SEMARAK ILMU
PUBLISHING
202103268166(003316878-P)

Semarak Proceedings of Applied Sciences and Engineering Technology

Journal homepage:
https://semarakilmu.my/index.php/spaset/index
ISSN: 3083-9807

Computer-Based FTC System for Flexible Robot Manipulator System under Actuator and Sensor Faults

Siti Fadilah Abd Latip[1,*], Abd Rashid Husain[2], Mohd Ariffanan Mohd Basri[2]

[1] Department of Instrumentation and Control, Kolej Kemahiran Tinggi MARA Kemaman, Terengganu, Malaysia
[2] Department of Mechatronics and Control, School of Electrical Engineering, Universiti Teknologi Malaysia, Johor, Malaysia

ABSTRACT

Industry demand high reliability in their system especially in a hazardous working environment. This work proposed a computer-based Fault Tolerant Control (FTC) system under simultaneous actuator and sensor faults of a flexible robot manipulator system under the event of loss effectiveness on more than one component can be a critical fault scenario in industrial system. This proposed method is simulated using a Matlab/Simulink software that interface with a data acquisition (DAQ) NI-PCI6221 board using an ISA bus data communication. In this approach, the FTC system has an adaptive feature where it able to accommodate the faults automatically using an adaptive proportional-integral-derivative (APID) controller. Unlike the conventional PID controller, all the proposed APID control parameters, namely, K_p, K_i, and K_d are adjusted online through online adaptation laws even under variation of fault scenarios. The proposed APID controller is shown to provide an accurate positioning control with faster response even under the variation of types of faults using the computer-based measurement in DAQ system and control systems that is designed based on the real-time Matlab/Simulink toolbox as compared to the conventional PID controller.

Keywords: *Computer-based; fault tolerant control; adaptive PID controller; actuator and sensor faults*

1. Introduction

Industry usually involves large equipment and complex operation processes that operate by machines and humans. In such system, failures could result in very critical and unpredictable behavior of the industrial machines, thus leading to unsafe operations especially after operating for a long period. Therefore, it is important to design a system with high reliability that is able to adapt with a faulty condition while it continues to satisfy its goal. This type of system is called fault tolerant control (FTC) system. FTC system has been applied in many industrial applications such as nuclear power plant, wind turbines and robot manipulator system in industrial automation field [1-3].

FTC is an active research field and has received considerable attention over the past several decades in achieving reliability and maintainability in technical systems [4]. In fact, there are a few works on FTC of a flexible manipulator under variation of fault scenarios can be found in Sakuishi *et al.,* [5]. Methods in FTC can be classified into two groups, namely the passive approach and the active approach [6,7]. The passive approach utilizes robust control techniques to design fixed control parameters for maintaining the stability and performance of systems throughout normal or faulty

[*] *Corresponding author.*
E-mail address: siti.fadilah@mara.gov.my

https://doi.org/10.37934/spaset.1.1.7683a

cases. In contrast to active fault tolerant control (AFTC), both fault parameters and the system state variables need to be estimated on- line in real- time in order to design the control parameters. However, only an AFTC against actuator and sensor failures of flexible robot manipulator system is considered in this paper.

Almost every device faces with problems on fault in their system including flexible robot manipulator system. In flexible robot manipulator system, the failures could be from actuator, sensor or other components either from electrical or mechanical parts. These failures may lead to unsatisfied performances which results in an inaccurate hub angle position and big excitation on the vibration of the tip of the flexible arm. Due to these issues, there are several works that have been done regarding to the faults of flexible robot manipulator system. Most of the studies involved the misfunctioning of the measuring device for the deflection of the tip of the flexible robot manipulator that degrade the performance of the vibration of the beam. Izumikawa *et al.,*[8] developed a proportional-derivative (PD) switching controller as a solution to the normal and faulty condition of sensor fault of flexible manipulator system. The same author is then improved the previous work in year 2002 and introduced a reaction force observer for fault detection and compensation in order to get better fault detection and estimation [9]. In year 2006, Izumikawa improved the estimation delay by proposing a robust control using a loop shaping design procedure approach to get better fault compensation in the system. The studies on sensor fault of flexible robot continues with the studies of Tan *et al.,*[10] where this author developed a 'virtual sensor' based on linear observer that is optimize in linear matrix inequality toolbox. A Generalized Internal Model Control method has been designed in Yubai *et al.,*[11] that able to maintain the performance even in condition of total malfunction or disconnected.

