Fuzzy-PID Position Control of a Three Fingered Robot Hand for Grasping Varying Loads

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ABSTRACT

In previous study, PID control was used to control the joint's motor position of a three fingered robot hand. However, it can be observed that PID control alone could not cater the nonlinearities caused by varying weight loads and friction from the gears. Both the settling time and rise time increased as the weight exceeded 20g, thus deteriorated the transient response performance. Therefore, this paper discusses the development of an intelligent system with PID control namely Fuzzy-PID control for a 6-DOF robot hand. The proposed control is capable of tuning the PID gains automatically when different loads are applied. Fuzzy Inference System was established based on the previous investigation on the effects of varying loads with the transient response parameters where the settling time and rise time have been taken as inputs and PID gains as the outputs. The proposed control specifically focused on one of the 2-DOF robotic finger. The same control inputs were applied to the motors of the other two fingers to provide synchronous motion. Finally, the proposed control was verified in real-time experiments for varying weight loads from 0g to 100g with 20g increments in terms of percent of overshoot, settling time, rise time and steady state error. From the experimental results, Fuzzy-PID control proved that it is capable to improve T_S by the maximum of 17.75% and the maximum of 1.21% of T_R compared to PID control only. No significant improvement was observed for percentage of overshoot and steady state error. Furthermore, the proposed control has successfully applied for random weights grasping by the 6-DOF robot hand with T_S and T_R improvement of 14.51% for joint 1, 9.82% for joint 2 and 3.54% of joint 1 and 2.69% of joint 2 respectively compared to PID control.

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Hence, the proposed Fuzzy-PID can be applied for grasping objects with different weight in future work.

Keywords: *PID Optimization, Fuzzy-PID Control, Auto-Tuning Gain, Fuzzy Control*

Introduction

Over the past few decades, robots have been used to assist human to execute one or multiple tasks with flexibility as compared to typical automated machine. Current research and development in robotic technologies are aimed for creating robust and autonomous manufacturing system due to the demand in the industry [1]. Producing robots that could imitate human capabilities is beneficial to many fields such as medical, rehabilitation, industry, and military use. A feedback controller could be used to automate a robot control system by reducing the error signal between the required reference and the measured variables from sensors. One of the widely used control algorithm is Proportional-Integral-Derivative (PID). PID control is a feedback control mechanism that is incontestable for application in both industry and academic researches despite of many other advanced control methods presented in recent studies. It is important to choose a suitable tuning algorithm for appropriate PID settings to avoid poor tuning which may cause poor transient response performance, and in turn increases the cost. Thus, the aims of PID controller tuning is to determine the best gains that meet required closed-loop system transient performance. Meanwhile, work by Sonoda et al. [2] managed to produce a nonlinear PI force control for a 2-DOF robotic finger with twisted string actuation [3]. Jacobian of the finger's kinematic was used to cater the nonlinearities.

There are five tuning methods which are trial and error, feature based, analytical, optimization and intelligent methods. Trial and error is a simple, low cost, easy to tune and requires no knowledge of the system. The tuning process for PID gains value is based on experience but satisfactory of the performances and robustness of the system are not guaranteed and it may consume longer time to achieve the optimal value of gains. Other than trial and error method, the feature based method is also a popular technique for PID tuning. Feature based methods consist of well-known conventional approaches such as Cohen-Coon (CC) and two types of Ziegler-Nichols (ZN) which are step response and continuous cycling methods. ZN method need to increase proportional gain until the process become marginally stable before ZN variables could be calculated thus, may cause oscillatory to the output which leads to dangerous situations in actual experiments. Method proposed by Astrom and Hagglund [4] known as relay based PID tuning was introduced to solve this problem by producing limited and controlled oscillation of the process response to estimate the ZN variables. A work by Nunes [5] implemented this technique using Java as the tuning software to tune the PID parameter for a multivariable level control system consisting of five tanks. However, the result showed that the tuning method was able to improve the control performances only at the specific reference used during the tuning process. On the other hand, Zalm claimed in his report in [6] that CC method could not perform better than ZN. Furthermore, CC requires wide range of practical processes, large delays and model equation of the process. Tavakoli [7] proposed an optimal method for PID for first order plus time delay system using given model equations. From the simulation results, his proposed method proved to perform the best in terms of Integral Time-weighted Absolute Error (ITAE), Integral Squared Error (ISE) and Integral Absolute Error (IAE) compared to ZN and CC methods.

