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FAULT TOLERANT CONTROL FOR WHEELS MOBILE ROBOT WITH ACTUATOR FAULTS

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Abstract. The central focus of this article revolves around mitigating the repercussions of faults occurring within the actuator - a pivotal element with the potential to significantly impede a two-wheeled mobile robot's performance and operational efficiency. A specialized observer is devised to vigilantly monitor the dynamic state of the robot's system, enabling swift detection and evaluation of actuator faults that may manifest during its operation. From this information, the observer can gauge the extent of the fault's impact on the overall system, thereby furnishing vital insights for building a fault-tolerant control law. The control law is based on mathematical principles, information from observers, and the Lyapunov stability theory. The results obtained from simulations conducted using MATLAB-Simulink affirm the effectiveness of our suggested control law and make a small contribution to robotics and control engineering.

Keywords: *WMR, Faults observer, Lyapunov stabilizer, mobile robot.*

I. INTRODUCTION

Design approaches for fault-tolerant control systems (FTCS) have been formulated and classified into redundant design and fault compensation [1]. Redundant design in fault-tolerant control systems offers increased reliability and availability. However, it comes with drawbacks, including higher costs due to replication, system complexity from managing redundancies, challenges during component switches, potential fault interactions, limitations in redundancy, and potential faults needing to be detected accurately. Fault compensation in fault-tolerant control involves adjusting control actions, algorithms, or parameters in real-time to counteract the effects of faults, ensuring system functionality even in the presence of faults. This approach mitigates faults directly without relying solely on redundant components. So, faults compensation control will be a good choice in FTCS.

In robot control, fault-tolerant control (FTC) plays a crucial role. It enables robots to maintain reliable operation across diverse working environments, effectively preventing work termination resulting from tolerable faults [2]. Fault-tolerant control strategies are approached for linear systems in [3-5]. However, in the robot system, its multivariable nature and characterized by strong interactions and time-varying parameters [6], the study of fault-tolerant control has practical significance.

The actuator is a relatively susceptible component to failure in the wheel mobile system. It refers to deviations from regular operation, affecting its ability to function correctly. Faults can include failure actuator [7], stuck fault, partial loss of control effectiveness fault [8], and bias-actuator faults [9]. Detecting and addressing actuator faults is crucial for maintaining robot reliability.

Several noteworthy fault-tolerant control methods targeting actuator faults have been introduced to address the issues of system performance degradation and instability resulting from faults [10,11]. Among these methods, Adaptive Fault-Tolerant Control (AFTC) has been well-established as a practical approach to handling actuator faults and system uncertainties [12].

Intelligent methods such as neural networks and fuzzy logic have been integrated into FTC schemes for nonlinear systems [13,14] by offering the capability to identify unknown nonlinear characteristics [15]. The adaptive technique allows for the real-time estimation of unidentified parameters and expedites swift adaptations of control gains in reaction to parameter alterations. It is to be a viable method for designing controllers to compensate for actuator faults [16].

Using the principles of Lyapunov stability theory and the estimated faults value of the fault observer, we propose a control law that ensures the robot effectively withstands adverse influences of actuator faults. This research contributes valuable insights and solutions to the growing body of knowledge in fault-tolerant control, further propelling the advancements in robotics.

II. KINEMATICS OF WHEEL MOBILE ROBOT

The Wheel Mobile Robot (WMR) used in this article has three wheels, including 2 active wheels driven by 2 DC servo motors and 1 passive wheel. The robot is designed so that the center of gravity of the robot is on the midpoint of the shaft connecting the two motors. The robot structure is shown in Fig. 1, where $\{OXY\}$ is the fixed coordinate system, $\{O_B X_B Y_B\}$ is the coordinate system attached to the robot's body, r is the radius, and L is the distance between the two wheels, θ is the orientation angle of the robot in the $\{OXY\}$, $\dot{\varphi}_1$, $\dot{\varphi}_2$ are the angular velocities of the left and right wheels, respectively.