PID controller is one of the mostly used for a linear controller in industry that is still applicable until now. The popularity of the PID controller is mainly due to its structural simplicity and easily designed. The key for designing a PID controller is the determination of the controller gains in the PID controller. However, the PID controller usually needs some prior manual retuning to make a successful industrial application. Recently, the PID controller has been combined with different methods such as fuzzy logic, neural network and particle swarm optimization (PSO) [12-14]. However, some of these methods require heavy computational demand and it is an offline tuning which is not suitable for the real-time applications especially under a system with faulty conditions. This is due to constraint of the fixed-gain properties in the PID controller that make the controller failed to accommodate the faults in the event of faults.

Motivated by the aforementioned issues, in this paper, a computer-based FTC system using Matlab/Simulink real-time toolbox that interface with DAQ NI-PCI6221 board is proposed to tackle the effects of actuator and sensor faults for flexible robot manipulator system in real-time. The proposed method is carried out using a computer with Intel Core i5-4200U CPU with 1.60 GHz that connected serially to DAQ board as ISA bus data communication. In this control approach, the control algorithm is designed to be adaptive using an adaptive proportional-integral-derivative (APID) control approach that derived in the sense of Lyapunov function to ensure the stability of the system in a closed-loop. This proposed control approach offers advantage where it can automatically online tune the PID controller gains by applying an adaptive law. Finally, to investigate the effectiveness of the developed APID controller, a comparison with the traditional PID controller. There will be three cases are conducted: a) fixed efficiency factor; b) fixed efficiency factor at time interval and c) intermittent fault at time interval. It is shown by the experimental results that the developed APID controller without requiring preliminary offline learning can achieve desired position and tracking control performance.

The structure of this paper is as follows. Section II briefly described the problem formulation for FTC under multiplicative actuator and sensor faults for flexible robot manipulator system and the controller design for the adaptive PID control design. Section III provides the design procedure for the proposed computer-based FTC system using APID control approach using Matlab/Simulink real-time software and DAQ NI-PCI6221 system. Section IV presents the results, analysis and comparison method between PID controller and the proposed computer-based FTC system using APID controller. Finally, the paper is concluded in Section V.

2. Problem Formulation

2.1 Problem Formulation for Actuator and Sensor Faults

Similar to other system, flexible robot manipulator also tends to has failures in the system. In this paper, the controller is designed to deal with the multiplicative (loss of effectiveness) actuator and sensor faults that occurred simultaneously in the system.

The dynamic mathematical model of flexible robot manipulator system under actuator and sensor faults is described in an affine form that written as follows:

$$\ddot{X}(t) = f(X,t) + g(X)\eta_a u(t)$$
$$Y(t) = h(X,t)\eta_s \qquad (1)$$

where $f(X,t)$, $g(X)$, η_a, η_s, and $u(t)$ are the nonlinear dynamic function, nonlinear control function, actuator efficiency factor, sensor efficiency factor and control input respectively. This problem formulation can be described in a block diagram shown in Figure 1. Both actuator and sensor efficiency factors are defined as $0 \leq \eta_a = \eta_s < 1$ in the event of loss of actuator and sensor effectiveness and $\eta_a = \eta_s = 1$ when the actuator and sensor are fault free.

