



Robust Interactive PID Controller Design for Medical Robot System

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Abstract: In this paper, the design and application of robust interactive PID control for a medical robot system is presented. The aim is to solve the problem of precise position tracking required for human walking, using a simple type of control while taking into account the interactions of the systems' input and outputs. The medical robot system can be interpreted as pendulum links to obtain a complete motion of all muscles. Two control actions are required to be applied for the two joints. The interactions of this multivariable system have been examined using the relative gain array (RGA). In this work, PID and Fuzzy PID controllers are implemented with interactions effects. In addition, two other non-conventional types of PID control structures have been considered for comparison, where the RGA cannot be applied. These are the two-degree PID (2DoFPID) and nonlinear PID (NPID) controllers. Simulation results show that in the case of not considering the interaction effects, the Fuzzy PID controller can provide an improvement of 44% as compared with conventional PID controller. While this improvement has been increased to 70% with the consideration of interaction effects. Meanwhile, NPID controller shows higher rise and settling times (almost more than 2 seconds for the settling time). While 2DoFPID controller shows difficulty in implementation due to its highly chattered control signals with higher overshoots in the transient response as compared with the results of the interactive Fuzzy PID controller. Finally, robustness against disturbances and system uncertainties has been tested with all the developed controllers. It has been concluded that the interactive Fuzzy PID controller achieves better performance in terms of less ISE, settling time, rise time, and overshoot.

Keywords: Medical robot system, Fuzzy PID, Nonlinear PID, Two-degree PID, Relative gain array.

1. Introduction

An attractive phenomenon is a human movement where the humans have a changeable ability of place position, where scamper, running, and walking are a point of view to be considered. From the beginning of hominins, movement is considered an observable thing for humans, despite still the matter of the splinted way of our two-legged walking is conjecture. Sophisticated environments, tools, and equipment were built by humans within a very skilled manner to use in the new community. Humanoid robots inherently have a major similarity with morphology humanlike and motion capabilities with in human environments [1]. The multivariable robotic system has high interaction effects between the system's inputs and outputs. These are usually considered as inhibited nonlinearities of the medical robotic system

that affects the system's performance. Moreover, they may cause a serious challenge for designing a suitable controller to reach the optimal response for different affections.

Practically, the motivation of studying the motion mechanism of the medical robot system is for different reasons such as moving in uneven ground, risky jobs, or environments with choppy supports like a ladder, also in restoring motion for the disabled [2]. Healthy stalks are important for humans to perform daily life activities such as seated, walk and run, from all these activities and more, walking is considered as the most important, which is characterized by particularly nonlinear dynamics and can be represented as a pendulum link as well as the swing leg system [3]. And for its importance for medical and health care applications, it has been considered recently as an active field of study; plenty of research works done to effectively control this type of system

with various interesting approaches. Starting with [3, 4] where they presented a trajectory tracking control method with feedback linearization controller of fixed and movable double pendulums for a joint self-impact model of the swing leg for a human. They gained an accepted error of normal ways of walking. In [5], the authors designed three degrees of freedom robotic leg with analysis of 2D plane motion and joints angle orientation. The results show considerably accepted average error for hip, knee, and ankle respectively. In [6], a fast gait-mode-detection method has been proposed. It shows the effectiveness of the gait-mode-based assistive strategy depending on using electromyography muscular activities.

The authors in [7-10], showed a robustly stabilize of the nonlinear pendulum links, hip, and knee of the human swing leg system. The desired response specifications have been obtained using the sliding mode control (SMC) robustness properties [7], full-state feedback H-infinity controller [8], dynamic output feedback by combining both H_2 state feedback and PID controllers with the cultural algorithm (CA) method as an effective optimization algorithm [9], and the H-infinity Sliding Mode Control (HSMC) by combining both of the H-infinity and SMC controllers robustness that considered as complex intelligent controller [10]. The applied controllers in [7-10] shows robust effective stabilization for the system and achieve better specifications of time response than those with applying either only H-infinity or SMC controllers.

Another work by [11] had implemented H_∞ loop-shaping as a robust controller. It resulted in better performance as compared to both PID and SMC controllers on the swing leg robotic system. Meanwhile, [12] presented 2nd order arm robot dynamic system with the classic Recursive Newton-Euler (RNEA) method. The authors used a feedback linearization method for motion control, which behaves equitable effectiveness for trajectory tracking of the system-based control.

In [13] the author designed a tracking controller to achieved position and stiffness of the variable stiffness joint. While in [14] the authors presented comparative effectiveness of both Genetic Algorithm-Back propagation neural network and a repeated event-triggered SMC sketch for lower limb human-robot for both simulation and experimental analysis.

A mechanism called COWALK-Mobile 2 presented in [15] showed that larger joints of both hip and knee torques were generated with smaller actuator torques as compared with a healthy walking human on a level surface. While [16] presented 3DoF

robotic arm motion controlled by of Fuzzy cascade controller tuned by Genetic algorithm-simple additive weighting (GA-SAW) compared with a conventional PID controller, which shows an undesirable transient response of both the settling time and rise time. Also, in [17], the design of an adaptive type-2 fuzzy backstepping controller is presented, where the convergence speed of the control algorithm has been improved, and its steady-state error has been reduced for the robot manipulator. While [18] introduces three types of techniques for tuning the robot manipulator, which are PID, Sliding Mode Control SMC, and Integral Sliding Mode Control (ISMC) using Intelligent Particle Swarm Optimization (PSO) to achieve the optimum controllers' parameters. Results show that ISMC with PSO had the best result for stable step response.

Eventually, PID control is a known multivariable lower-level control element that has been used with many technology transformations, such as mechanical systems to microprocessors. PID controllers provide robust and reliable performance for most systems if the PID parameters are tuned properly. Many types of PID controllers are considered nowadays in industrial applications for their improved performance such as using some intelligent ways for tuning the PID controller parameters [6-8], two degrees of freedom PID (2DoFPID) [19], and nonlinear PID (NPID) [20].

The main drawback that has been noticed in controlling the multivariable medical robot system is not considering the effects of interaction between the inputs and outputs.

Relative gain array is a widely used technique for the design of multivariable control systems. It is usually used to measure loop interaction in multivariable control system design.