The above conventional methods could produce only a set of PID gain parameters after an optimum value is obtained. When the system is disturbed, these values need to be retuned in order for the system to maintain its performance. Therefore, PID auto-tuning is one of the solutions for this drawback from using conventional method to improve the system performances. Current research trends has evolved with PID combined with embedded intelligent control algorithms to produce varied PID gains depending on the disturbance applied to the system. Several intelligent approaches include Fuzzy Logic Control (FLC), Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Artificial Neural Network (ANN).

FLC is based on expert knowledge that transforms a linguistic control strategy into automatic control strategy. Li has discussed an example of fuzzy application in [8] where he replaced the proportional term in PID controller with fuzzy logic to produce a hybrid Fuzzy P+ID and verified the effectiveness of his method to control a non-linear system. A work by Chopra et al. [9] applied four intelligent methods which are fuzzy logic, ANN, adaptive neuro fuzzy inferences system (ANFIS) and genetic algorithm (GA) for concentration control of a continuous stirred tank reactor. These four methods have been compared with each other and also with conventional ZN. The simulation results revealed that all intelligent methods provided good performances especially by ANFIS when compared to ZN. Besides, a work by Reza in [10] proposed two different Fuzzy-PID where the first system applied error and differential error as the FLC inputs while the second system applied error and integral error as the inputs. These two systems were combined to produce a hybrid Fuzzy-PID control for a DC motor system. The results of the two combined methods were observed to reduce the maximum overshoot and settling time compared to the classic PID control.

In comparison to other intelligent method types, Fuzzy-PID is inexpensive to develop and has ability to cover wider range of uncertainties in control. For instance, Upalanchiwar and Sakhare [11] adopted fuzzy Mamdani type for their modeled DC motor via simulation experiment in Matlab. Their work has proved that Fuzzy-PID as the solution for overcoming nonlinearities, parameter variability and uncertainty. The comparison between the conventional PID and Fuzzy-PID controls has found that Fuzzy-PID control produced better performances. In addition, Sood in [12] applied Fuzzy-PID control for autonomous robot motion. This study focused on the development of fuzzy inference mechanism to solve the robot motion problems. The results discussed the capability of Fuzzy-PID to decrease T_R, eliminate Steady State Error (SSE) and overshoot. Seneviratne [13] is also applied Fuzzy-PID control for 2-DOF robot manipulators to overcome the effect of change for loads and disturbances. The fuzzy-PID control aims to correct the errors simultaneously while the robot is moved. The simulation results reveals that the proposed control able to corrects errors by sudden change in payload and uncertainties.

In this paper, PID control is combined with an intelligent method for the position control of a robot hand. Previously, a three fingered robot hand has been developed for grasping two different object shapes as presented in [14]. The robot hand has six joints actuated using DC micromotors and controlled by a conventional PID. The fixed PID gains used however is applicable for limited range of object weights only. As the robot hand aims for expanding its capability to grasp variety object weights, the PID gain parameters need to be automatically varied accordingly. Thus, the disturbance due to the application of different loads to the finger is solved by the proposed auto-tune PID control which in this study applied Fuzzy-PID. Trial and error method is used to obtain the optimum PID gains to achieve the required best transient parameter which become the reference for the design of the Fuzzy Inference System (FIS). Verification is made based on transient response performances compared to conventional PID.

Methodology

Fuzzy Logic Control for Robot Hand System

Fuzzy Logic Control is known as an inference process that requires human based experiences [15]. Therefore, prior to this work, an experiment as illustrated in Figure 1 was conducted to investigate the effect of varying loads on the position transient response provide by fingertip of joint 2. The settling time, T_S and rise time, T_R were observed to be the transient parameters that significantly changes according to the disturbances as shown in Figure 2 , thus chosen as the inputs for FLC. Meanwhile, the identified optimal range of PID gain parameters are set to be the output for FLC.

Figure 3 illustrates the overall control block diagram that applies the Fuzzy-PID control. The disturbance, actual position angle, desired position, Fuzzy-PID input control and error are denoted by *d(t), r(t),* $U_f(t)$, and *e(t)*, respectively. $U_f(t)$ is used to solve the non-linearity caused by $d(t)$ and attempts to correct error between the *y(t)* and *r(t)*. The gain parameters K_{Pf}, K_{If} and K_{Df} calculated from FLC were designed based on Fuzzy Inference System (FIS) that will be explained in the following section. The gains were then provided to the PID for control.