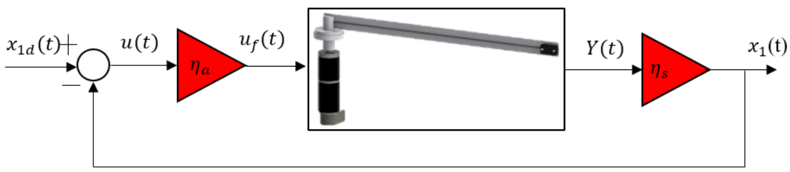

Fig. 1. Multiplicative fault as the basic fault models for SLFM system

where $x_{1d}(t)$, $u(t)$, $u_f(t)$, $Y(t)$ and $x_1(t)$ are reference input, control signal, faulty control signal, output of a system and faulty output respectively. Figure 2 shows the location of faults in the flexible robot manipulator system which is the actuator and sensor (AS) faults.

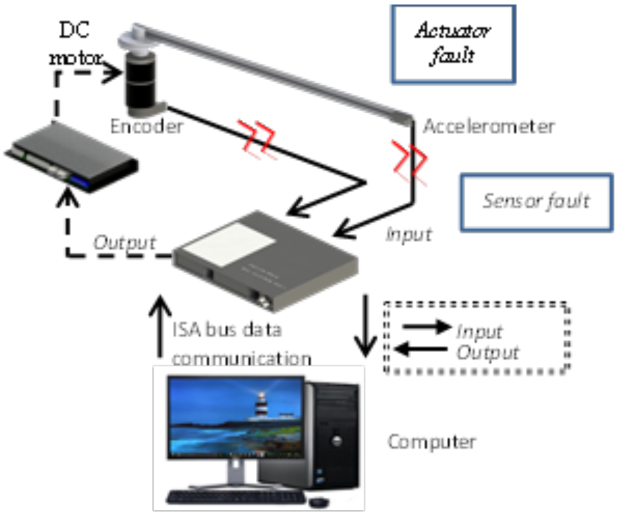

Fig. 2. The location of faults in real hardware of flexible robot manipulator system

2.2 Adaptive PID Control Algorithm

The main target in this paper is to control the flexible robot manipulator system so that it tracks the hub angular according to the desired position or trajectory in the presence of actuator and sensor faults. However, the conventional PID controller is not able to maintain the performance under faulty condition due to the constraint of the fixed-controller gains. Therefore, in this paper, a new adaptation law for PID controller is designed in order to deal with the multiplicative (loss of effectiveness) actuator and sensor faults. To ensure the stability of the adaptive PID controller in a closed-loop system, a Lyapunov function is used in the controller design. From the Lyapunov theorem, a system is asymptotically stable if $\dot{V}$ is negative definite. Hence, the adaptation law is designed as:

$$\dot{\hat{\Theta}}_{as} = -\beta^{-1}\eta_s s(t) g_1(x)\xi \quad (2)$$

3. Computer-Based Fault Tolerant Controller Design

In this work, the dynamic model and controller design is verified with the real hardware using Matlab/Simulink software. To synchronize the input and output signals from the hardware to a PC, the system is equipped with a precision interface circuit, NI PCI-6221 as a multifunctional data acquisition card.

The flexible arm is moved by a direct current (DC) motor as an actuator for the system. In this study, the DC motor, RE 40 manufactured by Maxon motor is considered, where a 4-Q-DC servo-amplifier type series analog DC servo-amplifier (ADS) is used to control voltages to the DC motors which determine speed and torque of the motors.

In order to move the DC motor, the motor driver must firstly be enabled in the Matlab. The setting to enable the Maxon motor driver, it must suit with the connection in DAQ NI PCI-6221 from the real hardware. The block digital output is used in Matlab/Simulink as shown in Figure 3 because in this step only requires digital values to enable and disable the motor driver. The Maxon DC motor is moved according to the voltage supplied from the motor driver. This voltage values vary with maximum voltage of ±12V.

