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FPGA BASED HIL CO-SIMULATION OF 2DOF-PID CONTROLLER TUNED BY PSO OPTIMIZATION ALGORITHM

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Abstract. *In this paper, the Two Degree of Freedom – Proportional Integral Derivative (2DOF-PID) controller has been analyzed and realized using Field Programmable Gate Array (FPGA). The controller parameters have been determined based on Particle Swarm Optimization (PSO) algorithm. These parameters have been employed to implement the controller in discrete-time model using MATLAB/Simulink platform. The implementation of the controller is extended to employ the Xilinx System Generator (XSG) platform. This platform is necessary for validating the digital model of the controller and support to implement the controller in hardware using FPGA. Finally, the FPGA based 2DOF-PID controller was used in Hardware In Loop (HIL) co-simulation. Both simulation and experimental results emphasize the effectiveness of 2DOF-PID controller for tracking reference input and rejecting the disturbance.*
Keywords: 2DOF-PID, PSO, XSG, FPGA, HIL co-simulation

1. **Introduction.** The three terms controller which is known as PID controller became the most popular controller that is employed in a broad type of control systems in the last seven decades according to its simplicity, reliability, robustness and effectiveness [1]. Several controllers have been proposed whose work is inspired by the principle of conventional PID controller work, including Fractional Order PID (FO-PID), Higher Order PID (HO-PID), and Integer Order PID (IO-PID) controllers, etc. [2-4]. Tuning the PID controller aims to determine the values of its three elements that result in achieved desired response. The remarkable superiority of PID controller is the possibility of intuitive tuning of its parameters without deep knowledge of control [5]. The basic idea adopted for tuning the PID controller was proposed by Ziegler-Nichols in 1942 based on the mathematical formula that describes the PID parameters as functions of some process's parameters [6,7]. Ziegler-Nichols method provides acceptable performance for integrating systems, but indicates poor behavior for high order systems with dominant time delay, nonlinear systems, and systems with higher uncertainties [7,8]. The optimization methods have been used for tuning the PID controller in order to improve the performance

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of the control system and overcoming the limitations that faced the traditional tuning methods [9]. In these methods, the best solution is obtained according to exploring the entire system response and seeking to minimize the predefined cost function. Many different optimization methods employed for tuning PID controller have been presented in the literature, such as Artificial Neural Networks (ANN) [9,10], Fuzzy Logic Control (FLC), particle swarm optimization, Genetic Algorithm (GA), and many others [11-13].

Recently, the attention to the behavior of the control system to reject disturbances has become the same degree as the attention to the performance of the system for tracking the reference signal [7]. In control applications, using the traditional PID controller which can be described as a one-degree-of-freedom (one closed-loop transfer function) structure, cannot achieve reference input tracking and disturbance rejection simultaneously [14]. In order to avoid this obstacle, a controller with two degrees of freedom was proposed, so it became possible to deal with reference signal tracking and disturbance rejection simultaneously [15-17].

The tremendous development in digital technology and the emergence of microprocessors and microcontrollers have inspired the use of digital controller. Generally, the digital PID has advantages that make it superior to its analog counterpart, the most important ones of which are low cost, speed and accuracy. Unfortunately, the traditional digital devices suffer from limitations of execution speed and overload for implementing complex systems [1]. Field Programmable Gate Array (FPGA) becomes the most popular alternative device for implementing digital systems. This popularity comes from its distinctive advantages, such as high execution speed due to its parallel processing facility, ease of construction, and lower power consumption [18-23]. However, realization of digital systems based on FPGA is quite problematic and needs practice to implement the design using Hardware Description Language (HDL) [19,21]. Xilinx System Generator (XSG) has been introduced as an interesting platform integrated with the MATLAB/Simulink platform to perform an automatic generation of the HDL code. This integrated platform can be employed for directly realizing the systems prototypes based on FPGA without the deep experience with the HDL. Moreover, this integrated platform has the ability to conduct Hardware In Loop (HIL) co-simulation [19,21]. HIL co-simulation is a platform which enables the validation of the controller design as an actual hardware collaborated with the process simulated by computer. This allows new controllers to be designed and tested with simulated systems without the risk of damaging real systems [21]. The work presented in this paper aims to build a digital 2DOF-PID controller using FPGA to overcome all the limitations mentioned above. This paper is organized as follows. The basic principle of the 2DOF-PID controller was presented in Section 2. The principle of the PSO optimization algorithm and its use for tuning 2DOF-PID controller was clarified in Section 3. Section 4 includes the implementation details of the control system based on MATLAB/Simulink and XSG. Simulation and experimental results are presented in Section 5, and Section 6 includes the conclusions.