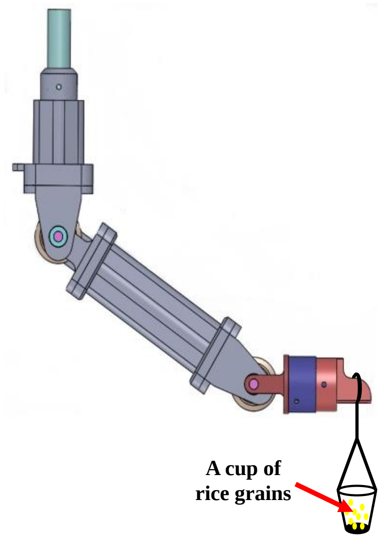


Figure 1: Load Applied to Fingertip

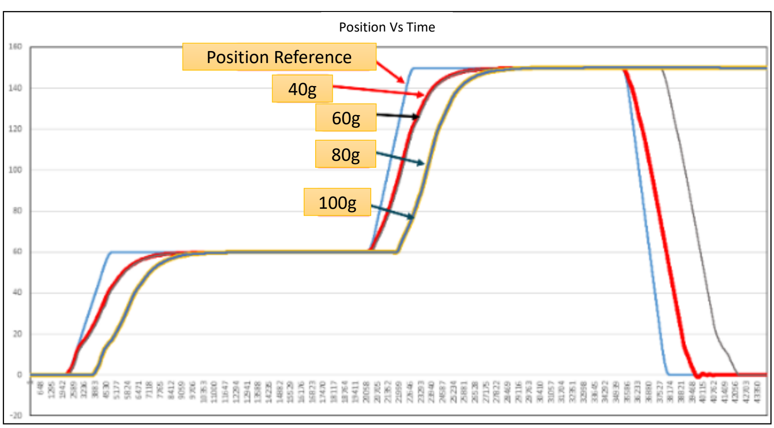


Figure 2: Setling Time and Rise Time Varied with Loads

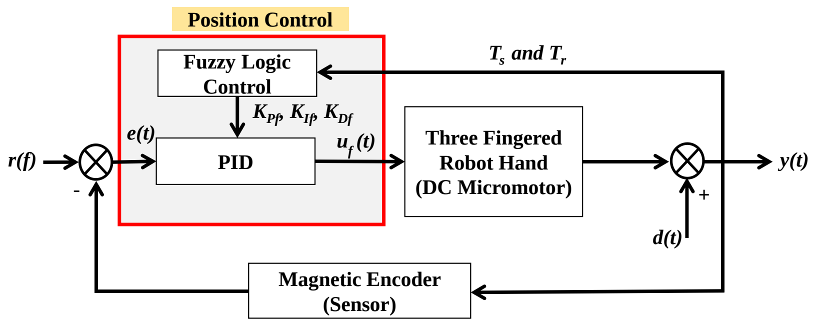


Figure 3: Overall control system block diagram

Fuzzy Inference System Design

A Fuzzy Inference System (FIS) is a technique of mapping an input space to an output space using fuzzy logic. The reasoning process of human language is formalized by FIS in terms of fuzzy logic language. FIS is used to make decision on the output according to situations of the inputs. FIS structure is generally has four modules which are fuzzification, knowledge base, inference and defuzzification as illustrated in Figure 4. The fuzzification role is to convert a crisp input into FLC to be used by the inference engine. Then, the process of mapping the input to the output is done by fuzzy inferences which may require further retuning in the actual process. This mapping consists of developing the membership function (MF) with the linguistic variables according to the selected MF method and range of each input and output. Finally, defuzzification converts each fuzzy results from the inference *(µy)* to the appropriate control actions within the crisp value.

In this study, fuzzy is used to automatically tune PID parameters which are K_{Pf}, K_{If} and K_{Df} according to the input from the transient response parameters. As discussed in the previous section, T_S and T_R are chosen as the input for the FLC. An investigation was implemented to observe the effect of gain parameters to the transient response parameters when different loads are applied. The results are used as reference to develop the fuzzy rule base. While input and output variables for FLC is identified, the linguistic variables for FLC’s membership function (MF) is determined. The proposed fuzzy set in linguistic variables are defined as SL: Smaller, SS: Small, MD: Medium, LL: Large, and TL: Larger.

In this case, triangular type is chosen to map the input and output in MF. Triangular has been chosen because it is most commonly used and can be asymmetrical and symmetrical in shape. Figure 5 shows MF of the same range for inputs (T_S and T_R) and three outputs (K_{Pf}, K_{If} and K_{Df}) in FLC. MF’s inputs and outputs range should be chosen such that it can cover all inputs and outputs of the system due to the different loads applied. The physical domain for each range T_S, T_R, ΔK_{Pf}, ΔK_{If} and ΔK_{Df} are { 0, 1, 2, 3, 4, 5, 6, 7, 8, 9,10}, { 0, 1, 2, 3, 4, 5, 6, 7, 8, 9,10}, {0.35, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.1, 1.2}, {0.2, 0.4, 0.6, 0.8, 1, 1.2, 1.4, 1.6, 1.8, 2} and {0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45}, respectively.