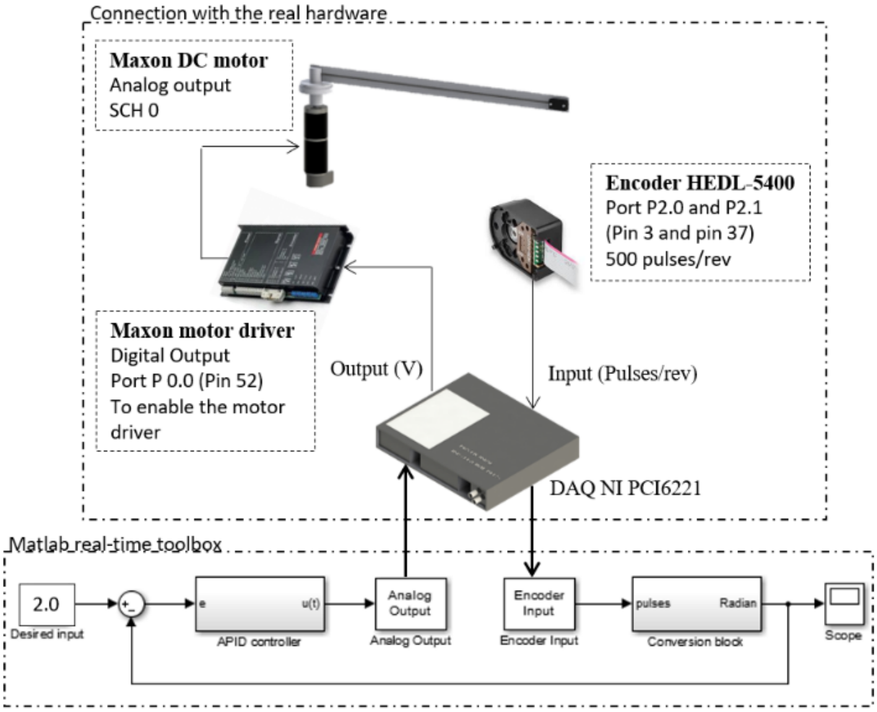

Fig. 3. The screenshot for Matlab Real-time Toolbox in Matlab/Simulink

The real-time measurement process involves in this work is the position of the flexible robot manipulator system. To emphasize, the sensor that used for the measurement is an encoder that located at the shaft of DC motor. This encoder is HEDL-5400 with 500 counts per turn. A precision interface circuit consisting of PCIQUAD04 with 4 input channels has been constructed for measurement and interfacing with the real-time system.

4. Results and Discussion

The effectiveness of the proposed controller under simultaneous actuator and sensor faults based on the existing experimental setup in achieving accurate and fast response for hub angular position of flexible robot manipulator system was investigated. To assess the performance of the closed-loop system, a 2.0 radian set-point reference is considered. The proposed controller is assessed on three different types of fault signals: i) fixed; ii) fixed fault at time interval and iii) incipient fault as shown in Table 1. The performance for fault compensation of fault tolerant control under variation of fault conditions are compared between the proposed APID controller and the conventional PID controller. As the objective is to control the flexible robot manipulator to move to the targeted point with faster response, integral of the absolute of the error (IAE) function is used as a performance index. For the conventional PID controller, the controller gains were tuned using signal constraint toolbox in Matlab/Simulink. From the tuning, the optimal PID controller gain values are, $k_p = 0.3;\ k_i = 0.001;\ k_d = 0.1$.

Table 1
Fault parameters on three types of faults

Types of faults	Fault parameter with time profile
Fixed	$\eta_a = \eta_s = 0.3$
Fixed at time interval	$\eta_a = \eta_s = \begin{cases} 0 & t < 0.3s \\ 0.3 & t > 0.3s \end{cases}$
Incipient fault	$\eta_a = \eta_s = \begin{Bmatrix} 0 & t < 0.3s \\ \frac{0.7}{3.7t} - 0.3 & 0.3s < t < 4s \\ 0.7 & t > 4s \end{Bmatrix}$

The performance of the proposed computer-based FTC controller under various fault conditions were measured using integral of the absolute error (IAE) function, which is defines as:

$$IAE = \int_0^L \left| x_{normal} - x_{fault} \right| \quad (3)$$

where x_{normal} is the response for fault-free condition, while x_{fault} is for system with actuator and sensor faults. Lower value of IAE indicates an improved controller system performance.