Consequently, the motivation of this paper is to design a suitable multivariable interactive controller for the medical robot system with the consideration of the interaction problem using the RGA evaluation. Accordingly, the main contributions of the proposed control method are as follows:

- 1- The effects of the systems' inputs and outputs interaction is considered and compensated for by calculating the RGA for different types of PID controllers. to reach the desired joint position degree.
- 2- The implementation of an intelligent approach like Fuzzy logic control algorithm for tuning the PID controller parameters to improve the system's response.
- 3- Comparison with other non-standard types of PID controllers, as 2DoFPID and NPID controllers.
- 4- Robustness of the developed controlled system is investigated by considering the presence of

disturbances and measurement noise in the model of the system. In addition, the robustness of the controlled system is also investigated by considering uncertainties with the model of the system.

Moreover, the results show that although (NPID) and 2DoFPID can provide acceptable performance, their application and tuning have some difficulties; although the NPID is more sensitive to the tuning of the controller's parameters. The 2DoFPID results in a highly disturbed control signal with a high overshoot in the resulted response.

The remaining of the paper will be structured as follows: many related works; the mathematical model of the medical robot system is presented in Section 2; Section 3 describes the interaction and RGA calculations. Section 4, has introduces the theoretical concepts of both the PID and Fuzzy PID controllers with proposing the interaction effects depending on the RGA calculations for both controllers. In Section 5, we present other types of PID controller. The proposed controllers' measuring performance is presented in Section 6. While in Section 7. the simulation implementation with a comparison of controllers' responses are presented with robustness test for both systems' disturbance and uncertainty. Finally, conclusions are given in Section 8.

2. System description and mathematical modeling

To represent the mathematical model of medical robot leg, the physics complications of the robot leg must be considered. The medical robot is represented by two links which are thighed in movement by each other, the first link that connected the basin with the knee effects the second link motion that connected the knee to the foreleg. Theoretically, the knee angle may have any value which is insensible to the value of hip rotation angle, where, for human legs, this assumption is not valid, and the shank cannot assume the rotation angles which are greater than that of the thigh.

However, the simplified medical robot system model may be considered as a double pendulum system where the unconstrained dynamic equation written as in Eq. (1), can be accomplished by accounting for the motion of the hip and knee with neglecting the ankle motion defined as [7, 11]:

$$M(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + G_t(\theta) = \tau \quad (1)$$

where $\theta, \dot{\theta}, \ddot{\theta}$ are 2x1 vectors of joint angles, joint angular velocities, and joint angular accelerations, respectively; $M(\theta)$ is 2x2 symmetric positive

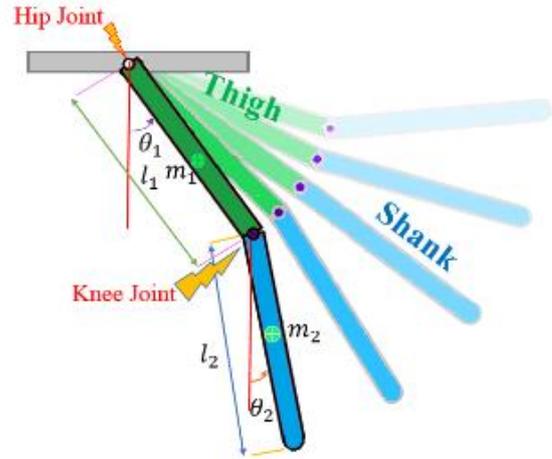


Figure. 1 Schematics of an unconstrained medical robot system [7, 11]

definite inertia matrix; $C(\theta, \dot{\theta})$ is 2x1 vector of Coriolis; $G_t(\theta)$ is 2x1 vector of gravitational torques and τ is 2x1 vector of actuator joint torques, where these matrix's depended on the robot specifications such as m_1 and m_2 are the thigh and shank masses, and they are 0.1 Kg, while l_1 and l_2 are thigh and shank lengths, respectively, and they equal to 0.55 m. θ_1 and θ_2 denoted the rotation angles of the hip and knee with respect to the perpendicular axis, τ_1 and τ_2 are the external torques that applied move the thigh and shank links, and g is gravitational and it's 9.81 m/s^2 . Fig. 1 shows a schematic of an unconstrained medical robot system.

The representation for the resulting system in state space is:

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (2)$$

$$y(t) = Cx(t) + Du(t) \quad (3)$$

where:

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -19.8873 & 3.8075 & -0.2155 & -0.2039 \\ 18.5281 & -22.2111 & 0.6116 & 0.2874 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 49.2616 & -69.4362 \\ -69.4362 & 197.0466 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}, \quad D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

The open-loop simulation response of both medical robotic system joints shows a high instability, as shown in Fig. 2, where a need for a suitable

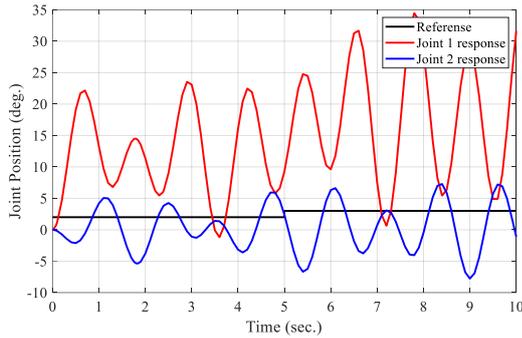


Figure. 2 Open loop medical robot system response

controller to improve the system's performance and stability.

3. Interaction and relative gain array (RGA) calculations

RGA is utilized to find the best pairing that corresponds to good controller performance. After applying RGA calculations to develop the required controllers. The interaction can be described with equations below [21] and illustrated in Fig. (3)

$$\Delta u_1 = g_{11} \Delta e_{11} + g_{12} \Delta e_{12} \quad (4)$$

$$\Delta u_2 = g_{21} \Delta e_{21} + g_{22} \Delta e_{22} \quad (5)$$

where Δu_1 and Δu_2 represent the control signal for first and second joints respectively, Δe_{ij} represent the errors' signal between input i and output j , and g_{ij} represent the process gain between input i and output j , e.g. g_{11} can be defined by

$$g_{11} = \frac{\left(\frac{\Delta u_1}{\Delta e_{11}}\right)_{\Delta e_{12}=0}}{\left(\frac{\Delta u_1}{\Delta e_{11}}\right)_{\Delta u_2=0}} \quad (6)$$