Three matrices in the fuzzy rule base for ΔK_{Pf}, ΔK_{If} and ΔK_{Df} will change accordingly when T_S and T_R are varied due to the increments of loads from 0 to 100g. Several if-then statements and the consequents of each statement of fuzzy prepositions based on user experience are applied to construct the fuzzy rule base. Table 1(a) to Table 1(c) tabulate 25 rules which define the rule base for the Fuzzy-PID control. The resulted K_{Pf}, K_{If} and K_{Df} from FLC are applied to the PID control of the robot hand system.

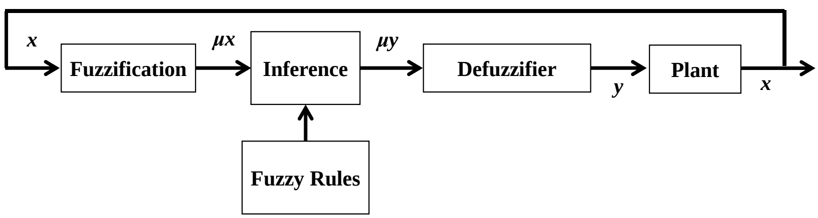
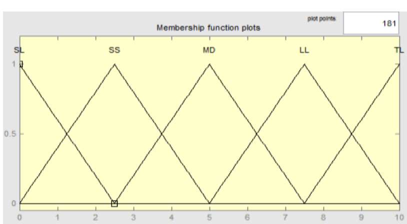
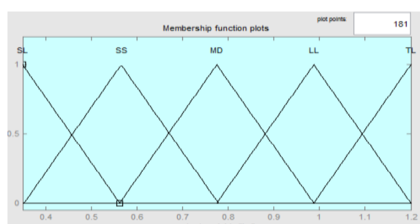


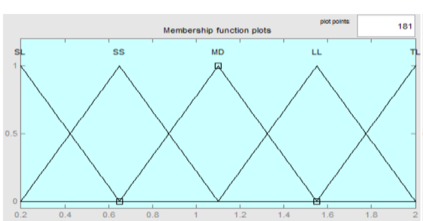
Figure 4: Fuzzy-PID block diagram



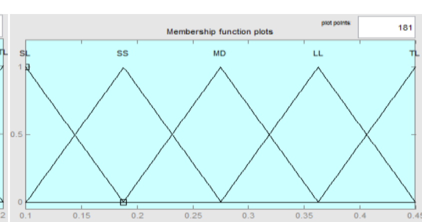
(a) MF Input Variable of T_S and T_R



(b) MF output variable of K_{Pf}



(c) MF Output Variable of K_{If}



(d) MF Output Variable of K_{Df}

Figure 5: Input and output MF

Table 1: Input and Output Rule Base

T_R \ T_S	SL	SS	MD	LL	TL
SL	SL	SS	SL	MD	SS
SS	SS	SL	SS	SS	SL
MD	MD	SS	MD	MD	LL
LL	LL	MD	SS	SL	SL
TL	MD	LL	SL	LL	SL

(a) Fuzzy rule base of K_{Pf}

T_R \ T_S	SL	SS	MD	LL	TL
SL	LL	LL	SL	SL	LL
SS	LL	SL	LL	LL	LL
MD	TL	SS	TL	TL	SL
LL	TL	SS	SS	TL	TL
TL	LL	SL	MD	SL	SL

(b) Fuzzy rule base of K_{If}

T_R \ T_S	SL	SS	MD	LL	TL
SL	SL	LL	LL	MD	LL
SS	SS	MD	TL	LL	TL
MD	MD	MD	TL	TL	TL
LL	SS	LL	MD	TL	TL
TL	MD	MD	MD	TL	LL

(c) Fuzzy rule base of K_{Df}

Verification of FLC in Real-Time Experiment

A load cell embedded inside the robot fingertip is used to measure the amount of loads applied during the first experiment. The purpose of this experiment how the loads give effect to the joint motor in terms of force in newton (N). The second experiment is to verify the performance of the proposed FLC when no load is applied. Similarly, the third experiment is to verify the control performance but with loads applied.

