Precise Control Method on Prosthetic Hand Using sEMG Signals

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Precise Control Method on Prosthetic Hand Using sEMG Signals *

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Abstract— **In this paper, a prosthetic hand precise control method will be used to control the position of the prosthetic hand finger`s motion depending on the sEMG signals as the control command, the PID controller using two different tuning methods genetic algorithm and Ziegler–Nichols. The two methods will be introduced and investigated. In the end, a comparison between the response of the system towards the tuning methods will be established, the system will build and simulate in the Sim-Mechanics environment provided by MATLAB software. All of this work is done as extended work of last paper under the topic 'An Approach for Accurate Pattern Recognition of Four Hand Gestures Based on sEMG Signals' using its classified motions with accuracy 99.76 as an input command to the controller in order to design one complete prosthetic hand depend on the sEMG signals [1].**

Keywords- PID controller ; prosthetic hand control ; sEMG; system identification

I. INTRODUCTION

1948, it was the starting date for Using EMG signal in the prothesis field [2][3]. 1957, Moscow at the Central Prosthetic Research Institute begin to use MES in the commercial prosthetic hand by driving stepper motor [4]. After that, they shifted from using a stepper motor to electromagnetic relays with a permanent magnet DC motor. After that, the control strategies of myoelectric devices had been investigated, and a new control approaches have been developed on-off control, in this strategy they used the amplitude for decoding the EMG signal information into on or off orders for the motors. The commands that send to the motor used in the prosthetic device had been determined by using the calculated amplitude of the EMG signals by RMS or MAV features. Many different control schemes developed for translating the EMG signal information, their classification is based on the controlling nature as simultaneous and sequential control. The highly used in the field of prosthetic hand is sequential control, nowadays the research is more focusing on employing the simultaneous control on the prosthesis control field. For sequential control is using the following control schemes for translating the EMG signals information: On-off control ， Proportional control, Direct control, Finite state machine control, Pattern recognition-based control (PR control), Posture control schemes, Regression control schemes

For this control scheme, some of it can be combined such as direct control with proportional control, posture control, and finite state machine for more effectiveness for myoelectric signals information decoding. The signals collected from the skin surface and preprocess as an earlier step for analog-to-digital conversion. Then the collected data will be used for interpreting the intention of the user then communicate with the controlled device that will actuate the suitable motor for achieving an intended activity chosen by the user.

Pattern recognition-based (PR) myoelectric control has been introduced as an alternate technique for the conventionally used techniques that are based on the amplitude of the EMG signals. The essential benefit of PR is to choose suitable muscle contraction according to the intended prosthetic hand movement. This can be done by using the proper classification method for the EMG signals that can classify the input signals into a discrete number of classes depending on the difference between the extracted features from the data [5]. Also, myoelectric control PR-based consists of some steps as data segmentation, signal preprocessing, feature extraction, feature selection (FS) that may depend on the features number, feature classification, and transfer this classified class into a command to the motor controller. generally, many features can extract from the data like time domain and frequency domain features extraction methods to categorize the information of signals. Time-domain feature widely used because of its simplicity.

In this paper, a PID controller for a position control that can control a prosthetic hand finger movement to perform a specific hand gesture depending on pattern recognition for EMG signals will be designed.

PID position control system is usually controlled by proportional-integral-differential PID control algorithms with PID coefficients tuned for optimizing operations. The objective of a PID controller in a position control system is to maintain a position setpoint at a given value and be able to accept new setpoint values dynamically [6].

The prosthetic hand motion will be done by receiving the control command from a pattern recognition which is responsible for the hand gestures classification. While the position sensor mounted on the starting point of the joint to

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measure the angle that the finger has been moved can feedback this information to the system. Design a controller that can control the hand fingers position, Fuzzy controllers and PID controllers, etc. which all of them can offer several advantages are available. However, for the purpose of this research, the more popular PID controller is adopted. Its choice is necessitated by the following benefits, such as its simplicity, versatility, speed, reliability, flexibility, and robustness which are essential.

