Lafi ALNUFAIE[1,*]

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A based self-acclimatizing nonsingular fast terminal sliding mode controller for container cranes robot

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This paper deals with design of nonsingular fast terminal sliding mode controller for a Container Cranes Robot. To attain the control objectives, a dynamic model allowing to control linear and angular moving is derived. A nonsingular fast terminal sling mode controller equipped with an adaptive gain is elaborated. This gain is provided by an adaptive type-2 fuzzy system adjusted according to an adaptation law deduced from the stability analysis. Simulation results are given to show the efficiency of the proposed method.

Keywords: Nonsingular Fast Terminal Sliding Mode Control,Type-2 Fuzzy Systems

1. Introduction

The robotic container crane systems can be considered as crucial elements in the transport chain of heavy cargoes, which allow to attain the desired position within a given interval time, with a very small swaying angle of the rope. From an academic point of view, a robotic container crane system can be considered a complex coupled nonlinear under actuated mechanical system, and moreover, where the number of independent control inputs is less than the number of freedom degrees [1], [2], [3]. So, the main control objective is to effectively transfer containers from one position to another, which is achieved by simultaneously controlling the actuated trolley position and the underactuated payload swing angle[4], [5]. This objective can be considered as a great challenge since we must reach a given point quickly with great precision while reducing the swing angle as much as possible, satisfy two contradictory constraints. Note that under actuated structure of this kind of systems leads to much difficulty for both controller design and stability analysis [3], [6] .To avoid the sway phenomenon, an input shaping control has been proposed [7],[8]. The main principle of these approaches is the command profiles are generated by convolving a time-optimal control signal that satisfies defined constraints and anappropriate shaper. Nevertheless, this kind of controllers loses its performance in the presence of uncertainties and external disturbances [9], [10]. We can cite also approaches

* Corresponding author: Lafi ALNUFAIE, Department of Electrical Engineering, Email: lalnufaie@su.edu.sa
[1] Department of Electrical Engineering College of Engineering , Shaqra University, Shaqra 11961,Saudi Arabia.

based on feedback linearization controller [9], [11], adaptive control [12], [13] andnonlinear predictive control[14], [15]. The common disadvantage of these approaches liesin the influence of uncertainties and disturbances on their performance since they are not robust. Sliding model control has been widely used in the literature to cope with uncertainties and external disturbances to control nonlinear systems due to its resilience against matched perturbations during the sliding phase [16], [17]. Considered as a special type of variablestructurecontrol, Sliding Mode Control is characterized by adiscontinuous control structure that switches as the system crosses certain manifold in the state space to drive the system trajectory to reach and subsequently remain on the sliding manifold. This leads to chattering phenomenon which considered as a very dangerous behavior because it can lead to system damaging. To overcome this problem, Ngo and Hong have proposed in [9], [12] to use an adaptive gain in the switching signal combined with saturation function, which can reduce the control performance and the robustness of the sliding mode control method. In [17], [18], a moving sliding manifold was proposed where an adaptive neuro-fuzzy inference system was used to generate the value of the manifold slope. However, the linear structure of sliding surface, with fixed or variable constant, does not guarantee the convergence to zero in a finite time. So, terminal sliding mode control has been presented as an alternative solution by introducing a nonlinear term in the control law to ensure the convergence of the tracking error on the sliding mode surface to zero in a limited time [1], [10]. Nevertheless, the classical terminal sliding mode control suffers from the possible occurrence of singularity problem (unbounded control signal) during approaching phase or sliding one ($s = 0$)[19]. To avoid singularity problem, an improved version of these approach, so-called Nonsingular terminal sliding mode control has been proposed, witch certainly allows to preserve the finite time convergence characteristics but this time becomes slower [20], [21]. Thus, nonsingular fast terminal sliding mode control can be considered as a solution to this problem by ensuring good robustness, avoiding singularity problems and guaranteeing convergence in a finite and fast time [22], [23]. In this paper, we propose a nonsingular fast terminal sliding mode controller for a Container Cranes Robot. Since the system is an under actuated system, we use the system modeling given in [9] to control withe the same single input to control both the horizontal displacement and the swing angle. Using Lyapunov approach, we show that the elaborated controller allows to attain the tracking objective in a finite time. To improve the design procedure, we have introduced an adaptiveintervaltype-2 fuzzy system to generate automatically theswitching gain according to an adaptation law deduced from the stability analysis. this choice is motivated by the capability of this kind of system to be insensible to uncertainties and measurement noise. The paper is organized as follows. In Section 2, the system dynamicsof a container crane are derived. In Section 3, the nonsingular fast terminal sliding mode controller is proposed, and the system stability is analyzed. The improved controller using an adaptive type-2 fuzzy system is presented in section 4, with type-2 fuzzy systemstructure and the new stability analysis. In Section 5, simulation results of the closed-loop system are discussed. Finally, in Section 5, conclusions are given.