The RGA had been introduced by Bristol as a tool for pairing controlled and manipulated variables in decentralized control system. It is a useful tool in proving the pairing selection between inputs and outputs for diametrical control design, as shown in Fig. 3, where the main idea of it is to estimate the election of each output on a specific open-loop variable of the controller. For a 2×2 matrix with elements g_{ij} , the RGA is represented as in the following equation:

$$RGA = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} \quad (7)$$

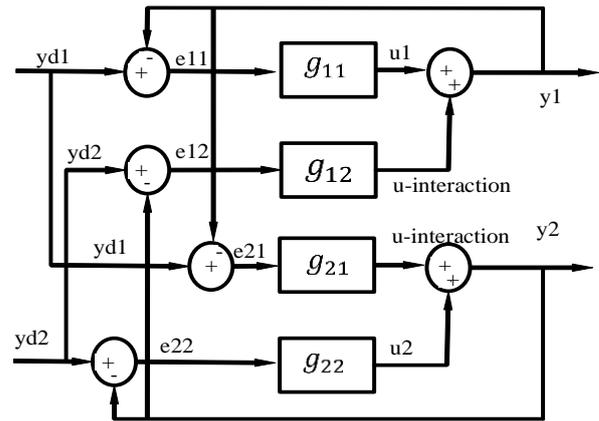


Figure. 3 Fully decoupled controller of medical robot system

As long as the RGA is square so that every row and every column sum is 1; so after substituting $g_{12} = g_{21} = 1 - g_{11}$ and $g_{11} = g_{22}$. The relative gains are dimensionless, and no matter for used units for process gains, on condition that they are consistent, the RGA will be as the following:

$$RGA = \begin{bmatrix} g_{11} & 1 - g_{11} \\ 1 - g_{11} & g_{11} \end{bmatrix} \quad (8)$$

From Eq. (8), if the process gain has a positive value in the diagonal this indicate that the interaction reduces the effect gain of the control loop. Higher controller gains are required; in another hand if the process gain has a negative off-diagonal element indicates that closing the loop will change the sign of effective gain. While it indicates to have an interaction between the control loops for process gain value between the conditions mentioned above.

Furthermore, linear behavior analysis was assumed. The changing of the operating conditions is probably the same as varying the process gains.

Consequently, the RGA recalculating under these conditions may modify the deductions in terms of both pairing and decoupling. For the reasons mentioned above, the RGA may only be considered as a technique for eliminating some of the pairing options and suggesting configurations that need to be evaluated further.

4. Interactive PID controller design based on RGA calculations for medical robot system

The PID (proportional-integral-derivative) controller is the most common and simple form of feedback. This makes it suitable to be implemented with RGA calculations, as well as applying the Fuzzy logic for tuning the PID controller parameters to

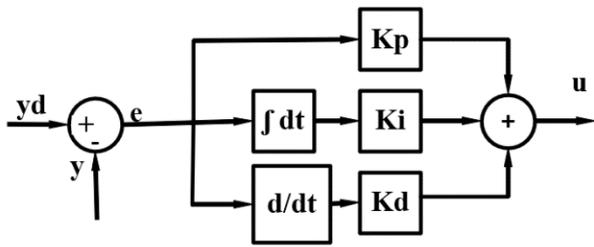


Figure. 4 Classical PID controller

reach a simple controller with high performances responses for the system.

4.1 Conventional PID controller

The conventional PID controller has advantages of structure simplicity, high robustness, the wide design process used in the simulated systems, and the efficacy and reliability, and besides the required accurate adjustment of its parameters, it also depended on the system's parameters to reach the desired performances [21]. It has been applied here to the medical robotic, as shown in Fig. 4. The output or control effort of a proportional (P) integral (I) and derivative (D) control algorithm is given, in general, by the following equation;

$$u(s) = K_p e(s) + K_i \frac{1}{s} e(s) + K_d s e(s) \quad (9)$$

where the K_p is the proportional gain, K_i the integral gain, K_d is the derivative gain, e is the error and u is the control signal.

4.2 Fuzzy logic PID controller

Fuzzy PID controllers are applied modern control system applications [22]. Fig. 5 shows the three main fuzzy structure parts, in Mamdani type which are: fuzzification, inference, and defuzzification. Fuzzy control algorithm work has been developed for tuning the PID controller parameters after verifying the rules of fuzzy control, membership functions, scaling factors, and defuzzification strategy with several trials where the inputs, e and de/dt are normalized using membership functions.

A parallel connection between the fuzzy module and PID parameters as shown in Fig. 6, where the fuzzy logic controller is tuning the parameters to reach the required performance [22] and the PID structure remains unchanged in spite of the presence of Fuzzy controller, which enables the application of RGA.

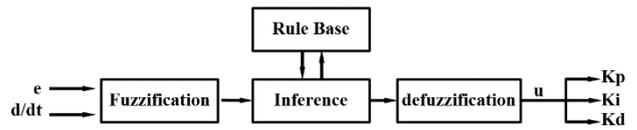


Figure. 5 Fuzzy controller structure

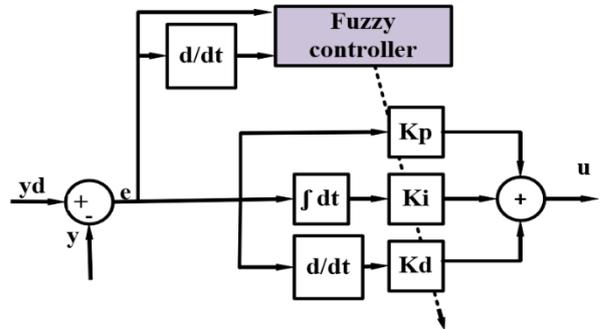
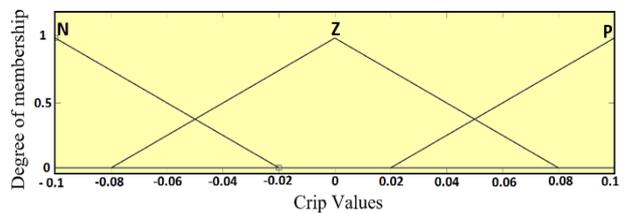
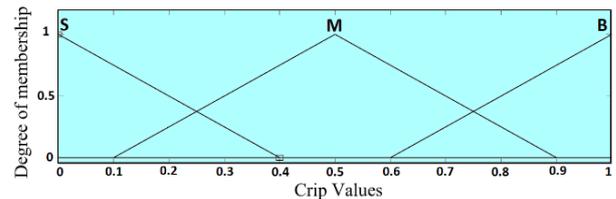


Figure. 6 Self tuning Fuzzy PID controller



(a)



(b)

Figure. 7 Membership variable function for: a) Both inputs e and de/dt . b) All outputs K_p , K_i , and K_d

Table 1. The rule base of Fuzzy

$de/dt \backslash e$	N			Z			P		
	K_p	K_i	K_d	K_p	K_i	K_d	K_p	K_i	K_d
N	S	S	S	S	S	S	S	S	S
Z	M	M	M	M	M	M	M	M	M
P	B	B	B	B	B	B	B	B	B

In this paper the following membership functions as show in figure (7-a) and figure (7-b) respectively; negative N, zero Z, positive P, so that the rules base as illustrated in Table 1.