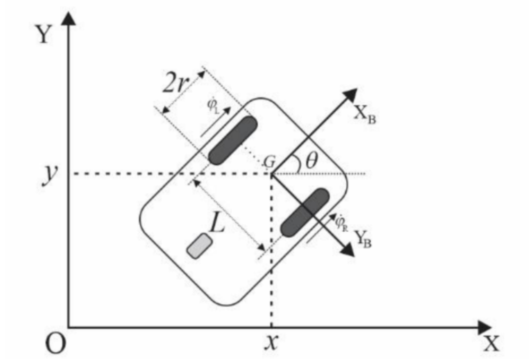

Fig. 1. *Robot's structure.*

Defined the robot's position in the $\{OXY\}$, $\{O_B X_B Y_B\}$ as $q = [x \quad y \quad \theta]^T$ and $q_B = [x_B \quad y_B \quad \theta_B]^T$. Via a transformation matrix $Rot(\theta)$, the relationship between fixed and robot coordinate systems can be represented [17]:

$$\dot{q}_B = Rot(\theta)\dot{q} \tag{1}$$

where: $$Rot(\theta) = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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The speeds of left wheel, and right wheel in the robot frame are $r\dot{\varphi}_L, r\dot{\varphi}_R$, respectively, therefore the translational speed and the rotational velocity in the robot frame be calculate shown as:

$$\begin{cases} v = \dfrac{r}{2}(\dot{\varphi}_R + \dot{\varphi}_L) \\ \omega = \dfrac{r}{L}(\dot{\varphi}_R - \dot{\varphi}_L) \end{cases} \tag{2}$$

We can deduce $\dot{q} = Rot(\theta)^{-1}\dot{q}_B$ from (1). So, So, the entire model, which is the robot velocity in the $\{OXY\}$ is:

$$\dot{q} = \begin{bmatrix} cos\,\theta & -sin\,\theta & 0 \\ sin\,\theta & cos\,\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{r}{2}(\dot{\varphi}_R + \dot{\varphi}_L) \\ 0 \\ \frac{r}{L}(\dot{\varphi}_R - \dot{\varphi}_L) \end{bmatrix} = \begin{bmatrix} \frac{r}{2}(\dot{\varphi}_R + \dot{\varphi}_L)\,cos\,\theta \\ \frac{r}{2}(\dot{\varphi}_R + \dot{\varphi}_L)\,sin\,\theta \\ \frac{r}{L}(\dot{\varphi}_R - \dot{\varphi}_L) \end{bmatrix} \tag{3}$$

Express (3) in a matrix form, and with the corresponding non-holonomic constraints of the robots being satisfy. The forward kinematic model of the robot can be described as follows:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} \tag{4}$$

III. MAIN RESULTS

In this section, a fault estimator and an FTC are designed for the WMR system in (4) with actuator faults. Then we propose a control strategy based on the obtained estimations to guarantee the stability of the system when faults occur.

A. Fault-tolerant controller

We define the tracking error model of the system as:

$$\begin{bmatrix} x_e \\ y_e \\ \theta_e \end{bmatrix} = \begin{bmatrix} cos\,\theta & sin\,\theta & 0 \\ -sin\,\theta & cos\,\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_B - x \\ y_B - y \\ \theta_B - \theta \end{bmatrix} \tag{5}$$

Differentiate both sides of (5):

$$\dot{e}_q = \begin{bmatrix} \dot{x}_e \\ \dot{y}_e \\ \dot{\theta}_e \end{bmatrix} = \begin{bmatrix} \omega y_e - v + v_B \cos\theta_e \\ -\omega x_e + v_B \sin\theta_e \\ \omega_B - \omega \end{bmatrix} \tag{6}$$

The current velocities control input used for robot tracking is given as:

$$\begin{bmatrix} v_c \\ \omega_c \end{bmatrix} = \begin{bmatrix} v_B \cos\theta_e + k_1 x_e \\ \omega_B + k_2 v_B y_e + k_3 \sin\theta_e \end{bmatrix} \tag{7}$$

k_1, k_2, k_3 are positive gain values.