2. **Two Degree of Freedom PID Controller.** The common structure of the 2DOF-PID controller is shown in Figure 1, where the controller structure contains two sections $C_f(s)$ and $C(s)$ [15,16]. The first section $C_f(s)$ represents the feedforward controller, and the second section $C(s)$ is the series or feedback controller. The transfer function $P_d(s)$ represents the effects of the disturbance d to the controlled variable y. The analog plant is given as $P(s)$ and the feedback detector is $H(s)$.

The transfer function from the reference input (r) to the y is given as

$$\frac{Y_r(s)}{R(s)} = \frac{P(s)[C(s) + C_f(s)]}{1 + P(s)C(s)H(s)} \tag{1}$$

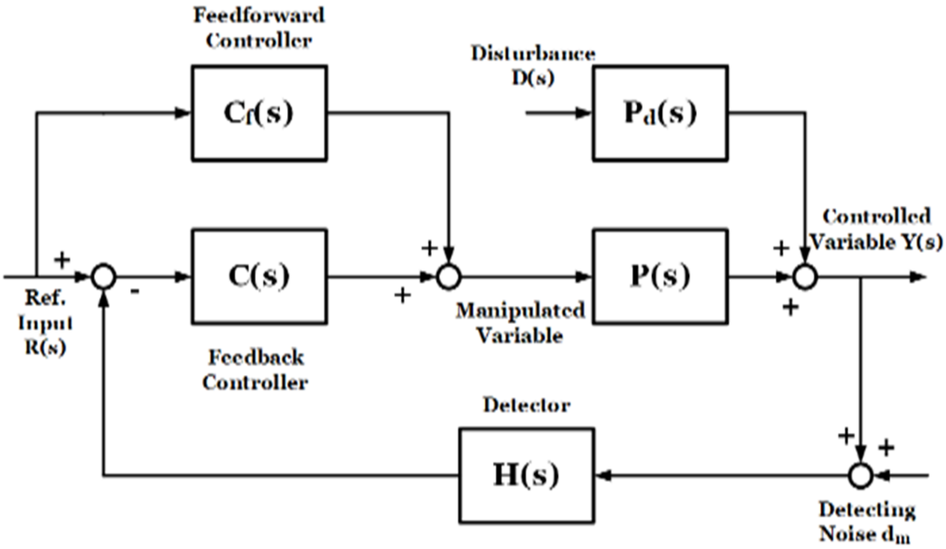


FIGURE 1. General structure of 2DOF-PID controller

The transfer function from d to y is given by

$$\frac{Y_d(s)}{D(s)} = \frac{P_d(s)}{1 + P(s)C(s)H(s)} \tag{2}$$

Therefore, the overall system response can be described as follows:

$$Y(s) = \begin{bmatrix} \dfrac{P(s)[C(s) + C_f(s)]}{1 + P(s)C(s)H(s)} \\ \dfrac{P_d(s)}{1 + P(s)C(s)H(s)} \end{bmatrix} \begin{bmatrix} R(s) \\ D(s) \end{bmatrix} \tag{3}$$

For unit step of reference input (r) and unit step of disturbance (d), the zero steady-state errors

$$e_{ssr} = r(t) - y(t) = 0|_{t\to\infty} \tag{4}$$

$$e_{ssd} = d(t) - y(t) = 0|_{t\to\infty} \tag{5}$$

can be achieved according to the following assumptions:

1) The detector is assumed to be

$$H(s) = 1, \text{ and } d_m = 0 \tag{6}$$

2) The disturbance signal is entering to the manipulated variable, i.e.,

$$P_d(s) = P(s) \tag{7}$$

Therefore, the resulting reduced structure of the continuous-time control system is shown in Figure 2, and the system response is given in (8).

$$Y(s) = \begin{bmatrix} \dfrac{P(s)[C(s) + C_f(s)]}{1 + P(s)C(s)} \\ \dfrac{P(s)}{1 + P(s)C(s)} \end{bmatrix} \begin{bmatrix} R(s) \\ D(s) \end{bmatrix} \tag{8}$$

where

$$P(s) = \frac{4.102 \times 10^{-5}s^3 - 1.083s^2 - 4.4 \times 10^4 s + 9.851 \times 10^8}{s^3 + 5968s^2 + 1.09 \times 10^7 s + 6.898 \times 10^9} \tag{9}$$