5. Comparisons with non-conventional PID controllers

In order to justify the applied approach, two other types of PID controllers have been implemented; the NPID and 2DPID. Which can be considered efficient robust PID controllers [19]. However, the interactive control approach cannot be applied; because of their

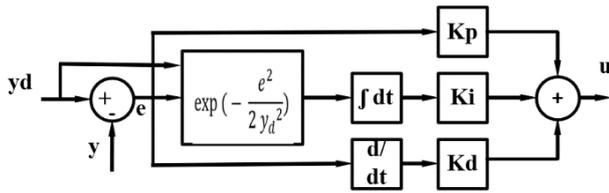


Figure. 8 The implemented NPID controller

nonlinear structures that are more complicated and have bad effects on the feasibility and robustness of the controlled system so it is difficult to use the RGA calculations with these types of controllers. The detailed description will be presented in the following:

5.1 Nonlinear PID controller

Nonlinear PID (NPID) controller depended on simplified proportional, and differential gains with nonlinear integral gain, that can be changed according to the error control signal [20]. Quickness, high accuracy, and no overshoot are considered as advantages of the NPID. The integral action contains a nonlinear function while the other (P and D) actions are linear. Hence, the error input to the integral action is scaled by a nonlinear function in the form of the product of the error and a nonlinear gain. Figure.8, shows the NPID controller block diagram. To evaluate all the control system performance integration of continuous time-weighted absolute error is applied, as in Eq. (10) [23]:

$$u(s) = K_p e(s) + \frac{1}{s} e^{-\left(\frac{e(s)^2}{2y_d^2}\right)} e(s) + K_d s e(s) \tag{10}$$

where the addition to the classical PID controller is represented by the exponential nonlinear function which provides a nonlinearity measured error as stated by e , and y_d as the desired response.

5.2 Two-Degree-of-Freedom PID controller (2DoFPID)

One of the interested applications of the PID controllers is the two-degree-of-freedom (2DoF) for its considerations the control performance regulatory with the robustness of the close loop system to upgrade the servo-control behavior. The features of 2DoF depended on the combination of both PI and PID control algorithms [19]. The 2DoF PID control algorithm is given by the following equation:

$$u(s) = K_p \left\{ \beta y_d + \frac{1}{T_i s} e(s) + \frac{T_d s}{\alpha T_d s + 1} e(s) \right\} \tag{11}$$

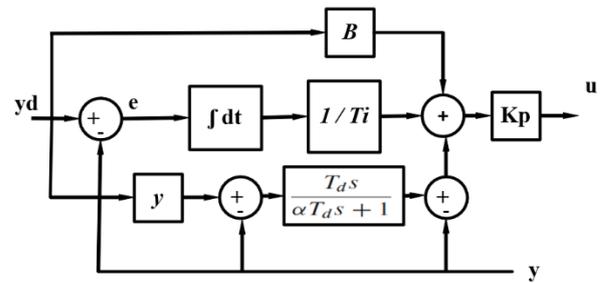


Figure. 9 Two degree of freedom of PID controller

where K_p is the main proportional controller gain, β and γ are the set-point weights, T_i is the integral time constant, T_d is the derivative time constant, and α is the derivative filter constant, as shown in Fig. 9. As it can be clearly noticed, the structure is more complicated than a conventional PID, RGA cannot be applied.

6. Performance measure of the robot controlled system

As can be seen from Eqs. (1) to (3), the models are quite standard approximations because of the system coupling of both inputs and outputs, this will tremendously increase the nonlinearity of the system and decrease performance quality.

Since it is required to improve the stability and performance of the medical robot system. Reasonable performance specifications need to be priority specified to test the effect of the previously mentioned controllers.

There are various system performance measures which can be used to measure the performance of the applied controller. The selected performance measure will be utilized for the comparison between the applied types of PID controllers. In this paper, the Integral Square Error is used, as in the following equation below [23]:

$$ISE = \int_0^{\infty} [e(t)]^2 dt \tag{12}$$

where $e(t)$ is a measure value of error at time t .

7. Simulation results

The simulation has been constructed using the medical robot system as described in Section 2. The previously described controllers in Sections 4 and 5 have been applied and tested as will be illustrated. The simulations experiments have been conducted using MATLAB/Simulink.

7.1 Interactive PID and Fuzzy PID controllers

The first step is evaluating the RGA for the robotic system described by Eqs. (2) and (3) in order to find the coupling status of the robotic system. It has been found that the major coupling is between input 1 and output 2. And according to the related property of RGA, there is an interaction between the control loops, therefore it would be better to minimize the interaction by introducing a suitable controller between these interacting variables. Meanwhile, the interaction between input 2 and output 1 has less effect of interaction. Consequently, PID controllers have been designed for each pairing of the controlled system.

Fig. 10 and 11 present the joints position responses of the closed loop tracking controlled system using the proposed interactive PID and interactive Fuzzy PID controllers compared with ordinary PID and Fuzzy PID controlled systems. Fig. 12 and 13 present the corresponding controllers' actions. From the results shown in figures and the transient response analysis, it's clear that the performance has noticeable improvement for both PID and Fuzzy PID controllers after considering the interaction effects, as shown in the results of Table 2,

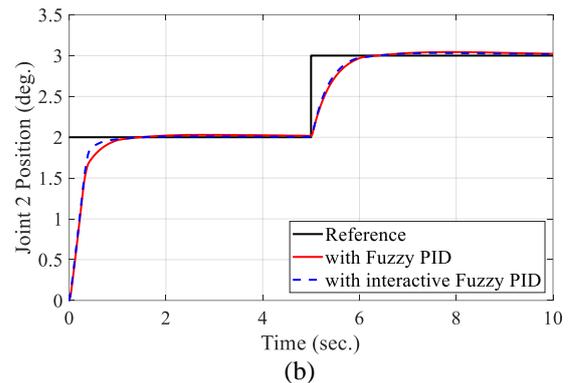
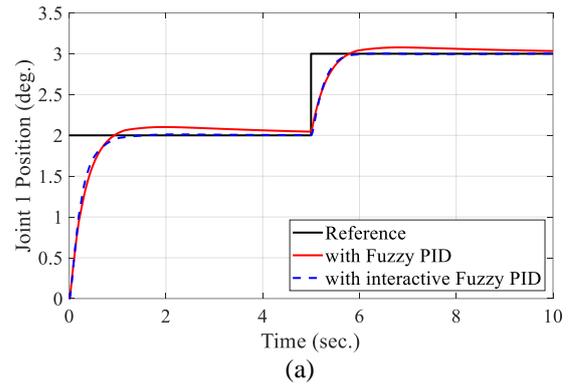