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Controller with the law (7) will be suitable for the robot's tracking control problem in case there is no fault on the actuator. Within the scope of the article, the author considers the case of a fault affecting the actuator, such as:

$$\begin{cases} v_f = v - \Delta v, \ 0 < \Delta v_{\min} < \Delta v < \Delta v_{\max} < v \\ \omega_f = \omega - \Delta\omega, \ 0 < \Delta\omega_{\min} < \Delta\omega < \Delta\omega_{\max} < \omega \end{cases} \tag{8}$$

The error model of the system be considered and presented as:

$$\dot{e}_q = \begin{bmatrix} \dot{x}_e \\ \dot{y}_e \\ \dot{\theta}_e \end{bmatrix} = \begin{bmatrix} \omega y_e - v + v_B \cos\theta_e + \Delta\omega y_e + \Delta v \\ -\omega x_e + v_B \sin\theta_e + \Delta\omega x_e \\ \omega_B - \omega + \Delta\omega \end{bmatrix} \tag{9}$$

Since Δv, $\Delta\omega$ are unknown, we must design a fault observer to design a control law for the robot.

By define:

$$\begin{cases} f(e_q) = \begin{bmatrix} y_e\omega_B \\ v_B \sin\theta_e - x_e\omega_B \\ 0 \end{bmatrix}; u = \begin{bmatrix} v_B\cos\theta_e - v \\ \omega_B - \omega \end{bmatrix}; \\ g_1(e_q) = g_2(e_q) = \begin{bmatrix} 1 & -y_e \\ 0 & x_e \\ 0 & 1 \end{bmatrix}; f_a = \begin{bmatrix} \Delta v \\ \Delta\omega \end{bmatrix} \end{cases} \tag{10}$$

(9) can be rewritten:

$$\dot{e}_q = f(e_q) + g_1(e_q)u + g_2(e_q)f_a \tag{11}$$

According to [20], with system state e_q , input u are known, and $\dot{f}_a = 0$ an observer was introduced to estimate the disturbance in (11):

$$\begin{cases} \dot{z} = -L(e_q))\left(g_2(e_q)z + g_2(e_q)p(e_q + f(e_q) + g_1(e_q)u\right) \\ \hat{f}_a = z + p(e_q) \end{cases} \tag{12}$$

where, $p(e_q)$ and $L(e_q)$ be chosen satisfying: $L(e_q) = \dfrac{\partial p(e_q)}{\partial e_q}$

Hence, the control law is proposed:

$$\begin{bmatrix} v \\ \omega \end{bmatrix} = \begin{bmatrix} v_r \cos\theta_e + k_x x_e + 2y_e\hat{\Delta}\omega + \hat{\Delta}v \\ \omega_r + k_y v_r y_e + k_\theta \sin\theta_e + \hat{\Delta}\omega \end{bmatrix} \tag{13}$$

B. Lyapunov stability analysis

The positive definite Lyapunov function is selected as:

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$$V = \frac{x_e^2 + y_e^2}{2} + \frac{1 - cos\theta_e}{k_y} \tag{14}$$

Derivation of (14) and replace $\dot{x}_e, \dot{y}_e, \dot{\theta}_e$ from (9), we obtained:

$$\dot{V} = x_e\left(-v + v_B \cos\theta_e + 2\Delta\omega y_e + \Delta v\right) + \frac{\sin\theta_e\left(\omega_r - \omega + k_2 y_e v_B \Delta\omega\right)}{k_2} \tag{15}$$

Writing the control law given in Equation (13) into Equation (15):

$$\begin{aligned}\dot{V} &= x_e\left(-\left(v_B \cos\theta_e + k_1 x_e + 2y_e\hat{\Delta}\omega + \hat{\Delta}v\right) + v_B \cos\theta_e + 2\Delta\omega y_e + \Delta v\right) + \dots \\ &\quad + \frac{\sin\theta_e\left(\omega_B - \left(\omega_B + k_2 v_B y_e + k_3 \sin\theta_e + \hat{\Delta}\omega\right) + k_2 y_e v_B + \Delta\omega\right)}{k_2} \\ &= -k_1 x_e^2 - \frac{1}{k_2}\sin^2\theta_e < 0\end{aligned} \tag{16}$$

According to the Lyapunov stability theorem [18]. The system to be asymptotic stability.