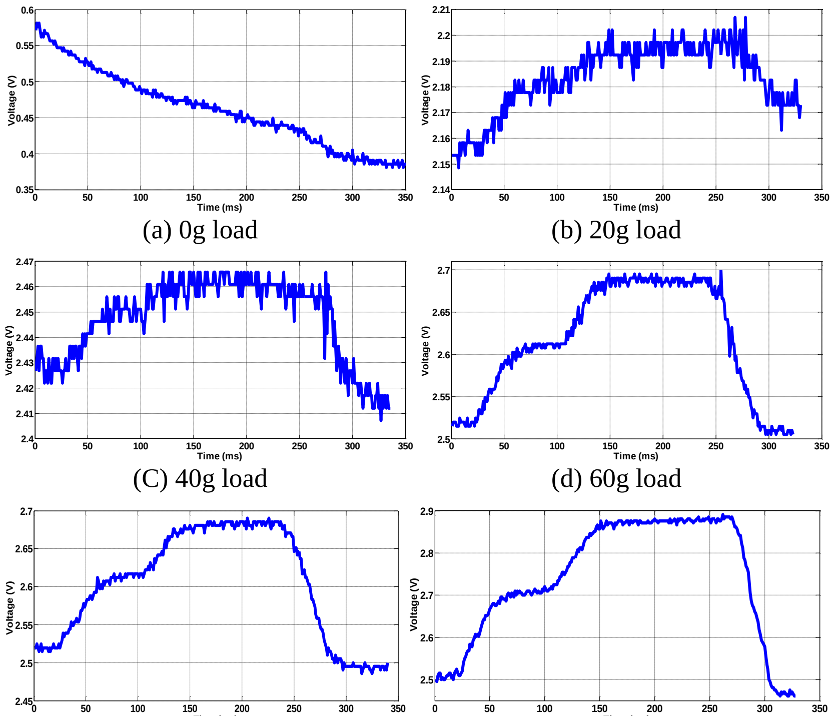
The joint motor of the robot finger are commanded to their predetermined angle position respectively. The resulted motor position measured by encoders is evaluated in terms of the performance of transient response parameters. FLC is required to modify the input and output range of MF if the required transient parameters such as zero percent of overshoot and zero steady state error are not satisfied. In the fourth experiment, comparison of control performance between PID and FLC with load of 0 to 100g applied to the 2-DOF finger is implemented in joint 2. Finally, the control is verified for robot grasping of several random objects with different weights.

Results and Discussion

Load Cell with Varying Load Test

The graph in Figure 6 represent force measured in voltage by locating load sensor at the fingertip of the robot finger. The horizontal axis represents the voltage out from the load cell while vertical axis represents the time history.

When no load is attached to the fingertip, the force which is measured in voltage by the load cell is almost 0V. From Figure 6(c) to (f), it can be observed that when heavier load is applied, the voltage increased. In addition, according to Figure 6(e), it can be shown that the amount of forces increases with the increase of motor position in degree. This can be shown from the similar shape of the force measurement with the position reference as in Figure 7. This is due to the effect of gravity when the finger is lifted with the change of position from 40 to 80 degrees.



(a) 0g load (b) 20g load

(C) 40g load (d) 60g load

(e) 80g load (f) 100g load

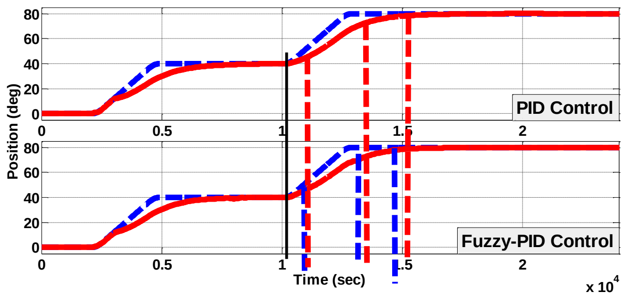
Figure 6: Effect of Varying Loads to Load Sensor

Varying Load Test with PID and Fuzzy-PID Control

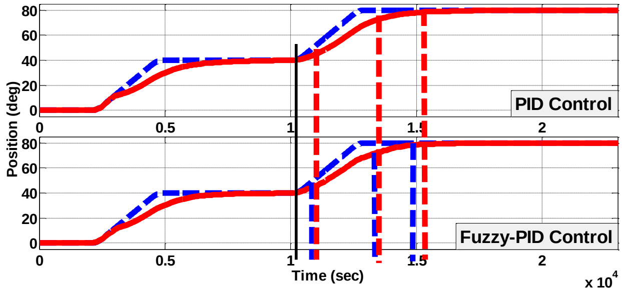
Figure 7 shows the difference between the experimental data for PID and Fuzzy-PID control when applying varying loads to the 2-DOF finger which is implemented in joint 2. The horizontal axis represents the motor positions while vertical axis represents the time history. The red line indicates the actual motor position and the dotted blue line indicates the reference position.