Figure. 11 Response of the medical robotic system under Fuzzy PID controller with and without the interaction effects for (a) 1st joint position and (b) 2nd joint position

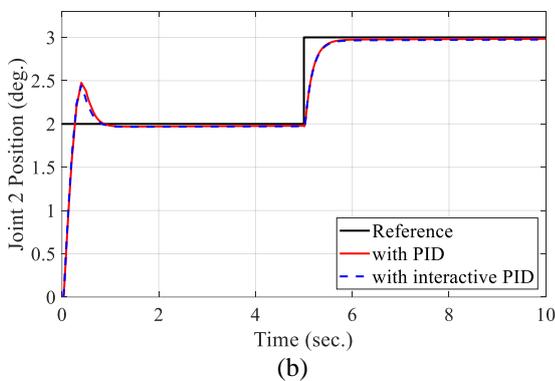
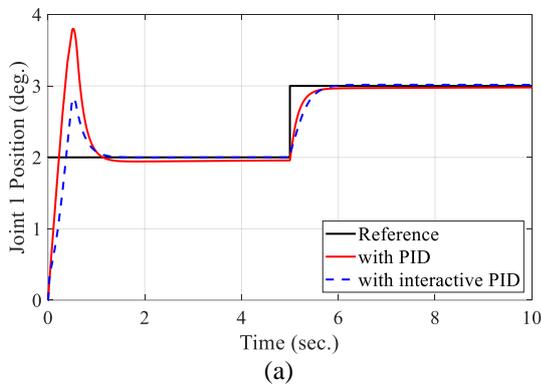


Figure. 10 Response of the medical robotic system under PID controller with and without the interaction effects for (a) 1st joint position and (b) 2nd joint position

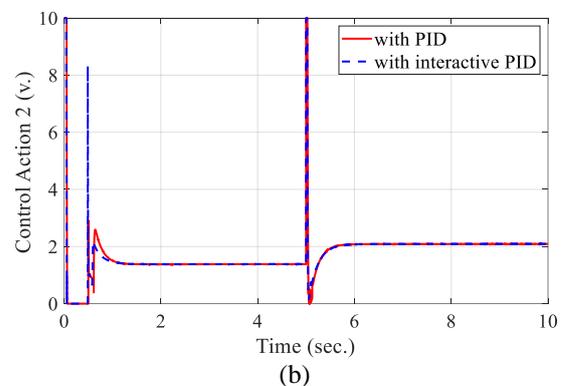
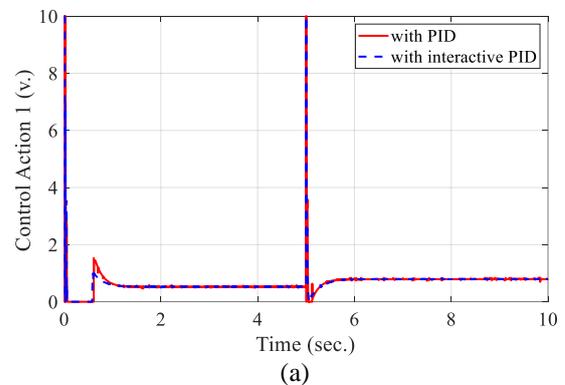


Figure. 12 Control action using the PID controller before and after adding the interaction effects for (a) 1st medical robot joint position and (b) 2nd medical robot joint position

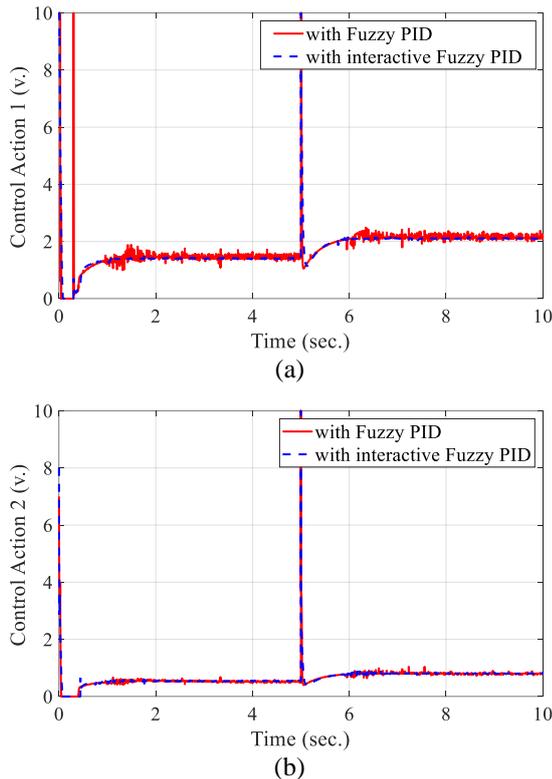


Figure. 13 Control action using the Fuzzy PID controller before and after adding the interaction effects for (a) 1st medical robot joint position and (b) 2nd medical robot joint position

Table 2. The PID controllers type Performance comparison

Controller	Medical robot joint	Rise Time(sec.)	Settling Time (sec.)	Overshoot %	Steady state error	ISE
PID	1 st Joint	0.081	1.5	1.8	0.045	52.187
	2 nd Joint	0.088	1.3	0.5	0.035	50.024
Interactive PID	1 st Joint	0.170	1.2	0.82	0.017	38.306
	2 nd Joint	0.078	1.2	0.42	0.037	36.352
Fuzzy PID	1 st Joint	0.187	1.15	1.02	0.02	28.432
	2 nd Joint	0.171	1.3	---	0.024	28.539
Interactive Fuzzy PID	1 st Joint	0.139	0.97	---	0.001	28.268
	2 nd Joint	0.164	0.85	---	0.017	28.545

where simulation results show an improvement of about 44% for the Fuzzy PID controller as compared with the conventional PID controller. On the other hand, the comparison shows a 70% improvement in steady state error after considering the interaction effects.