IV. NUMERICAL SIMULATION

Based on MATLAB/Simulink, simulations are conducted to verify the effectiveness of the proposed fault-tolerant controller. The parameters of the wheeled robots used in the simulations are given in Table 1.

Fault affecting the actuator is introduced at time t>8s with: $f_a = \begin{bmatrix}\Delta v \\ \Delta\omega\end{bmatrix} = \begin{bmatrix}0.2v \\ 0.2\omega\end{bmatrix}$

Parameter of observer be select: $p(q_e(t)) = \begin{bmatrix}x_e \\ \theta_e\end{bmatrix}$; $L(q_e(t)) = \begin{bmatrix}100 & 0 & 0 \\ 0 & 0 & 100\end{bmatrix}$;

Table 1. *Parameter of robot.*

Mass (kg)	r (m)	R (m)	I (kg m^2)
15	0.1	0.5	2.5

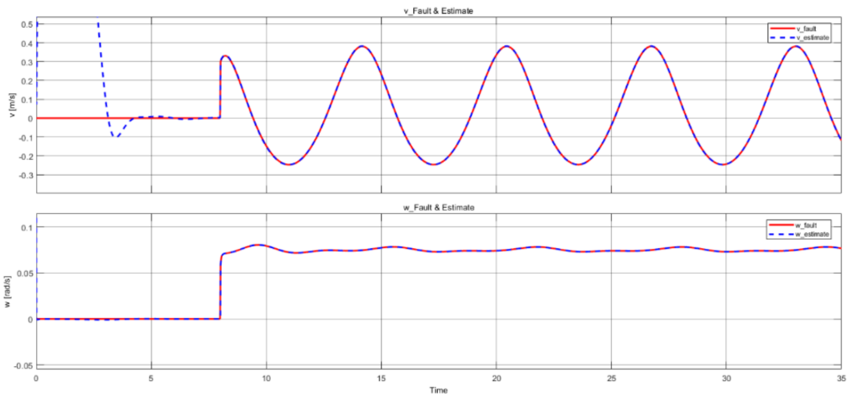

Fig. 2. *Fault's estimate from Observer.*

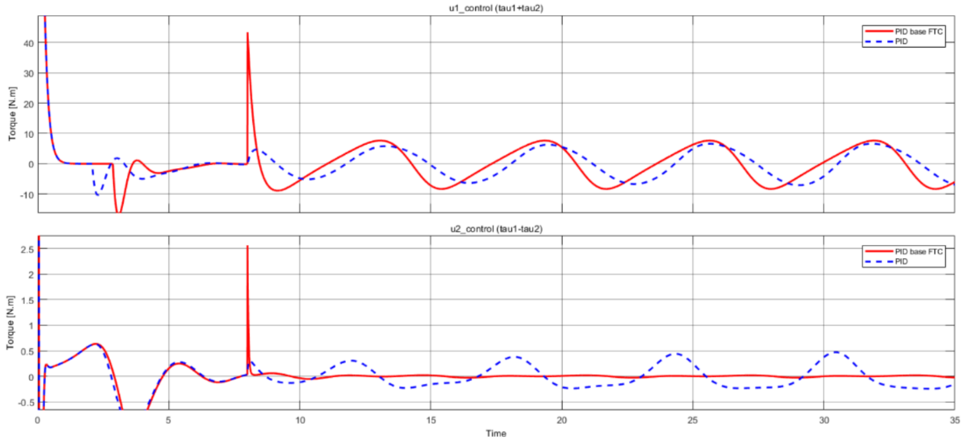

Fig. 3. *Signal control to Dynamic model.*

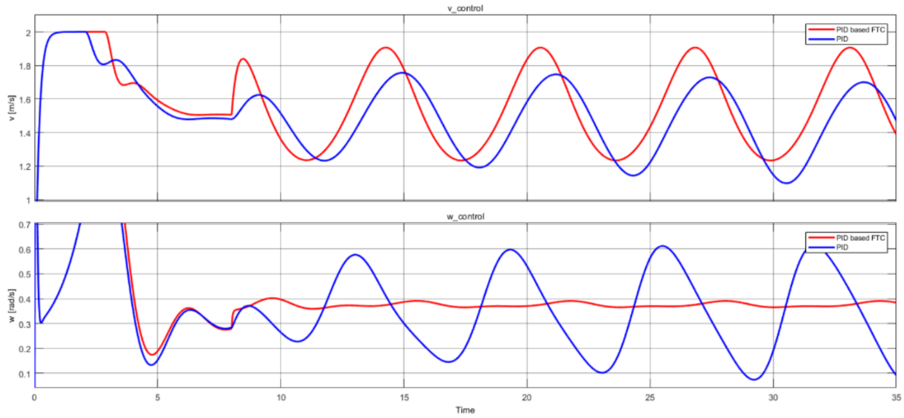

Fig. 4. *Signal control to Kinematic model.*

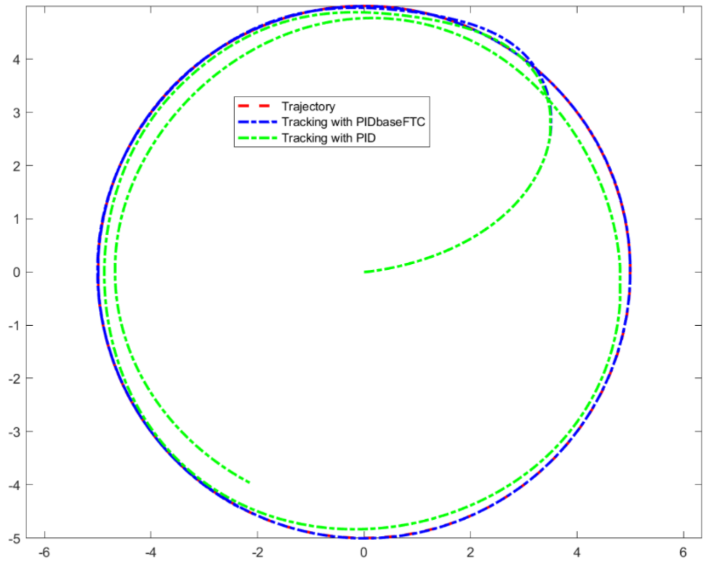

Fig. 5. *Trajectory tracking.*

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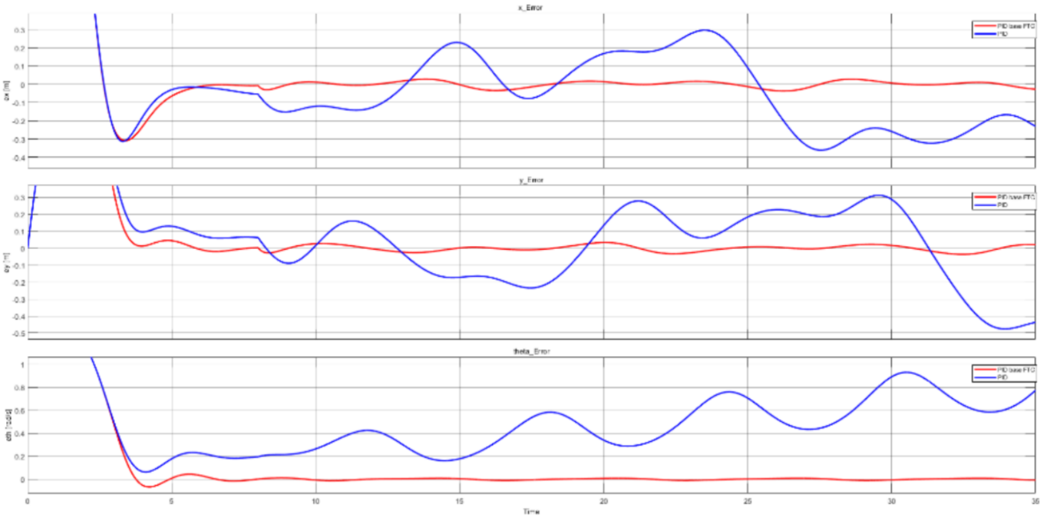

Fig. 6. *The tracking error of x, y, theta*.