$$C(s) = K_p\left(1 + \frac{1}{T_I s} + T_D s\right) \tag{10}$$

$$C_f(s) = -K_p(\alpha + \beta T_D s) \tag{11}$$

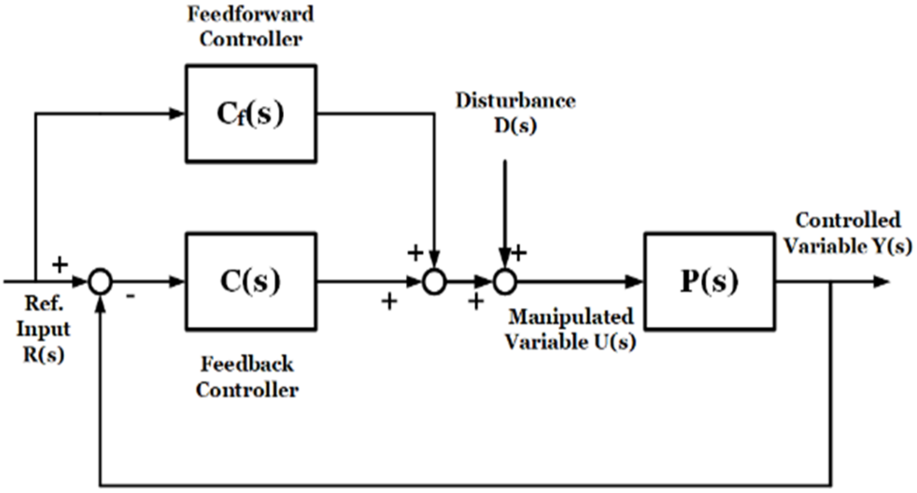


FIGURE 2. Reduced structure of 2DOF-PID controller

In order to obtain the discrete-time governing equations of the control system, the bilinear transformation has been employed for obtaining the discrete-time form of Equations (10) and (11).

$$C(z) = C(s)\big|_{s=\frac{2}{T}\frac{z-1}{z+1}} \tag{12}$$

$$C_f(z) = C_f(s)\big|_{s=\frac{2}{T}\frac{z-1}{z+1}} \tag{13}$$

where T is the sampling period and it is set equal to 100 µsec.

Therefore, Equations (12) and (13) will be

$$C(z) = K_p \left[\frac{\left(1 + \frac{2T_D}{T} + \frac{T}{2T_I}\right) z^2 + \left(\frac{T}{T_I} - \frac{4T_D}{T}\right) z + \left(\frac{T}{2T_I} + \frac{2T_D}{T} - 1\right)}{z^2 - 1} \right] \tag{14}$$

$$C_f(z) = K_p \left[\frac{\left(\alpha + \frac{2\beta T_D}{T}\right) z + \left(\alpha - \frac{2\beta T_D}{T}\right)}{z + 1} \right] \tag{15}$$

Re-arrange (14) and (15) to the following forms

$$C(z) = \frac{Lz^2 + Mz + (L-2)}{z^2 - 1} \tag{16}$$

where $L = K_p \left(1 + \frac{2T_D}{T} + \frac{T}{2T_I}\right)$, $M = K_p \left(\frac{T}{T_I} - \frac{4T_D}{T}\right)$

$$C_f(z) = \frac{Nz + (N-2)}{z + 1} \tag{17}$$

where $N = K_p \left(\alpha + \frac{2\beta T_D}{T}\right)$

$$P(z) = P(s)\big|_{s=\frac{2}{T}\frac{z-1}{z+1}} = \frac{0.0001436z^{-1} + 0.0004951z^{-2} + 0.000104z^{-3}}{1 - 2.464z^{-1} + 2.018z^{-2} - 0.5488z^{-3}} \tag{18}$$

From Equations (15)-(18), the following difference equations set can be derived:

$$x(n) = -x(n-1) + Nr(n) + (N-2)r(n-1) \tag{19}$$

$$w(n) = w(n-2) + Le(n) + Me(n-1) + (L-2)e(n-2) \tag{20}$$

$$v(n) = x(n) + w(n) \tag{21}$$

$$u(n) = v(n) + d(n) \tag{22}$$

$$\begin{aligned} y(n) = {} & 2.464y(n-1) - 2.018y(n-2) + 0.5488y(n-3) + 10^{-5}(14.36u(n-1) \\ & + 49.51u(n-2) + 10.4u(n-3)) \end{aligned} \tag{23}$$

Since the purpose of using this controller is to improve the system's response to the reference signal and the disturbance signal at the same time, there must be a criterion to measure this response and it is called the cost function, which can be described by the following relationship:

$$g(n) = \sum_{n} |r(n) + d(n) - y(n)| \tag{24}$$

where $g(n)$ is the integral of the absolute error IAE.

3. **Particle Swarm Optimization.** Particle Swarm Optimization (PSO) algorithm, which is designed for optimizing numerical functions [24]. The PSO algorithm arranges the particles in the search space of the considered function, and each of these particles determines its current location and the cost function. The next movement of the particles will be determined according to the combining of some portions of its current and best locations by those with members that have unpredicted disturbances [24,25]. The algorithm enters the next iteration when all the particles are moved.