4.1 Results and performance evaluation

The conventional PID controller was employed first and followed by APID controller. The results for hub angular position control for both conventional PID and APID controller are shown in Figure 4. Based on the results, the conventional PDI controller was unable to control the hub angular to its desired position under three types of faults. Under the same types of faults, the APID controller was executed. The results of APID control approach from Figure 4 shows the desired set-point angular position obtained superior performance compared to the responses in the conventional PID controller. The evaluation for the control performance in terms of time response and IAE calculation are shown in Table 2. Based on the table, the APID obtained 66.67%, 59.57% and 37.5% improvement compared to the conventional PID controller when measured using IAE function. It can be observed that the APID controller obtained lower IAE values for all types of faults in comparison to the conventional PID controller. The responses on the control input for both controllers under all types of faults is shown in Figure 5. From all the results, show that the proposed computer-based FTC controller using APID approach able to obtain better performance compared to the conventional PID controller. Moreover, the proposed controller also able to prove that it can maintain the performance even under faulty conditions.

Table 2
The performance evaluation for the hub angularposition control using IAE

Experimental work	Settling time, t_s (s)		Steady-state error, e_{ss}		IAE	
	PID	APID	PID	APID	PID	APID
CASE1	12.15	5.435	0.035	0.028	2.473	0.8241
CASE 2	10.13	3.395	0.047	0.013	2.694	1.089
CASE 3	5.75	4.772	0.071	0.036	3.928	2.455