7.2 Nonlinear PID and Two-Degree-of-Freedom PID (2DoFPID) Controllers

The medical robot responses, as shown in Fig. 14 and 15, for both 1st and 2nd joints position and control signal for the NPID controller, where it is clear that the controller's response in tracking the desired signal with the unexpected transient response and having a smaller steady-state error. Also, the performance of the system with NPID controller suffers from a relatively higher sensitivity to parameter variations.

While, Fig. 16(a) and 16(b), show the 2DoFPID controller joints position for both automatic and manually tuning types respectively, which obviously have undesired overshoot also higher settling time for the controller manually tuned as compared with the auto. controller response and Fig. 17(a), and Fig. 17(b), shows the 2DoFPID controller control signal for both automatic and manually tuning types respectively, that shows very high chattering to be implemented with the system.

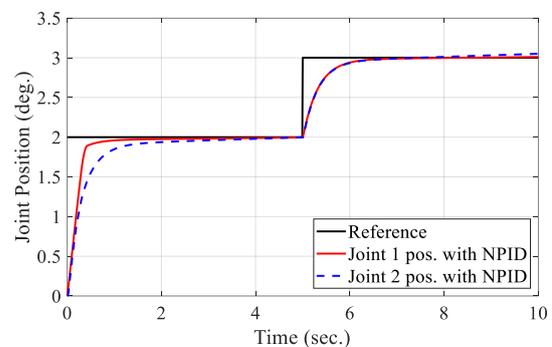


Figure. 14 NPID controller response for both 1st and 2nd medical robot joints position

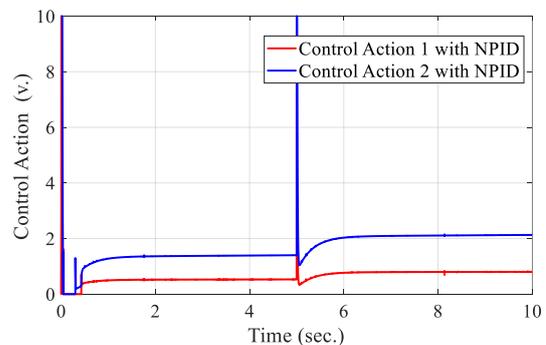


Figure. 15 NPID control action response for both 1st and 2nd medical robot joints position

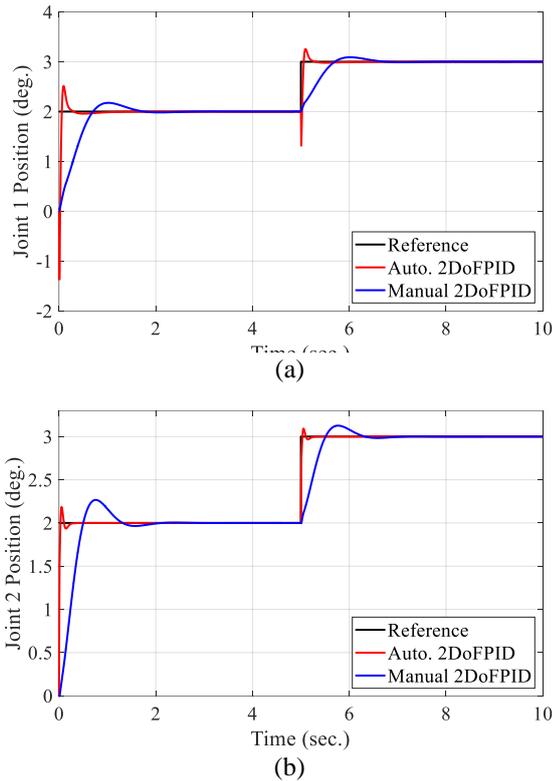


Figure. 16 Two types 2DoFPID controllers response for: (a) 1st medical robot joints position and (b) 2nd medical robot joints position

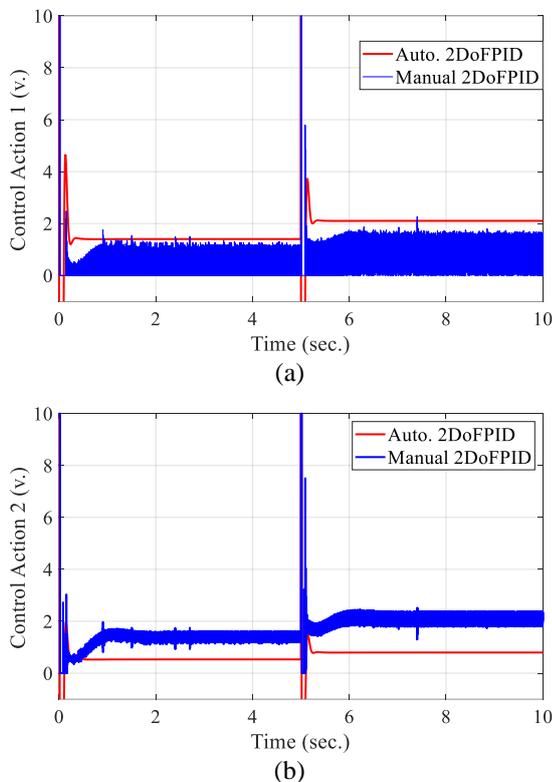


Figure. 17 2DoFPID control action (a) 1st medical robot joints position and (b) 2nd medical robot joints position

Table 3. The PID controllers type Performance comparison

Controller	Medical robot	Rise Time (sec.)	Settling Time	Overshoot %	Steady-state error	ISE
Interactive PID	1 st Joint	0.170	1.2	0.82	0.017	38.306
	2 nd Joint	0.078	1.2	0.42	0.037	36.352
Interactive Fuzzy PID	1 st Joint	0.139	0.97	---	0.001	28.268
	2 nd Joint	0.164	0.85	---	0.017	28.545
NPID	1 st Joint	0.162	1.4	---	0.04	3.062e+3
	2 nd Joint	0.148	3.5	---	0.02	3.015e+3
2DoFPID	1 st Joint	0.011	1	1.26	0.003	2.501e+3
	2 nd Joint	0.004	0.4	1.09	0.003	2.497e+3

7.3 Comparison of the PID controllers

Table 3 illustrate a summary of the transient behavior for the systems after applying the previously described types of PID controllers. It can be noticed that response suffers high percentage overshoot and oscillatory behavior with PID and 2DoFPID controllers. Using the Fuzzy logic controller for tuning PID parameters structure helps to reduce the percentage overshoot considerably. Nevertheless, the settling time has decreased reaching its lowest time with interaction Fuzzy PID controller. Obvious improvements can be seen in the transient behavior as well as the robustness against uncertainty. Considerable improvements have been gained in the steady-state error values of the proposed controllers. It is clear that the proposed interactive Fuzzy PID control structure can robustly stabilize the medical robot controlled systems.