The graphs are arranged concurrently to conventional PID and Fuzzy-PID according to the cases –no load, 40g, 60g, 80g and 100g. It can be observed that the transient response performances of the robot hand system are affected even though conventional PID control was applied. The affected system occurred while implementing conventional PID control proofs that; the optimal gain parameter value –K_P: 0.4, K_I: 1.45 and K_D: 0.10 for zero load applied does not suitable for load case situation. Therefore, the investigation for the varying load is significant to study for developing the FLC.

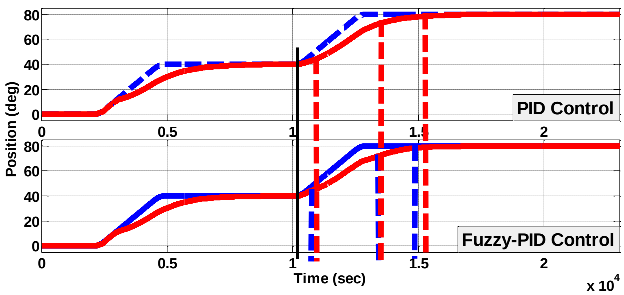
The findings also revealed that T_S gradually increases when the load is increased. Similarly, T_R gradually increases in significantly when the load is increased. The experimental data is also tabulated in Table 2 to presents the effect of gain parameters to the transient response of T_S and T_R for conventional PID and Fuzzy-PID control. Comparatively, Fuzzy-PID control has improved T_S by 7.47% and T_R by 1.21% for no load test. Meanwhile, for five different loads of 20g, 40g, 60g, 80g and 100g, Fuzzy-PID control has improved T_S by 7.55%, 14.96%, 14.21%, 13.04%, 17.75% and T_R by 0.43%, 0.40%, 1.19%, 2.33%, 0.05%, respectively. These percentage improvement revealed that the proposed control method of Fuzzy-PID is able to provide the variation set of gain parameters while input for transient response performance (T_S and T_R) declines. These percentage of improvement are presented in Figure 8. Other than that, it can be observed that there is no %OS and error occurred for both control methods when applying different loads.



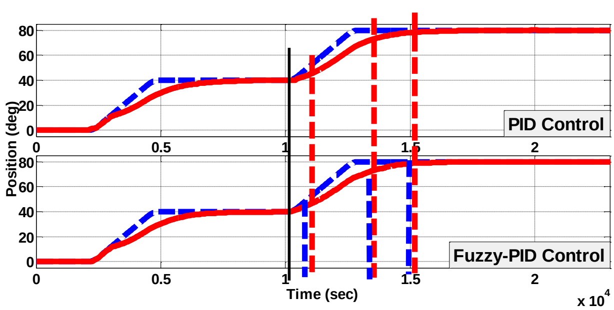
(a) Without Load



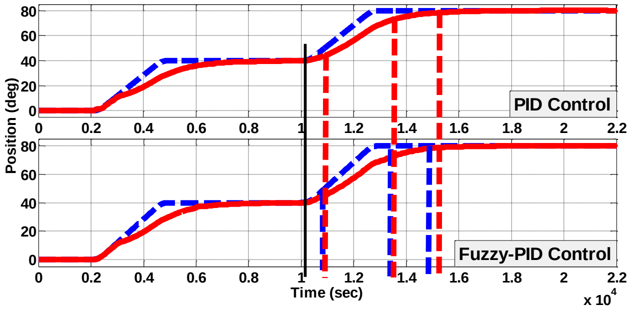
(b) 40g load



(c) 60g load



(c) 80g load



(d) 100g load

Figure 7: Effect of Weight Varying Loads (Top: PID, Bottom: Fuzzy-PID)

Table 2: Effect of Gain Coefficients to the Transient Response Parameter

Weight (g)	**Control**	**T_S**	**T_R**
0	PID	5.09	2.48
	Fuzzy-PID	4.71	2.45
20	PID	5.30	2.30
	Fuzzy-PID	4.90	2.29
40	PID	5.48	2.51
	Fuzzy-PID	4.66	2.50
60	PID	5.56	2.52
	Fuzzy-PID	4.77	2.49
80	PID	5.60	2.58
	Fuzzy-PID	4.87	2.52
100	PID	5.69	2.50
	Fuzzy-PID	4.68	2.50