2. Dynamicalmodelofroboticcontainercrane

A simplified diagram of a robotic container crane is given by figure. 1, where X is the horizontal displacement of the robot; θ is the load swing angle; m_r and m_l are the weights of the robot body and the load, respectively; and l and f are the length of the rope and the driving force of the robot, respectively. Assuming that the entire system is fiction-free and the ropes have no mass and undergo no elastic deformation, and using both kinetic and potential energy expression, the dynamic of the robot system can be described by:

$$\ddot{X} = a_1 + b_1 \cdot f \tag{1}$$

$$\ddot{\theta} = a_1 + b_1 \cdot f$$

$$a_1 = \frac{m_l\, g\, \sin(\theta)\cos(\theta) + m_l l \dot{\theta}^2 \sin(\theta)}{m_r + m_l \sin^2(\theta)}$$

$$b_1 = \frac{1}{m_r + m_l \sin^2(\theta)}$$

$$a_2 = \frac{-(m_r - m_l)g\, \sin(\theta) + m_l l \dot{\theta}^2 \sin(\theta)\cos(\theta)}{m_r l + m_l \sin^2(\theta)}$$

$$b_2 = \frac{\cos(\theta)}{m_r l + m_l \sin^2(\theta)}$$

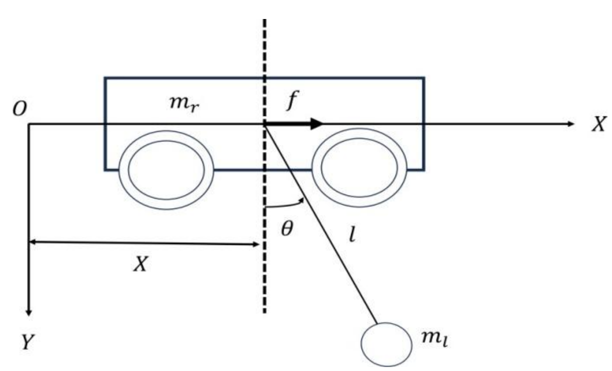

Figure1: Schematic illustration of a container crane.

If we define the state vector as:

$$x = [x_1, x_2, x_3, x_4]^T = \left[x, \dot{x}, \theta, \dot{\theta}\right]^T$$

The equation (1) can be rewritten as follows:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = a_1 + b_1 \cdot f \\ \dot{x}_3 = x_4 \\ \dot{x}_4 = a_2 + b_2 \cdot f \end{cases} \qquad (2)$$

Since the objective to force the system states, $x_1$and x_3,to track the reference trajectories $x_d$and θ_d respectively, we can define the errors as follows:

$$\begin{cases} e_1 = x_1 - x_d \\ e_3 = x_3 - \theta_d = x_3 \end{cases} \qquad (3)$$

Due to the sway angle minimization, we have $\theta_d = 0$

3. Proposedapproachdesign.

To the control law, we define the sliding surface as follows:

$$s = e_1 + k_1|e_1|^{\alpha_1}Sing(e_1) + k_2|\dot{e}_1|^{\beta}Sing(\dot{e}_1) ++ e_3 + k_3|e_3|^{\alpha_2}Sing(e_3) \qquad (4)$$

Where$k_1, k_2, k_3, \alpha_1, \alpha_2$ and β are positive constants with $1 < \beta < 2$, $\beta < \alpha_1$ and $1 < \alpha_2 \cdot Sing(e_1)$, denotes the signum function. The architecture of this surface let to ensure a fast convergence of the tracking error to zero. Indeed, if initial the position is far from the desired one, then the term $e_1 + k_1|e_1|^{\alpha_1}Sing(e_1)$, will be dominant, which leads to a fast convergence. In the case where the system is near the desired trajectory, the term $k_2|\dot{e}_1|^{\beta}Sing(\dot{e}_1)$, must ensuring a finite time convergence [24].