Based on the above, the PSO optimization algorithm needs to state the following parameters.

D: is the size of the search space.

x_i: is the position of the ith particles in the D. $x_i = (x_{i1}, x_{i2}, \ldots, x_{iD})$.

v_i: is the velocity of the ith particles in the D. $v_i = (v_{i1}, v_{i2}, \ldots, v_{iD})$.

According to the pre-defined cost function, the best position vector of the particles will be stated as $P_i = (P_{i1}, P_{i2}, \ldots, P_{iD})$, and P_g is the global position vector that keeps track the best cost function (g_{best}).

Therefore, the updated velocities and positions of the particles are determined using the following equations [24,25]:

$$v_{id} = w \times v_{id} + C_1 r_1 (P_{id} - x_{id}) + C_2 r_2 (P_{gd} - x_{id}) \tag{25}$$

$$x_{id} = x_{id} + v_{id} \tag{26}$$

where C_1 is the cognitive parameter, C_2 is the social parameter, w is the inertia weight and it is calculated as follows:

$$w = w_{\max} - (w_{\max} - w_{\min}) \left(\frac{iteration\ no.}{\max no.\ of\ iterations} \right) \tag{27}$$

One of the main objectives of this paper is to determine the best values of the 2DOF-PID parameters using the PSO optimization algorithm. To achieve this goal, the difference equations (19)-(24) are adopted to extract the cost function. Therefore, the task of the PSO is to minimize the cost function $g(n)$ by searching the best values for L, M, and N. The PSO algorithm has been implemented using MATLAB and it is configured based on the parameters shown in Table 1.

Table 1. PSO parameters

Parameter name	Value
Size of swarm	1000
Dimension of the problem	3
Maximum iteration	50
Cognitive C_1	0.3
Social C_2	0.3
$w_{\max}$	1.2
$w_{\min}$	0.1

The values of the 2DOF-PID parameters associated with the gbest are $L = 1.1334$, $M = 6.3514$, and $N = 6.9795$. These parameters will be employed for realizing and testing the 2DOF-PID controller based on different platforms.

4. **Implementation of the Control System.** Firstly, the discrete-time structure of the control system has been implemented using MATLAB/Simulink platform. The second implementation stage was the Xilinx System Generator (XSG) that implements the digital structure of the controller. Finally, the hardware implementation of the digital controller is achieved using FPGA sp605 evaluation kit and it is employed in HIL co-simulation. Figure 3 depicts the 2DOF-PID controller configured in structural mode. In this mode, the controller parameters have been embedded in the difference equations. The controller structure receives the reference input signal and the error signal, while the disturbance signal is added externally.

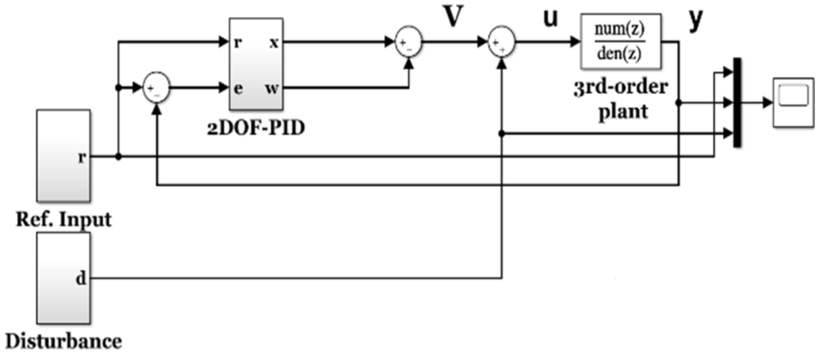


Figure 3. Discrete-time control system with 2DOF-PID controller based on MATLAB/Simulink

The structural block of the controller was implemented using XSG as shown in Figure 4. Figure 4(a) shows the complete control system based on XSG, and the detailed structure of the controller is shown in Figure 4(b). In this work, HIL co-simulation is engaged for the verification of the 2DOF-PID controller by implementing it on the FPGA hardware kit and cooperating with the MATLAB/Simulink package.

The implementation process is performed using the co-simulation facility provided by XSG platform. The hardware digital 2DOF-PID controller is shown in Figure 5. The controller receives the reference input signal, error signal, and disturbance signal from the software, and it sends the resulting control signal to the software. The data exchange between the hardware and software is through the JTAG-USB cable.

5. **Simulation and Experimental Results.** Simulation has been performed in MATLAB/Simulink environment to validate the performance of the designed 2DOF-PID controller. Two types of reference input signal were employed for validation.

The first one was stepped input signal, while the second was square wave signal. Moreover, a unit pulse signal with duration of 0.5 sec is considered as a disturbance signal. Figure 6 shows the simulation results of the discrete-time control system with 2DOF-PID controller using Simulink.