7.4 Robustness analysis in presence of Disturbance and Noise

Meanwhile, in order to analyze the robust performance of the controlled systems, the input signal is subjected to a small input disturbance of +50% and - 20 % of reference input value with the addition of measurement noise of $\pm 2\%$ all the simulation time. The PID controllers designed alleviate the effects of both input disturbances and noise then stabilizes the close loop system. As shown in Fig. 18(a) and 18(b) for both 1st and 2nd joints

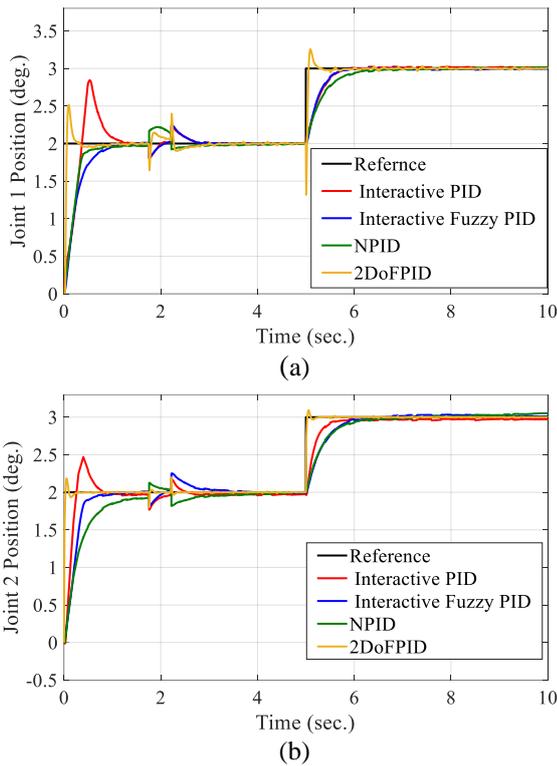


Figure. 18 The PID controllers type response for the medical robot: a) 1st joint with the addition of disturbance and measurement noise. b) 2nd joint with the addition of disturbance and measurement noise

position response, a comparison between the applied types of PID controllers shows the close loop response for each type and the ways to over gates the outside effects also to demonstrate the effectiveness of the applied approaches listed in Table 4.

It is clearly noticed from these graphs that the proposed PID controller types especially interactive Fuzzy PID controller in Fig. 18(a) and 18(b) can maintain better tracking performance as compared with the other controllers' types, even in the presence of both disturbance and noise.

7.5 Robustness analysis in presence of uncertainty of (∓ 0.03)

Lastly, the robustness of the system to variations in the system model is examined. As described in Section (2), the model state space parameters can vary with certain bounded values, the robust performance is analyzed for perturbations of ($\mp 3\%$) of the nominal system model parameters values, as in ($A = A \pm 0.03 * A$), for testing the power of the designed robust controller. In simulation, these uncertain models are compared to the original models of the system. Four sets of experiments have been conducted based on the PID controller types; interactive PID, NPID, 2DoFPID and interactive

Table 4. The PID controllers type Performance comparison with disturbance (0.5) and measurement noise (0.02)

Controller	Medical robot joint	Rise Time (sec.)	Settling Time(sec.)	Overshoot %	Steady state error	ISE
Interactive PID	1 st Joint	0.08	3	32.4	0.02	57.25
	2 nd Joint	0.15	2.6	---	0.04	55.31
Interactive Fuzzy PID	1 st Joint	0.16	2.55	---	0.00	37.48
	2 nd Joint	0.18	2.4	---	0.02	37.48
NPID	1 st Joint	0.12	2.8	19.7	0.02	270.9
	2 nd Joint	0.12	2.7	---	0.02	293.3
2DoFPID	1 st Joint	0.01	3.1	20.3	0.00	2.501e+3
	2 nd Joint	0.00	2.3	8.26	0.001	2.496e+3

Fuzzy PID and for both medical robot joints as illustrated in Fig. (19), (20), (21) and (22).

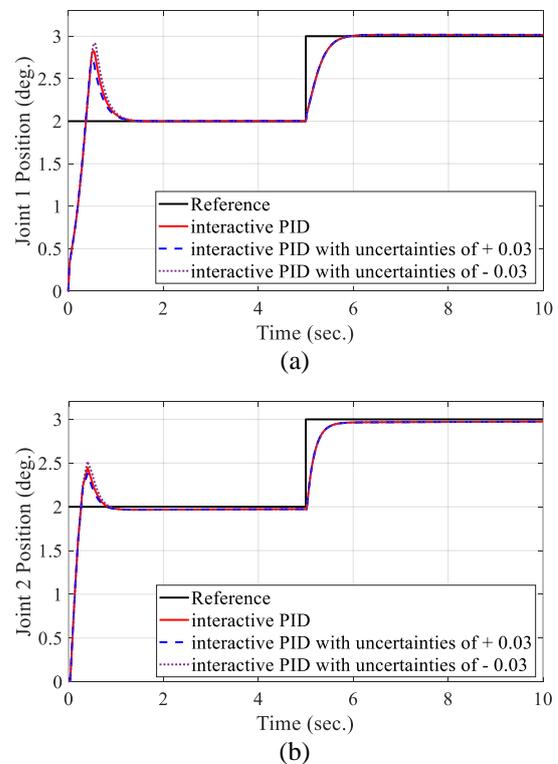
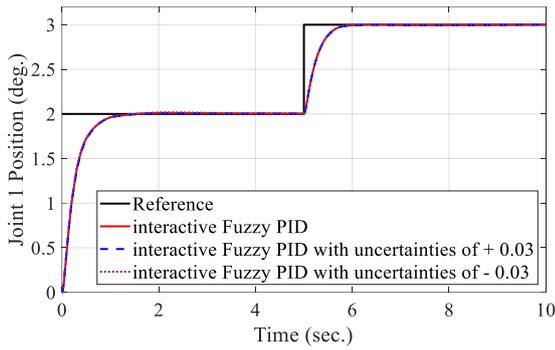
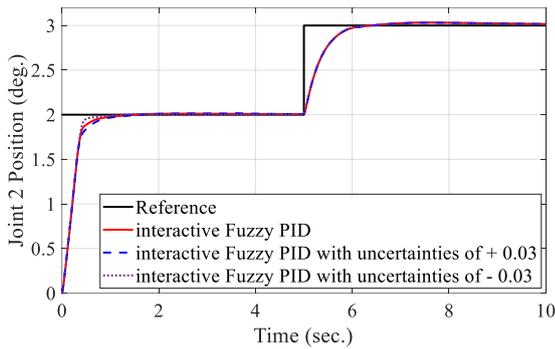