Theorem1: Consider the system dynamics (2) with chosen sliding surface(4),the following controllawensurestheconvergenceofsanditstime-derivatives˙tozeroinafinitetime:

$$f =- \frac{a_1 + [\beta k_2]^{-1} |\dot{e}_1|^{1-\beta} [\dot{e}_1 + \alpha_1 k_1 |e_1|^{\alpha-1} \dot{e}_1]}{b_1} - \frac{[\beta k_2]^{-1} |\dot{e}_1|^{1-\beta} [1+ \alpha_1 k_3 |e_3|^{\alpha_2-1} \dot{e}_3 + k_4 s]}{b_1} \qquad (5)$$

Proof:

The time derivative of the sliding surface can be written as:

$$\dot{s} = \dot{e}_1 + \alpha_1 k_1 |e_1|^{\alpha_1-1} \dot{e}_1 + \beta k_2 |\dot{e}_1|^{\beta-1} \ddot{e}_1 + \dot{e}_3 + \alpha_2 k_3 |e_3|^{\alpha_2-1} \dot{e}_3 \qquad (6)$$

Using equations (2),(3) and(5),we obtain:

$$\dot{s} = -k_4 s \quad (7)$$

To analyze the stability of the system, we consider the following Lyapunov function:

$$V = \frac{1}{2}s^2 \quad (8)$$

Taking the time derivative of V in(8) and using(7),we can obtain:

$$\dot{V} = s\dot{s} = -k_4 s^2 \quad (9)$$

Then, from (9), we can conclude that the sliding surface s converge to zero in finite time. Furthermore, according to (7) the time derivative of the sliding surface also converges to zero when s reaches zero. This completes the proof of our Theorem1.

4. Controller improvement.

We have proven mathematically that the control law (5) allows to force the system to track the reference trajectories and their convergence in a finite time is guaranteed. The presence of the term $(k_4 s)$ in the control law (5) certainly make sit possible to ensure the approaching phase and to force the system to reach the sliding surface, but the choice of the gain k_4 requires a certain compromise [25][18]. Indeed, a big value yields to quick convergence but it causes chattering. Otherwise, we have a slow response and smoother control signal. One solution consists of using a variable gain whose value changes depending on the position of the system relative to the sliding surface .In this work, we propose to use an adaptive type-2 fuzzy system to generate the gain k_4.

4.1. TYEPE-2FUZZYSYSTEM

Type-2 fuzzy logic can be considered as an extension of classical fuzzy logic. It makes it possible to take in to account the uncertainties at several levels of the fuzzy system structure. Then type-2 fuzzy systems are quite efficient in handling disturbances and uncertainties [17]. In our case, we propose to use an Interval Type-2 (Takagi-Sugeno) fuzzy system to calculate the value of k_4 to reduce the computing time compared to a classical type-2 fuzzy system [15]. The input of this system will be the sliding surfaces to which we associate 5 triangular type-2 fuzzy sets, as shown in figure 2, namely Z (zero), PS (positive Small), PM (Positive Medium), PB (positive Big), NS (Negative Small), NM (Negative Medium) and NB (Negative Big). Also, we define 5 intervals for the output. $\hat{k}_4$

4.2. UNITMODIFIEDCONTROLLAWDESIGN

In the case where we don't have enough information to define the consequent part of the type-2 fuzzy system, it is more convenient to adjust this parton-line according to adaptation law deduced from the stability analysis.

According to this, we can define the output of the fuzzy system as follows:

$$\hat{k}_4 = \emptyset^T(s) \cdot \omega \qquad (10)$$

Where $\emptyset(s)$ represents the regressive vector and ω the consequent vector containing the conclusion values of the fuzzy rules.

Theorem 2:

Consider the system dynamics (2) with chosen sliding surface (4), the following modified control law ensures the convergence of s and its time-derivative s˙ to zero in a finite time:

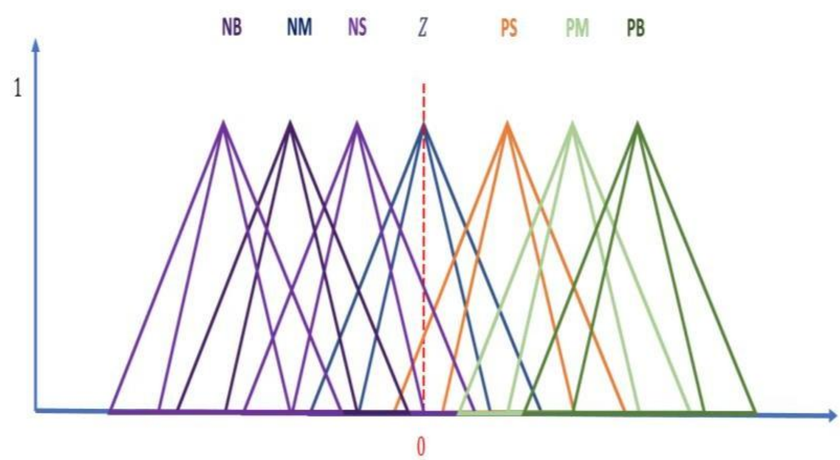

Figure2: Type-2 fuzzy sets of input s.