The implementation of the 2DOF-PID controller based on XSG has been also validated with the same conditions of reference input and disturbance. The simulation results of these cases are shown in Figure 7.

Figure 8 shows the experimental results obtained when the hardware 2DOF-PID controller using FPGA is employed in HIL co-simulation. The same reference input and disturbance signals are considered in this process. The results of simulation and experiments confirmed the advantage of this controller from tracking the reference signal and rejecting disturbance.

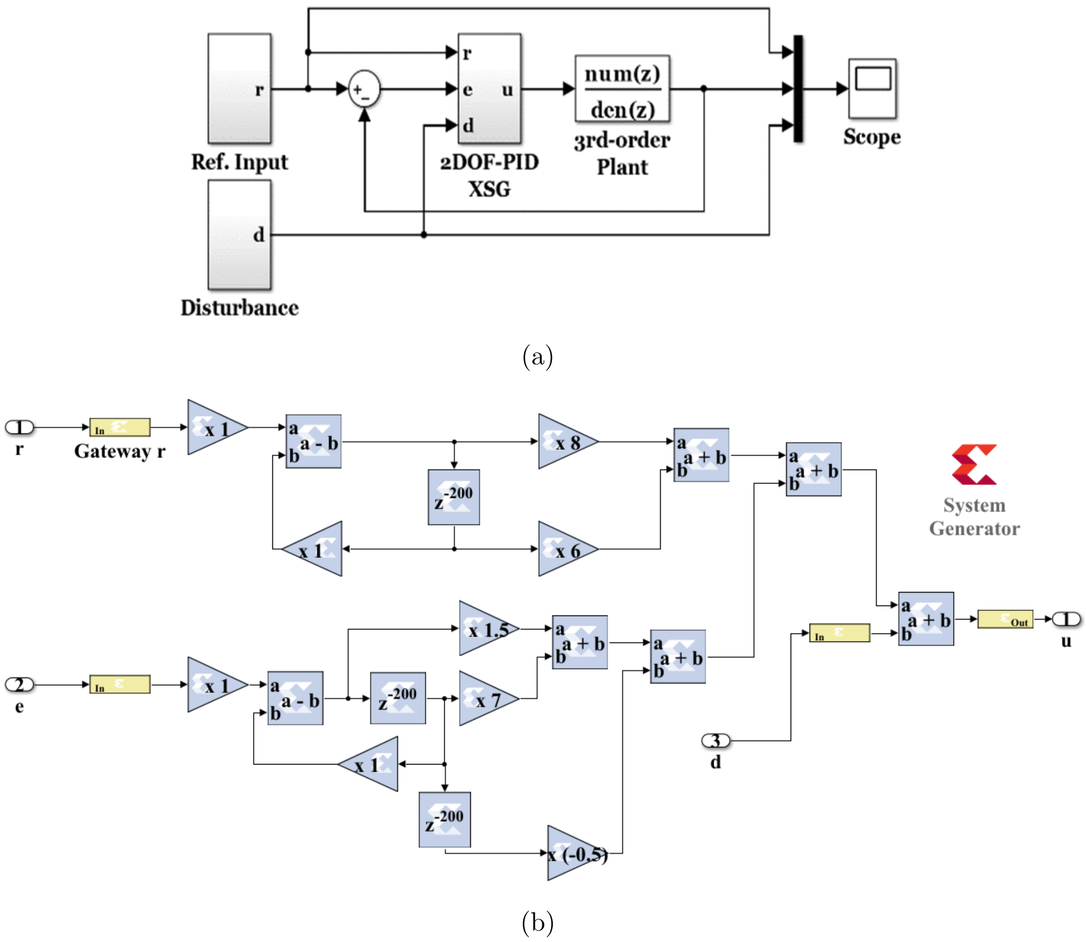


FIGURE 4. Structural mode of 2DOF-PID controller in XSG: (a) Complete control system; (b) detailed structure