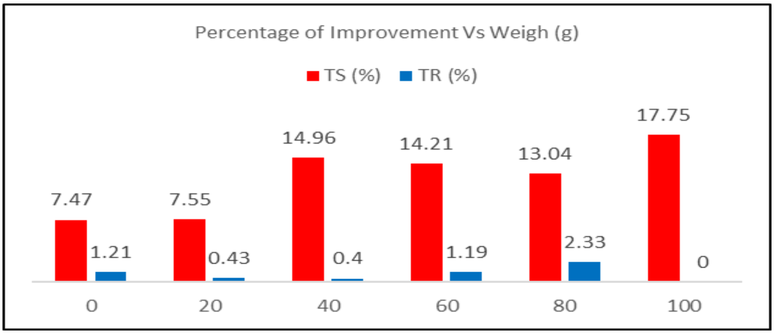


Figure 8: Percentage of Improvement for T_S and T_R

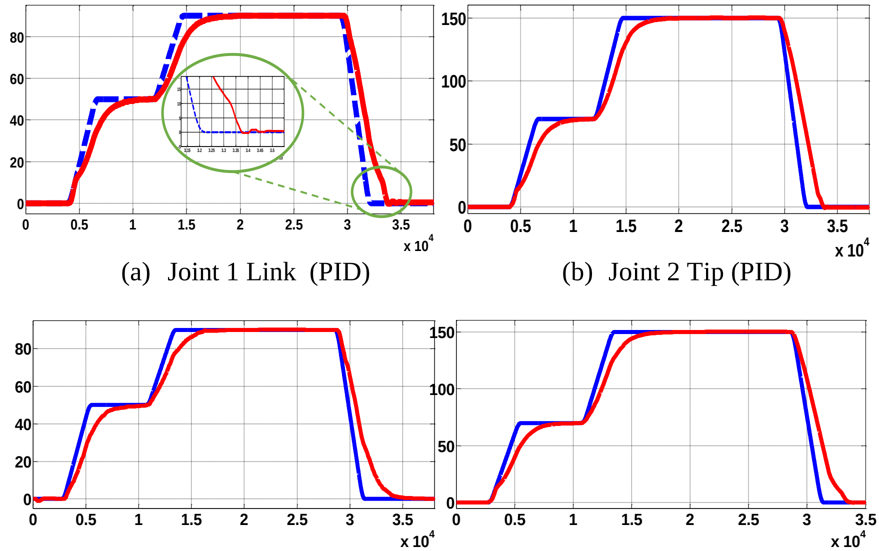
Grasping Random Weight with PID and Fuzzy-PID Control

Figure 9 until Figure 11 show the difference between the experimental data for PID and Fuzzy-PID control for grasping three random weight loads; 64.82g, 94.62g and 110.21g. The horizontal axis represents the motor positions of joint 1 and joint 2 while vertical axis represents the time history. The red line and the blue dotted line indicates the actual motor position and the reference position, respectively. The recorded data was involved two different joint because both fingers are not applied same angle position as their trajectory for grasping task. Thus, the closed-loop control system for both joint 1 and joint 2 are separated, but both control system is being execute in parallel. The purpose of recorded data for joint 1 is to verify the proposed control is applicable to implement in joint 1 robot finger. The performances of T_S and T_R for both controls are tabulated in Table 3. T_S is found to increase as the load increases and Fuzzy-PID control are revealed to improve the transient response performance compared to PID control.

Comparatively, Fuzzy-PID control has improved the T_S by 6.77%, 6.08% and 11.15% for joint 1 and 9.82%, 14.51% and 7.69% for joint 2. Meanwhile, T_R has overall improved by the application of Fuzzy-PID control. Furthermore, the fluctuations of SSE that happened when joint 1 return to the angle position 0° as indicated in Figure 9(a) and Figure 10(a) have been solved significantly. The details of improvement in percentage for T_S and T_R for both joints are tabulated in Table 4.