$$f = -\frac{a_1 + [\beta k_2]^{-1}\,|\dot{e}_1|^{1-\beta}\,[\dot{e}_1 + \alpha_1 k_1\,|e_1|^{\alpha-1}\,\dot{e}_1]}{b_1} - \frac{[\beta k_2]^{-1}\,|\dot{e}_1|^{1-\beta}\,[1+\alpha_1 k_3\,|e_3|^{\alpha_2-1}\,\dot{e}_3 + k_4 s]}{b_1} \qquad (11$$

Proof:

Let consider the following Lyapunov function:

where γ is a learning constant. Using the control law (11) , the time derivative of the sliding. surface can be written as: From (2) and (The time derivative of V can be expressed as:

$$\begin{cases} \dot{s} =- k_{40}s - \hat{k}_4 s \\ \quad =- k_{40}s - \emptyset^T(s)\cdot \omega s \\ \quad =- k_{40}s - \omega^T(s)\cdot \emptyset s \end{cases} \quad (13)$$

Using (13), the time derivative of V can be written as:

$$\begin{cases} \dot{V} = s(- k_{40}s - \omega^T(s)\cdot \emptyset s) + \frac{1}{\gamma}\omega^T\dot{\omega} \\ \quad =- k_{40}s^2 + \frac{1}{\gamma}\omega^T(\dot{\omega} - \gamma\emptyset s) \end{cases} \quad (14)$$

if choose the following adaptation law for ω.

$$\dot{\omega} = \gamma s\cdot \emptyset(s) \quad (15)$$

Equation (14) becomes:

$$\dot{V} =- k_{40}s^2 \quad (16)$$

Then the convergence of the sliding surface and its time derivative is guaranteed using the modified control law (11). This completes the proof of our Theorem.

5. Simulation and results.

Simulation was run to verify the effectiveness of the proposed approach. Our objective wasto accuratelycontrolthe positionofthe loadmlwithaslittlethe swayangleof the rope aspossible.Inotherwords,theloadmlissupposedtoreachthedesignatedposition,andthe angle of the rope is supposed to be stabilized around 0 by the proposed approach. The specific parameters for simulations are as follows:

We take: $l = 0{,}7m;\ \ m_r = 4{,}5Kg\ \ and\ m_l = 1Kg$

The simulation results are shown in figure 3. We remark that the control objectives are reached and we do not have overshoot. we have done simulations for 3 different reference values for x and for each case, we have a good convergence towards the desired value as shown in figure 4, which confirms the objectives of the developed approach.