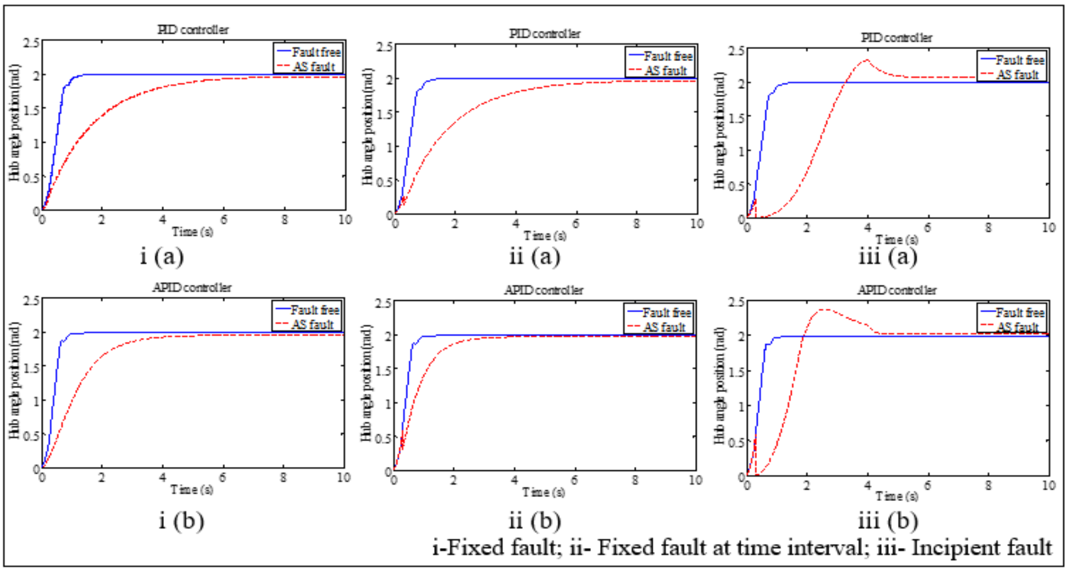

Fig. 4. The hub angle position using: (a) PID and (b) APID controllers

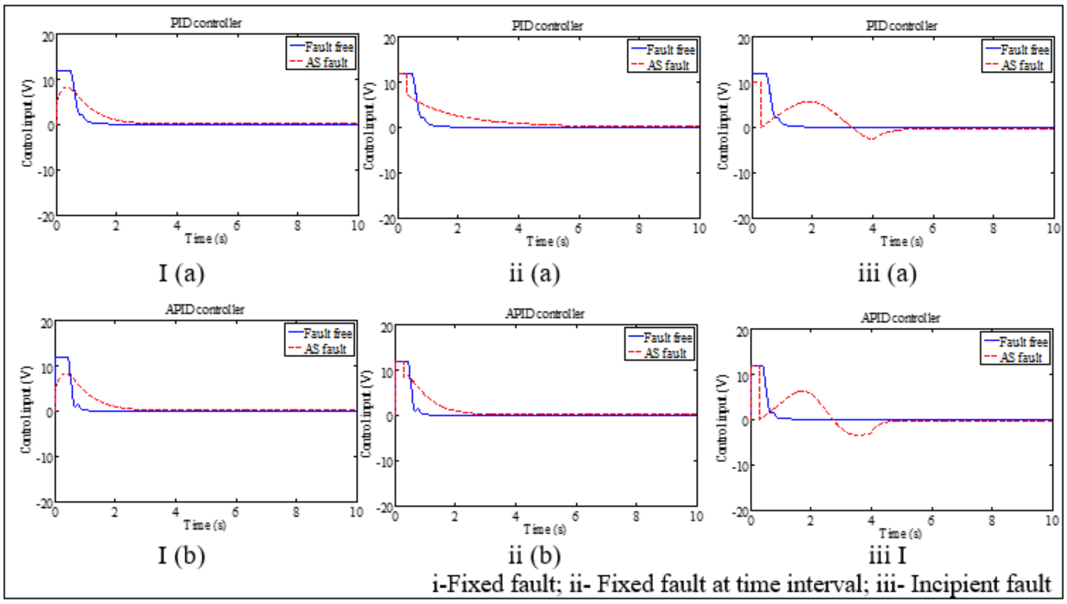

Fig. 5. Control input using: a) PID and b) APID controller

5. Conclusions

This paper addresses the strategies to handle the problem with actuator and sensor faults that occur simultaneously in a flexible robot manipulator system using a computer-based FTC system. The adaptation law in the controller design is able to accommodate faults automatically using DAQ NI-PCI6221 in Matlab/Simulink software environment with the sampling time of 1 ms. Effective tracking control of the hub angular position and faster response time are achieved under variations of faults using the proposed control method as compared to the conventional PID controller. The PID gains, k_p, k_i, and k_d are able to be adaptively tuned under all the cases of fault scenarios in online system. Experimental results have demonstrated the effectiveness of the proposed technique where the system is able to recover from the fault and achieve tracking performance even while the system is still running. This proves that the control approach is applicable with the industrial for better instrument measurement and control purpose for industry process control purposes.

Acknowledgement
I would like to express my heartfelt gratitude to my PhD supervisors, Assoc. Prof. Dr Abdul Rashid bin Husain, and Prof. Zaharuddin bin Mohamed and my colleague, Dr. Mohd Ariffanan bin Mohd Basri for their invaluable guidance, expertise, and support throughout the course of this research.