Table 3: Effect of Weighing Loads to the Transient Response Parameter

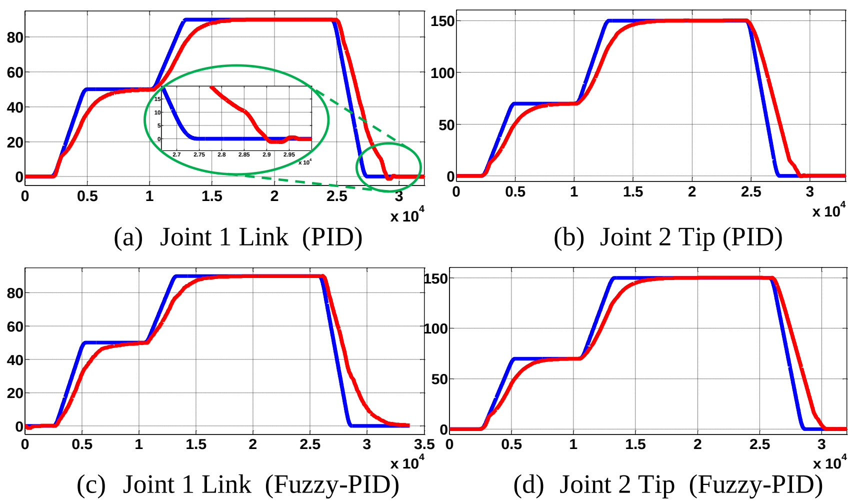
Weight (g)	Joint	Control	T_S	T_R
64.82	Joint 1	PID	5.02	2.36
		Fuzzy-PID	4.68	2.38
	Joint 2	PID	5.26	2.54
		Fuzzy-PID	4.94	2.50
94.62	Joint 1	PID	5.20	2.48
		Fuzzy-PID	4.62	2.50
	Joint 2	PID	5.50	2.60
		Fuzzy-PID	4.96	2.53
110.40	Joint 1	PID	5.10	2.54
		Fuzzy-PID	4.36	2.45
	Joint 2	PID	5.33	2.59
		Fuzzy-PID	4.92	5.55



(a) Joint 1 Link (PID) (b) Joint 2 Tip (PID)

(c) Joint 1 Link (Fuzzy-PID) (d) Joint 2 Tip (Fuzzy-PID)

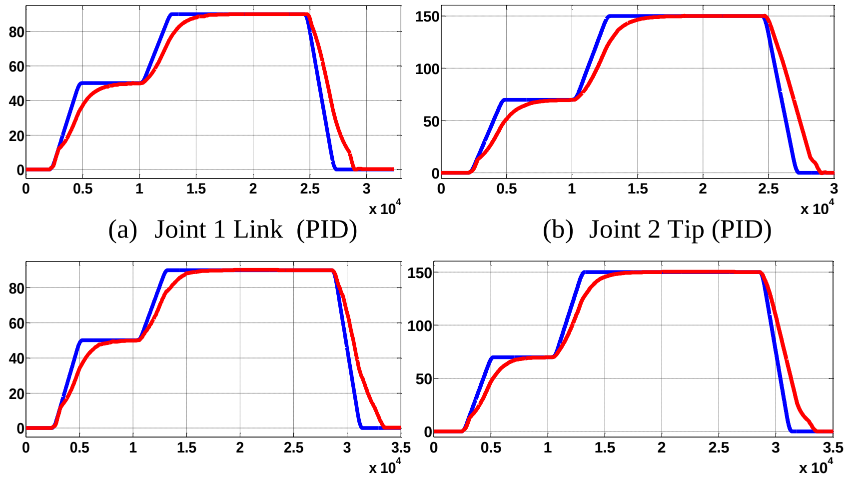
Figure 9: Grasping for 64.82g



(a) Joint 1 Link (PID) (b) Joint 2 Tip (PID)

(c) Joint 1 Link (Fuzzy-PID) (d) Joint 2 Tip (Fuzzy-PID)

Figure 10: Grasping for 94.62g



(a) Joint 1 Link (PID) (b) Joint 2 Tip (PID)

(c) Joint 1 Link (Fuzzy-PID) (d) Joint 2 Tip (Fuzzy-PID)

Figure 11: Grasping for 110.21g

Table 4: Effect of Weighing Loads to the Transient Response Parameter

Weight (g)	**Joint**	**Improvement of T_S (%)**	**Improvement of T_R (%)**
64.82	Joint 1	6.77	-0.85
	Joint 2	6.08	1.57
94.62	Joint 1	11.15	-0.81
	Joint 2	9.82	2.69
110.40	Joint 1	14.51	3.54
	Joint 2	7.69	1.54

Conclusion

The development of Fuzzy-PID control that automatically tunes the PID gains was implemented to the position control of a 2-DOF robot finger to lift varying weight loads from 0 to 100g with 20g increments. According to real-time experimental results, Fuzzy-PID proved to be better compared to PID in terms of T_S, T_R, SSE and %OS. Fuzzy-PID was capable to improve T_S by the maximum of 17.75% and the maximum of 1.21% of T_R compared to PID control only while no significant improvement for %OS and SSE was observed. Furthermore, the proposed control has successfully applied for random weights grasping by the 6-DOF robot hand with T_S and T_R improvement of 14.51% for joint 1, 9.82% for joint 2 and 3.54% for joint 1 and 2.69% for joint 2 respectively compared to PID control. Thus, the development of Fuzzy-PID control with multi inputs and multi outputs proved to be capable of solving the declining transient response performance when dealing with increasing load weights. However, in order to overcome the limitation of FLC that requires more investigation to cover greater load range can be considered in future work.

Acknowledgment

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