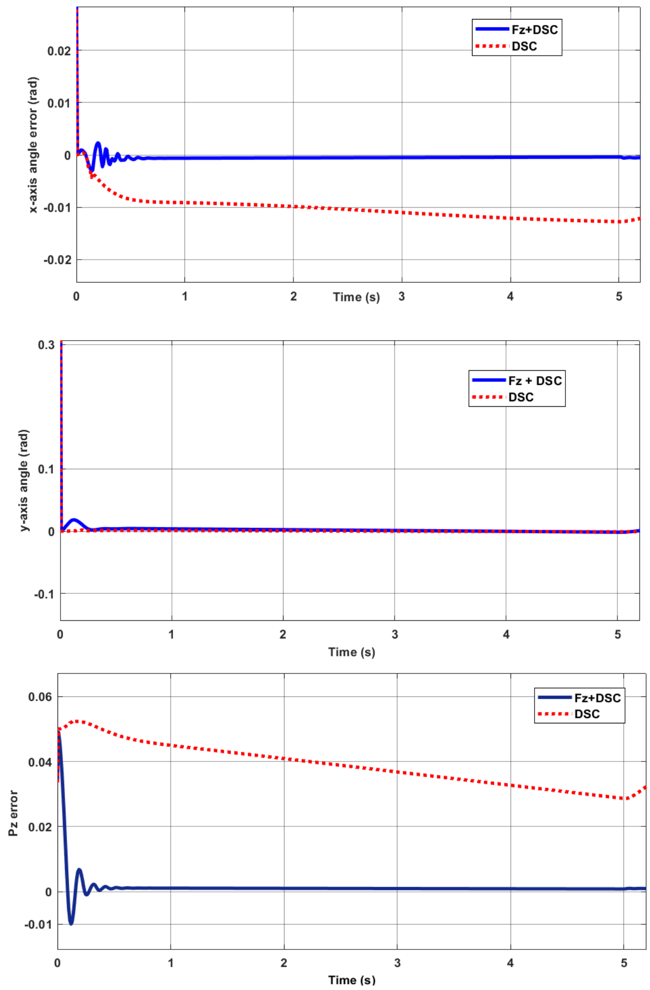
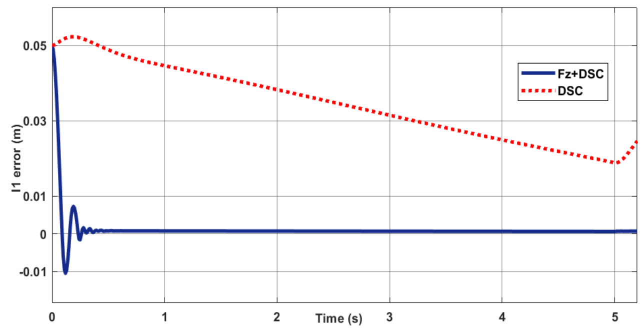


Figure 5. Tracking errors of α, β and P_z



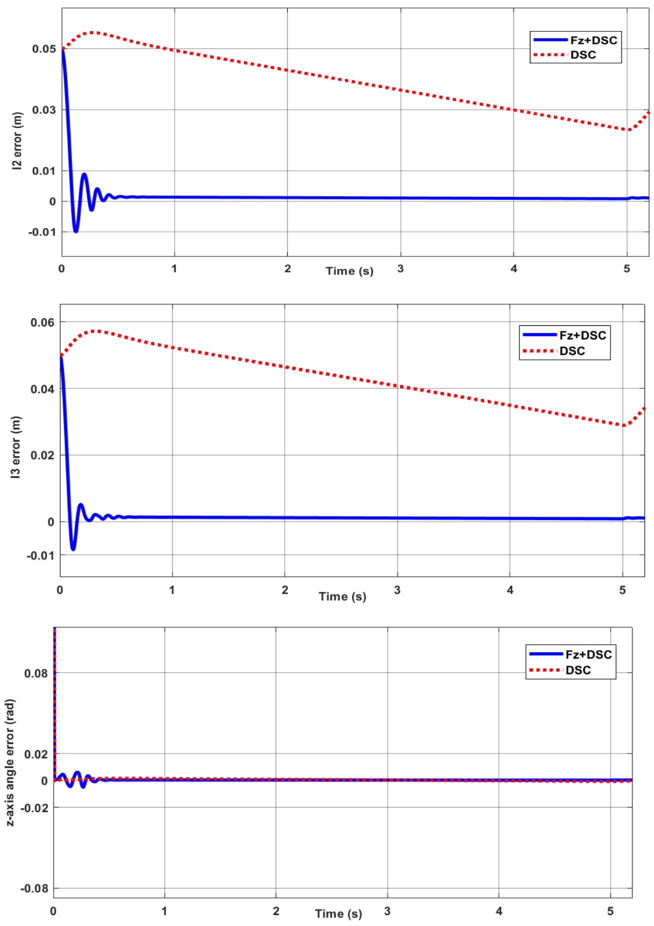


Figure 6. Tracking errors of l_1, l_2, l_3 and γ

5. CONCLUSION

This paper proposed the controller using DSC combined with fuzzy law for the 4DOF platform using in car driving simulators. The dynamic surface control guaranteed system stable with disturbances in certain parts of the system, while fuzzy tuning schemes are employed to ensure the system approach the sliding surface flexibly and quickly in the presence of system's uncertainties. Overall, the designed controller is proven to solve the problems mentioned and showed the effectiveness of the technique. The simulation results illustrated the superior performance in control quality of the proposed controller in compared to the model-based DSC technique. In the future work, we are looking forward to developing a robustness controller to deal with the model affected by unknown external forces.

ACKNOWLEDGEMENT

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