The faults affect the robot system after 8 seconds in the simulation. Fig. 1 shows the timely and accurate response of the observation system. Based on the detected error estimation, the controller gives an appropriate signal to compensate for the faults and ensure the task of tracking the set trajectory (Fig. 3,4). Fig. 5,6 show the efficient and stable operation of the proposed controller.

V. CONCLUSION

In this paper, we investigate the fault tolerant control problem for a WMR system with actuator faults and nonlinearities. Here, the actuator's constant gain faults and bias faults are considered. An estimator is designed to estimate the states and the actuator faults simultaneously. Based on the Lyapunov stability theory and estimating the states and the faults, the corresponding control law is constructed for the actuator faults. The simulation resulting demonstrated the effectiveness and feasibility of the control law. Our next phase involves implementing the optimization methodology within the FTC design to enhance control performance to a greater extent.

REFERENCES

[1] Yingwei Zhang, Shuying Wu, and Yuan Wei, Fault-Tolerant Control of Nonlinear System, *International Journal of Control, Automation, and Systems*, **9**(6), 2011, pp. 1116-1123.

[2] X. Qi, J.-T. Qi, D. Theilliol, Y.-M. Zhang, J.-D. Han, D.-L. Song and C.-S. Hua, *Journal of Intelligent & Robotic Systems*, **73**(1-4), 2014, pp. 535-555.

[3] E. Naderi and K. Khorasani, *Automatica*, **85**, 2017, pp. 165-178.

[4] Tae H. Lee; Chee Peng Lim; Saeid Nahavandi, *IEEE Systems Journal*, **13**, Issue 2, 2019, pp. 1981-1990.

[5] Li-Ying Hao, Lian-Sheng Zhou, *Actuators*, 2022, **11**(8), pp. 241.

[6] Koubaa, A., Bennaceur, H., Chaari, I., et al., Springer, Berlin, 2018.

[7] Li, X.-J., Yang, G.-H., *IET Control Theory Applic*., **6**(10), 2012, pp. 1544-1551.

[8] Jin, X., Qin, J., Shi, Y., et al., *IEEE Trans. Syst. Man Cybern. Syst*., **48**(10), 2018, pp. 1816-1825.

[9] Qin, J., Zhang, G., Zheng, W.X., et al., *IEEE Trans. Cybern*., **49**(5), 2019, pp. 1605-1615, DOI: 10.1109/ TCYB.2018.2805167.

[10] Q. Y. Fan and G. H. Yang, *IEEE Trans. Cybern. PP*, **99**, 2017, pp. 1-12.

[11] M. Atitallah, M. Davoodi, and N. Meskin, *Asian J. Control*, **20**(6), 2018, pp. 2195-2206.

[12] Xiao-Zheng Jin, Ye-Xing Zhao, Hai Wang, Zhen Zhao, Xue-Ping Dong., *IET Control Theory & Applications*, **13**(11), 2019, pp. 1665-1672.

[13] Paul M. Frank, Birgit Köppen-Seliger, *International Journal of Approximate Reasoning*, **16**, Issue 1, 1997, pp. 67-88.

[14] Yang Cui, Guangren Duan, Xiaoping Liu & Hongyu Zheng, International Journal of Fuzzy Systems, **25**, 2023, pp. 1895-1906.

[15] J. A. Farrell and M. M. Polycarpou, Adaptive Approximation Based Control: Unifying Neural, Fuzzy and Traditional Adaptive Approximation Approaches, Wiley-Interscience, Hoboken, NJ, USA, 2006.

[16] Xiao-Ni Zhang, Jian-Liang Wang, Control and Decision Conference (CCDC), 2012 24th Chinese, 10.1109/CCDC.2012.6244655.

[17] Imil Hamda Imran, Allahyar Montazeri, 2020 International Conference Nonlinearity, Information and Robotics (NIR), 10.1109/NIR50484.2020.9290205.

[18] Chen, W.-H., Ballance, D. J., Gawthrop, P. J., and O'Reilly, J. A nonlinear disturbance observer for robotic manipulators, *IEEE Trans. Ind. Electron*., **47**(4), 2000, pp. 932-938.

[19] H. Khalil, Nonlinear Systems, Prentice Hall, Upper Saddle River, NJ, 2002.

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