References
[1] Hatami, Ehsan, Hassan Salarieh, and Naser Vosoughi. "Design of a fault tolerated intelligent control system for a nuclear reactor power control: Using extended Kalman filter." *Journal of Process Control* 24, no. 7 (2014): 1076-1084. https://doi.org/10.1016/j.jprocont.2014.04.012
[2] Badihi, Hamed, Youmin Zhang, and Henry Hong. "Wind turbine fault diagnosis and fault-tolerant torque load control against actuator faults." *IEEE Transactions on Control Systems Technology* 23, no. 4 (2014): 1351-1372. https://doi.org/10.1109/TCST.2014.2364956
[3] Freddi, A., S. Longhi, A. Monteriù, D. Ortenzi, and D. Proietti Pagnotta. "Fault tolerant control scheme for robotic manipulators affected by torque faults." *IFAC-PapersOnLine* 51, no. 24 (2018): 886-893. https://doi.org/10.1016/j.ifacol.2018.09.680
[4] Benosman, Mouhacine, and K-Y. Lum. "Passive actuators' fault-tolerant control for affine nonlinear systems." *IEEE Transactions on Control Systems Technology* 18, no. 1 (2009): 152-163. https://doi.org/10.1109/TCST.2008.2009641
[5] Sakuishi, T., Y. Izumikawa, K. Yubai, and J. Hirai. "Fault-tolerant control of flexible arm based on dual Youla parameter identification." In *9th IEEE International Workshop on Advanced Motion Control, 2006.*, pp. 451-455. IEEE, 2006. https://doi.org/10.1109/AMC.2006.1631701
[6] Izumikawa, Yu, Kazuhiro Yubai, and Junji Hirai. "Fault-tolerant control system of flexible arm for sensor fault by using reaction force observer." *IEEE/ASME transactions on mechatronics* 10, no. 4 (2005): 391-396. https://doi.org/10.1109/TMECH.2005.852442
[7] Zhang, Qi, Xiaodong Zhang, Marios M. Polycarpou, and Thomas Parisini. "Distributed sensor fault detection and isolation for multimachine power systems." *International Journal of Robust and Nonlinear Control* 24, no. 8-9 (2014): 1403-1430. https://doi.org/10.1002/rnc.3141
[8] Izumikawa, Yu, Kazuhiro Yubai, and Takamasa Hori. "Vibration suppression control of flexible arm robot by PD gain switching considering sensor failure." In *2002 IEEE International Conference on Industrial Technology, 2002. IEEE ICIT'02.*, vol. 2, pp. 684-689. IEEE, 2002. https://doi.org/10.1109/ICIT.2002.1189247
[9] Izumikawa, Yu, Kazuhiro Yubai, and Junji Hirai. "Fault-tolerant control system of flexible arm for sensor fault by using reaction force observer." *IEEE/ASME transactions on mechatronics* 10, no. 4 (2005): 391-396. https://doi.org/10.1109/TMECH.2005.852442
[10] Tan, Chee Pin, and Maki K. Habib. "Tolerance towards sensor faults: an application to a flexible arm manipulator." *International Journal of Advanced Robotic Systems* 3, no. 4 (2006): 46. https://doi.org/10.5772/5720
[11] Yubai, Kazuhiro, Tsubasa Sakuishi, and Junji Hirai. "Compensation of performance degradation caused by fault based on gimc structure: Application to a redundant sensor fault of flexible arm." *Electrical Engineering in Japan* 168, no. 3 (2009): 48-58. https://doi.org/10.1002/eej.20830
[12] Santos, M., and A. L. Dexter. "Control of a cryogenic process using a fuzzy PID scheduler." *Control Engineering Practice* 10, no. 10 (2002): 1147-1152. https://doi.org/10.1016/S0967-0661(02)00062-X
[13] Ren, Tsai-Jiun, Tien-Chi Chen, and Chun-Jung Chen. "Motion control for a two-wheeled vehicle using a self-tuning PID controller." *Control engineering practice* 16, no. 3 (2008): 365-375. https://doi.org/10.1016/j.conengprac.2007.05.007
[14] Jaafar, Hazriq Izzuan, and Zaharuddin Mohamed. "PSO-tuned PID controller for a nonlinear double-pendulum crane system." In *Modeling, Design and Simulation of Systems: 17th Asia Simulation Conference, AsiaSim 2017, Melaka, Malaysia, August 27–29, 2017, Proceedings, Part II 17*, pp. 203-215. Springer Singapore, 2017. https://doi.org/10.1007/978-981-10-6502-6_18