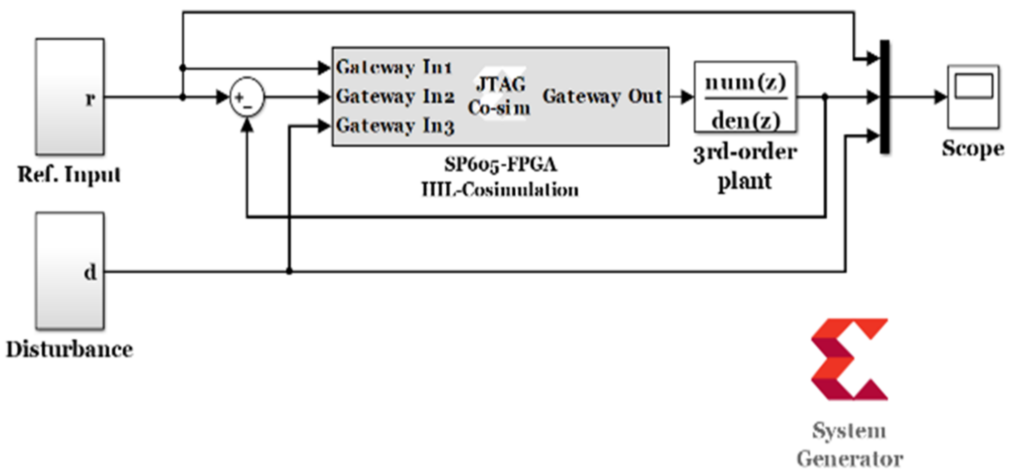
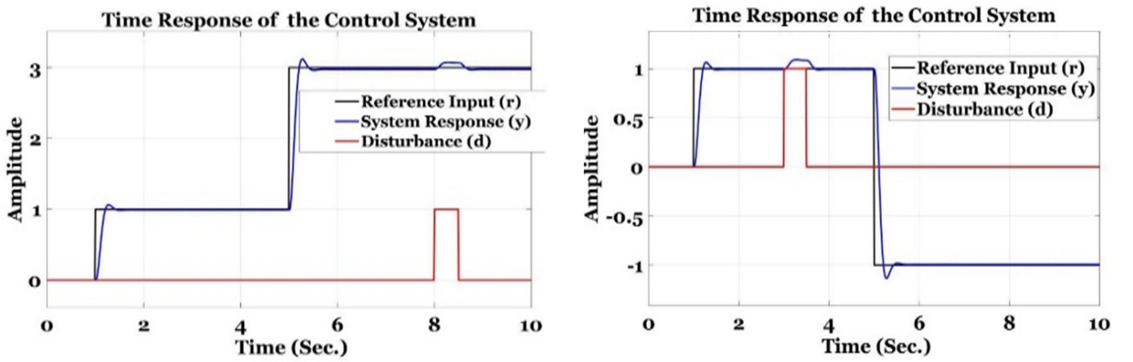


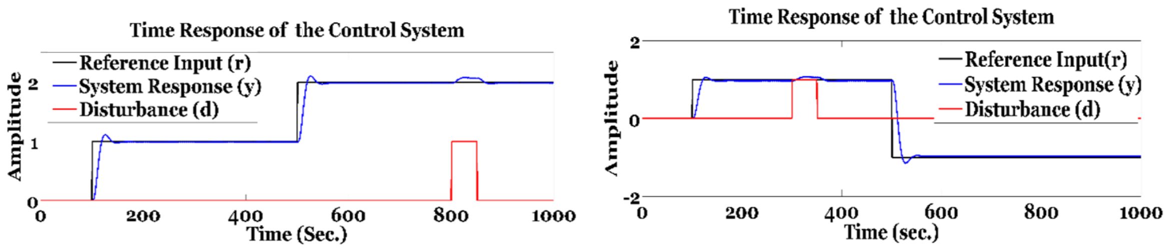
FIGURE 5. Hardware implementation of 2DOF-PID using FPGA

6. **Conclusions.** The work presented in this paper concerned with the implementation of the 2DOF-PID controller based on FPGA. To accomplish this task, the discrete-time controller was derived and its parameters are extracted using PSO algorithm. Validation of the discrete-time model of the controller is achieved based on MATLAB/Simulink platform. The XSG was employed to facilitate the implementation of the digital controller



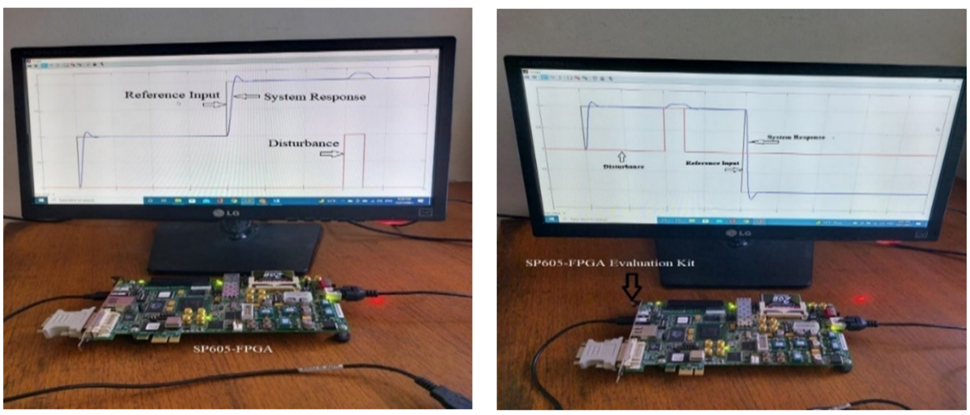
(a) (b)