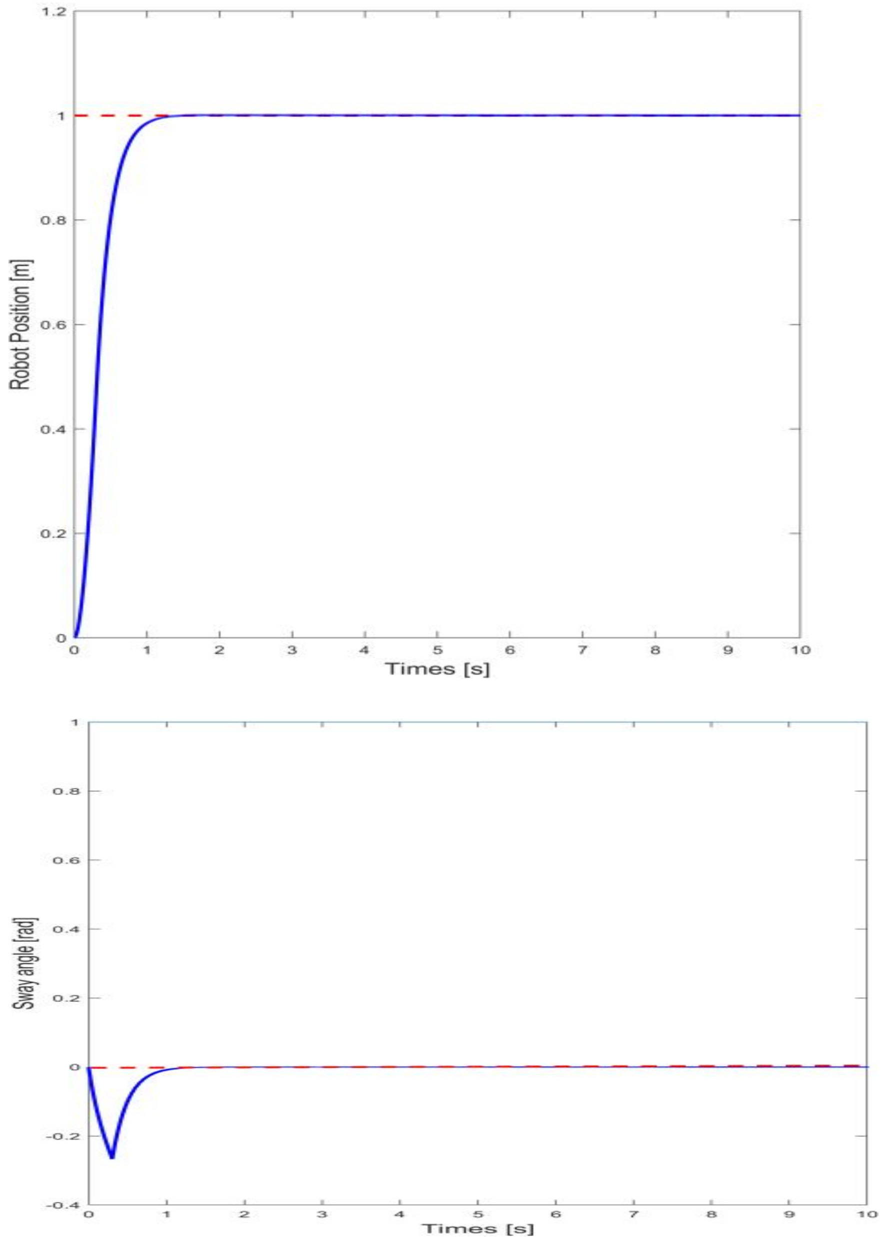

Figure3:Evaluation of position x for different reference value.

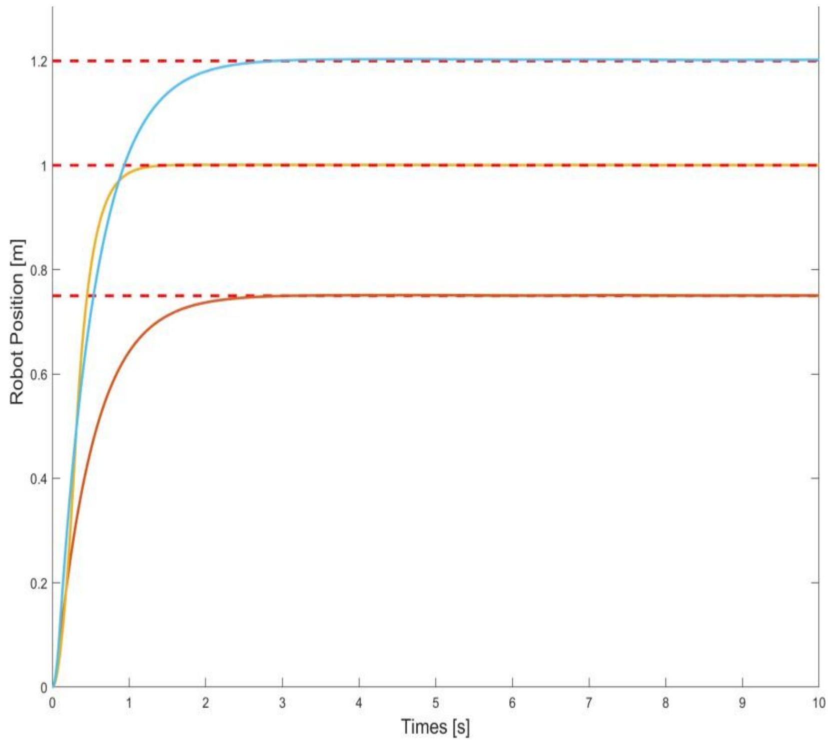

Figure4: Evolution of positions x for different reference value

6. Conclusion.

In this paper, a type-2 fuzzy non singular fast terminal sliding mode controller for container cranes robot was in vestigated.Thankstotype-2 fuzzy logic, we have introduced an adaptive switch gain to maintain the good tracking performances and to eliminate chattering. The stability of the proposed controller was also addressed. Simulation results are provided to prove the effectiveness of the proposed control approach. As future work, we propose to developedadesignprocedureallowingto simplifythecontrollerdesign.

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