Figure. 19 The PID controllers with interaction response with the addition of ∓ 0.03 uncertainties (a) for the medical robot 1st joint and and (b) for the medical robot 2nd joint

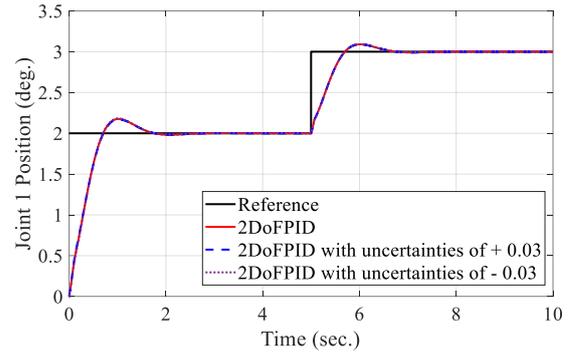


(a)

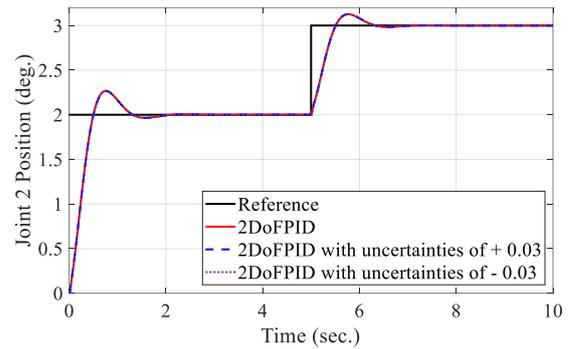


(b)

Figure. 20 The Fuzzy PID controllers with interaction response with the presence of ± 0.03 uncertainties: (a) for the medical robot 1st joint and (b) for the medical robot 2nd joint

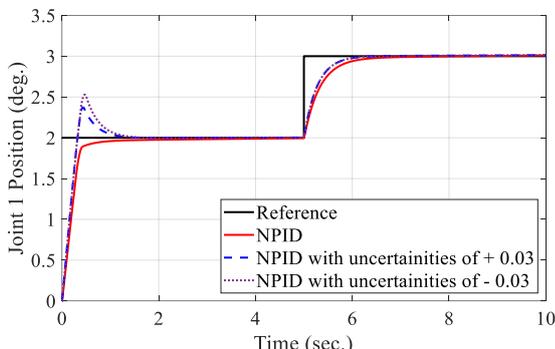


(a)

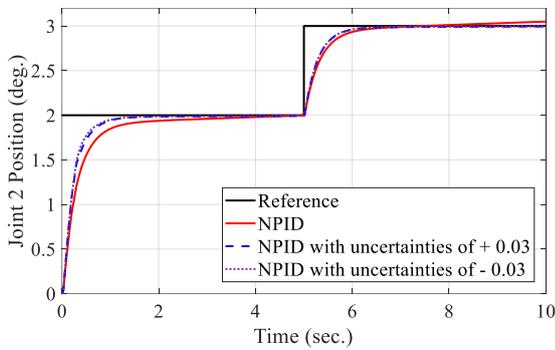


(b)

Figure. 22 The 2DoFPID controllers response with the addition of ± 0.03 uncertainties: (a) for the medical robot 1st joint and (b) for the medical robot 2nd joint



(a)



(b)

Figure. 21 The NPID controllers response with the addition of ± 0.03 uncertainties: (a) for the medical robot 1st joint and (b) for the medical robot 2nd joint

Table 5. The PID controllers type Performance comparison with uncertainties of ± 0.03

Controller	Medical robot	Rise Time	Settling Time(se)	Overshoot(%)	Steady state	ISE
Interactive PID	1 st Joint	0.088	1.5	1.86	0.02	48.693
	2 nd Joint	0.08	1.1	1.22	0.03	46.336
Interactive Fuzzy PID	1 st Joint	0.187	0.95	---	0.001	27.831
	2 nd Joint	0.171	1.03	---	0.015	27.937
NPID	1 st Joint	0.123	1.2	1.18	0.01	178.07
	2 nd Joint	0.128	1.1	---	0.02	174.91
2DoFPID	1 st Joint	0.011	1.4	1.25	0.001	2.5e+3
	2 nd Joint	0.004	0.4	1.09	0.001	2.5e+3

It can be clearly noticed from these graphs, as well as the results shown in Table 5, that the proposed

interactive Fuzzy PID controller in Fig. (20) can maintain better tracking performance as compared with the other controllers. Small changes can be seen in the tracking error. This undoubtedly assured the assumption that the proposed controller can be applied in uncertain conditions. It also demonstrates the assumption that it is not necessary to implement a precise model since reasonably considering imaginable uncertainties and mismatches.

The maximum stability is 1 % of the designed controller performance even with the system's uncertainty that indicating the effectiveness of the used controllers except for the NPID controller that has some undesired overshoot in the addition of uncertainty as shown in Fig. (21).

8. Conclusions

This paper proposed the design of an interactive control mechanism based on RGA evaluation for medical robotic system. Well-tuned PID controllers have been developed for each element of the control structure. The goal is to provide a simple, efficient and robust control structure for systems with long and/or varying system's working conditions.

Different variations of parameters have been investigated to test the robustness of the proposed methods. The performance of all the designed controllers has been compared in terms of rising time, settling time, overshoot, steady-state error, and ISE calculations. The simulation results show that a considerable superiority can be noticed with the interactive Fuzzy PID controller, where better damping performance has been achieved as compared with the other PID controllers for all applied cases of simulation. Furthermore, the proposed interactive structure is robust against parameters variations.

The inclusion of other important factors will be considered in the future, as the presence of friction and time delays. In this case, different approach as active disturbance rejection control method will be considered to realize a robust optimal framework.

Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, Safanah; methodology, Shaymaa and Safanah; software, Shaymaa and Safanah; validation, Shaymaa; formal analysis, Shaymaa and Safanah; investigation, Shaymaa and Safanah; resources, Shaymaa and Safanah; data curation, Shaymaa; writing original draft preparation,

Safanah; writing review and editing, Shaymaa and Safanah; visualization, Safanah and Shaymaa; supervision, Safanah; project administration, Shaymaa and Safanah; funding acquisition, not funded.

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