FIGURE 6. (color online) System response with discrete-time 2DOF-PID controller: (a) Stepped reference; (b) square wave reference



(a) (b)

FIGURE 7. (color online) System response with digital controller based on XSG: (a) Stepped reference; (b) square wave reference



(a) (b)

FIGURE 8. System response with digital controller based on FPGA: (a) Stepped reference; (b) square wave reference

in real time using FPGA device. The target device was FPGA Spartan 6-sp605 evaluation kit. The simulation and experimental results show the promising functionality of the 2DOF-PID controller. Also these results verify the effectiveness of this controller for tracking the reference input and rejecting the disturbance. The use of XSG in an integrated environment with MATLAB/Simulink facilitates the design and builds reliable and high-accuracy digital systems with less effort and cost. This study can be extended to cope with other optimization techniques like Social Spider Optimization (SSO), Grey-Wolf Optimization (GWO), and Whale Optimization Algorithm (WOA) [26-32].

REFERENCES

[1] A. J. Humaidi, A. A. Oglah, S. J. Abbas and I. K. Ibraheem, Optimal augmented linear and nonlinear PD control design for parallel robot based on PSO tuner, *International Review on Modelling and Simulations*, vol.12, no.5, https://doi.org/10.15866/iremos.v12i5.16298, 2019.

[2] B. Hekimoğlu, Optimal tuning of fractional order PID controller for DC motor speed control via chaotic atom search optimization algorithm, *IEEE Access*, vol.7, pp.38100-38114, 2019.

[3] L. Wang and C. Zhong, Design of optimal fractional-order PID controllers using particle swarm optimization algorithm for DC motor system, *2015 IEEE Advanced Information Technology, Electronic and Automation Control Conference (IAEAC)*, Chongqing, China, 2015.

[4] M. Huba, D. Vrancic and P. Bistak, PID control with higher order derivative degrees for IPDT plant models, *IEEE Access*, vol.9, pp.2478-2495, 2021.

[5] Y. Li, K. H. Ang and G. C. Y. Chong, PID control system analysis and design, *IEEE Control Systems Magazine*, vol.26, no.1, pp.32-41, 2006.

[6] T. L. Blevins, PID advances in industrial control, *IFAC Proceedings Volumes*, vol.45, no.3, pp.23-28, 2012.

[7] V. Balaguer, A. González et al., Enhanced 2-DOF PID controller tuning based on an uncertainty and disturbance estimator with experimental validation, *IEEE Access*, vol.9, pp.99092-99102, 2021.

[8] A. J. Humaidi, H. T. Najem, A. Q. Al-Dujaili, D. A. Pereira, K. I. Ibraheem and A. T. Azar, Social spider optimization algorithm for tuning parameters in PD-like Interval Type-2 Fuzzy Logic Controller applied to a parallel robot, *Measurement and Control*, vol.54, nos.3-4, pp.303-323, 2021.

[9] K. H. Al-Waeli, R. Ramli et al., Offline ANN-PID controller tuning on a multi-joints lower limb exoskeleton for gait rehabilitation, *IEEE Access*, vol.9, pp.107360-107374, 2021.

[10] N. Merayo, D. Juárez et al., PID controller based on a self-adaptive neural network to ensure QoS bandwidth requirements in passive optical networks, *Journal of Optical Communications and Networking*, vol.9, no.5, pp.433-445, 2017.

[11] A. R. Nasser, A. T. Azar, A. J. Humaidi, A. K. Al-Mhdawi and I. K. Ibraheem, Intelligent fault detection and identification approach for analog electronic circuits based on fuzzy logic classifier, *Electronics*, vol.10, 2888, https://doi.org/10.3390/electronics10232888, 2021.

[12] A. Humaidi and M. Hameed, Development of a new adaptive backstepping control design for a non-strict and under-actuated system based on a PSO tuner, *Information*, vol.10, https://doi.org/10.3390/info10020038, 2019.

[13] H. Zhang, W. Assawinchaichote and Y. Shi, New PID parameter autotuning for nonlinear systems based on a modified monkey-multiagent DRL algorithm, *IEEE Access*, vol.9, pp.78799-78811, 2021.

[14] A. Leva and S. Seva, Structure-specific analytical PID tuning for load disturbance rejection, *IFAC-PapersOnLine*, vol.51, no.4, pp.137-142, 2018.

[15] A. J. Humaidi and A. I. Abdulkareem, Design of augmented nonlinear PD controller of Delta/Par4-like robot, *Journal of Control Science and Engineering*, 7689673, 2019.

[16] M. Araki and H. Taguchi, Two-degree-of-freedom PID controllers, *International Journal of Control, Automation and Systems*, vol.1, no.4, pp.401-411, 2003.

[17] B. X. Wang, X. Yan et al., An approach for setting parameters for two-degree-of-freedom PID controllers, *Algorithms*, vol.11, no.4, pp.1-18, 2018.

[18] A. J. Humaidi and T. M. Kadhim, Spiking versus traditional neural networks for character recognition on FPGA platform, *Journal of Telecommunication, Electronic and Computer Engineering*, vol.10, no.3, pp.109-115, 2018.

[19] R. Hassan, Performance investigation of digital lowpass IIR filter based on different platforms, *International Journal of Electrical and Computer Engineering Systems*, vol.12, no.2, pp.105-111, 2021.

[20] A. J. Humaidi, T. M. Kadhim, S. Hasan, I. K. Ibraheem and A. T. Azar, A generic Izhikevich-modelled FPGA-realized architecture: A case study of printed English letter recognition, *2020 24th International Conference on System Theory, Control and Computing (ICSTCC)*, pp.825-830, 2020.

[21] M. Q. Kasim, R. F. Hassan, A. J. Humaidi et al., Control algorithm of five-level asymmetric stacked converter based on Xilinx System Generator, *2021 IEEE 9th Conference on Systems, Process and Control (ICSPC2021)*, Malacca, Malaysia, 2021.

[22] A. J. Humaidi, S. Hasan and M. A. Fadhel, FPGA-based lane-detection architecture for autonomous vehicles: A real-time design and development, *Asia Life Sciences*, no.1, pp.223-237, 2018.

[23] A. J. Humaidi, S. Hasan and M. A. Fadhel, Rapidly-fabricated nightly-detected lane system: An FPGA implemented architecture, *Asia Life Sciences*, no.1, pp.343-355, 2018.

[24] A. J. Humaidi, S. K. Kadhim and A. S. Gataa, Optimal adaptive magnetic suspension control of rotary impeller for artificial heart pump, *Cybernetics and Systems*, vol.53, no.1, 2022.

[25] A. J. Humaidi and H. M. Badr, Linear and nonlinear active disturbance rejection controllers for single-link flexible joint robot manipulator based on PSO tuner, *Journal of Engineering Science and Technology Review*, vol.11, no.3, pp.133-138, 2018.

[26] T. Ghanim, A. R. Ajel and A. J. Humaidi, Optimal fuzzy logic control for temperature control based on social spider optimization, *IOP Conference Series: Materials Science and Engineering*, vol.745, no.1, 012099, 2020.

[27] A. Al-Qassar, A. I. Abdu-Alkareem, A. F. Hasan, A. J. Humaidi, K. I. Ibraheem, A. T. Azar and A. H. Hameed, Grey-wolf optimization better enhances the dynamic performance of roll motion for tail-sitter VTOL aircraft guided and controlled by STSMC, *Journal of Engineering Science and Technology (JESTEC)*, vol.16, no.3, pp.1932-1950, 2021.

[28] A. Al-Qassar, A. S. Al-Obaidi, A. F. Hasan, A. J. Humaidi, A. R. Nasser, A. Alkhayyat and K. I. Ibraheem, Finite-time control of wing-rock motion for delta wing aircraft based on whale-optimization algorithm, *Indonesian Journal of Science & Technology*, vol.6, no.3, pp.441-456, 2021.

[29] A. I. Abdul-Kareem, A. F. Hasan, A. A. Al-Qassar, A. J. Humaidi, R. F. Hassan, I. K. Ibraheem and A. T. Azar, Rejection of wing-rock motion in delta wing aircrafts based on optimal LADRC schemes with butterfly optimization algorithm, *Journal of Engineering Science and Technology*, vol.17, no.4, pp.2476-2495, 2022.

[30] Z. A. Waheed and A. J. Humaidi, Design of optimal sliding mode control of elbow wearable exoskeleton system based on whale optimization algorithm, *Journal Européen des Systèmes Automatisés*, vol.55, no.4, pp.459-466, 2022.

[31] A. J. Humaidi, S. K. Kadhim, M. E. Sadiq, S. J. Abbas, A. Q. Al-Dujaili and A. R. Ajel, Design of optimal sliding mode control of PAM-actuated hanging mass, *ICIC Express Letters*, vol.16, no.11, pp.1193-1204, 2022.

[32] A. J. Humaidi, H. M. Badr and A. H. Hameed, PSO-based active disturbance rejection control for position control of magnetic levitation system, *2018 5th International Conference on Control, Decision and Information Technologies (CoDIT'18)*, Thessaloniki, Greece, pp.922-928, 2018.