In general, the PID usefulness being in the applicability to many types of control systems. Design by using analytical methods is not applicable especially when the system plant mathematical model does not exist PID is the best solution at that time. It's so amazing to know that most of the industrial controllers approximately half of it tell today are using PID controllers because of the high adjustability of that system onsite, there are several tuning methodologies for the PID control systems, fine-tuning of PID systems can be done on-site. There are four control models for PID are available as flowing where every model has advantages and disadvantage: Bang Bang (On-Off) Control, Proportional (P), Proportional and Derivative (PD), Proportional and Integral (PI), Proportional, Integral and Derivative (PID)

To implement a PID controller, the proportional gain KP, the integral gain KI, and the derivative gain KD must be determined carefully [7], controlling the prosthetic hand motors without using the PID controller will give some oscillation in the signal and some delay time in preforming the motion needed by reaching the desired position late after giving the order which will expose the user to some risks because of the delay of taking the action because the system is non-linear, controlling by function is the best way to control the non-linear systems and PID controller is the best choice to achieve this task.

In 2002 Zecca et al., PR based techniques for myoelectric control methods resort to the supervised machine learning algorithms during the training step by using the phantom limb effect, the system starts to learn to how to connect the different hand gesture with myoelectric patterns then, it will be adopted in the prosthetics hand daily use [8]. The first step of the PR is to extract the feature from the input data, the main part of myoelectric recorded data are selected and identified within 150 to 250 ms window time, relay on the subject skills (Smith et al., 2010) [9]. Despite the first scheme of a control method based on the pattern recognition available since the last fifties, the first controlled prostheses device (COAPT7) based on the surface electrode and pattern recognition are available commercially in the early of 2015. Developed at the Rehab Institute of Chicago, NECAL laboratory with cooperation with Dr. Todd Kuiken。(COAPT7) is still subjected to clinical trials in different rehabilitation centers in the USA, PR offers a distinguished advantage such as enabling the simultaneous, for multiple DoFs independent control. Young et al. (2013) proposed a method based on LDA classifiers parallel set to provide classification methods for simultaneous hand and wrist movements [10].In 2014, Ortiz-Catalan et al. the recent work has shown that the control of multi DoFs can be done using any classifier if it arranged properly in a distributed topology [11]. In 2014, Jiang et al. proposed a new control strategy depends on a method called (NMF) Non-negative Matrix Factorization that allows the proportional and simultaneous control for 2 DOF in specific extension /flexion and prono/supination of the wrist, while it needs for initial calibration the success rate was around 95% although this high result it's not recommended for the amputees because it requires a high number of EMG electrodes approximately reach to 16 electrodes [12]

II. Control Objective, Mathematical Model and Control Algorithm

A. *Control system Objective function and Description*

A five-FAULHABER-DC MOTOR OF SERIES 1024 SR motor will use to control the position (the angle) of the five fingers of the hand. each finger will represent on the simulation work as a revolute joint at the first portion of the finger and the other two portions will move relative to the first portion of the finger Controlling the position is done by using PWM (Pulse width modulation).

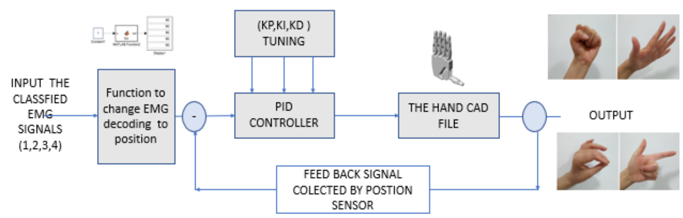

Fig. 1. The block diagram of the control system

The prosthetic hand control system block diagram is shown in Fig 1, which is a control system for the prosthetic hand that will need to control the hand to perform different motions such as fisted hand or finger flexion, extension fingers, tripod grasp, and index and thumps extension, by using the classified sEMG signals that coming from the forearm. It will consist of many subsystems like feedback sensor model that will update the system with the current position of the hand fingers, the sub coding system that will transfer the classified features of the sEMG signals into control command to the hand by written code, the CAD model that has been inputted to the MATLAB software to provide us with a valid system in the Simulink environment that can verify show us the model as a real model in simulation environment by that we can check the effectiveness and the robustness of the control system.

B. *Mathematical model of the system*

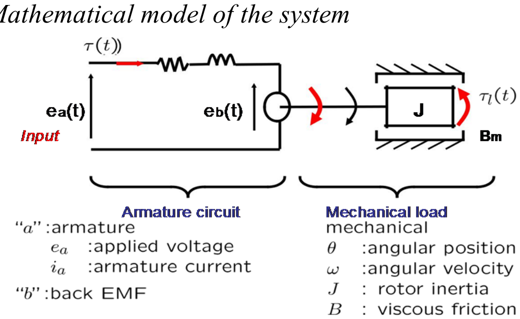

Fig .2. Model of DC motor

where some important relations can be listed in Table. 1:

Table 1. important relations

Armature circuit	$v_{source}(t) - e_b(t) = R_a i_a(t) + l_a \frac{di_a(t)}{dt}$
Motor torque	$T_m(t) = k_m i_a(t)$
Back EMF	$e_b = k_b \dot{\theta}(t)$.
Mechanical load	$T_m = j\ddot{\theta}(t) + b_{sh}\dot{\theta}(t) + k_{sh}\theta(t)$
Angular position	$\theta_{(t)} = \int \dot{\theta}(t)$

where Va = armature voltage, Ra = armature resistance , La = armature inductance, Ia = armature current, Eb = Back emf , ω = angular speed, Tm = motor torque , TL = load torque, θ = angular position of rotor shaft , J = rotor inertia , Bsh= viscous friction coefficient , Ksh = torque constant, Kb = Back emf constant.

Fig. 3 shows the basic block diagram of the DC motor model including their transfer functions. Va is the input supply; and θ is the angular position.

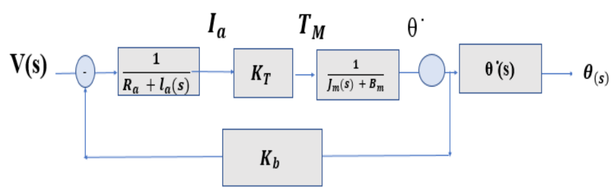

Fig. 3. The block diagram of the DC motor that explains the relationship between the input voltage and the output position (angle).

So, the relation between motor position and the applied voltage is given by the transfer function:

$$\frac{\theta_{(s)}}{v(S)} = \frac{k_t}{l_a J_m S^3 + (R_a + L_a B_m) S^2 + (R_a B_m K_b K_l) s} \quad (1)$$

The DC motor parameters are listed in Table. 2:

Table 2. DC motor parameters

Va = armature voltage	12 (V)
Ra = armature resistance	1.36 (Ω)
La = armature inductance	0.016 (H)
Ia = armature current	0.016 (A)
ω = angular speed	1277 (rad/sec)
J = rotor inertia	0.012 (kgm2)
Ksh = torque constant	0.00233 (Nm/A)
Kb = Back emf constant	0.00244 (Vs/rad)

And for the wiring mechanism and the overall plant transfer function is calculated by system identification and explained in detail in the next section. The overall plant transfer function is:

$$\frac{1.228e{-}05\ S^3 - 0.00826\ S^2 + 4.168\ S + 0.1582}{S^4 + 2.036\ S^3 + 0.6095\ S^2 + 0.02007\ S + 6.027e{-}07} \quad (2)$$

C. PID Control Algorithm

The mathematical equations for the PID can be expressed as follows:

$$c_{pid}(t) = k_p(t) + k_i \int e(t)dt + k_d \frac{de(t)}{dt} \quad (3)$$

$$\frac{C_{pid}(S)}{E(S)} = k_P + k_i \frac{1}{s} + k_d s \quad (4)$$

The block diagram can be figured with Fig. 4.

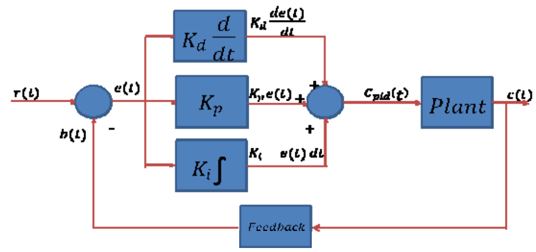

Fig. 4. The detailed block diagram of the PID control system.

PID Algorithm Parameters tuning is a process to select (Kp, Ti and Td) parameters for the controller for satisfying the requirements and the specifications of a needed performance. There are an experimentally tuning methods been introduced by Ziegler and Nichols, that method shows its importance and usefulness when we cannot calculate the plant mathematical models such the case of our research in some cases, it's also applicable to a known mathematical model as well, these rules offer proper value for Kp, Ti and Td that can provide stable performance for the control system. But sometimes some systems might respond with a maximum overshoot which is not acceptable for step response. Ziegler–Nichols rules is to give an educated probable value for the parameters and offer a sent point for starting tuning process, instead of offering the final value of Kp, Td and Ti in a single shot [13]. Also, they introduced a method based on the characteristics of the transient response of the given plant to calculate the values of Kp, Td, and Ti. Two methods were introduced by Zeigler-Nichol's to tune the PID 1st method open loop 2nd method closed-loop method. And there are many other ways to tune the PID parameters such as all the AI algorithms like genetic algorithm and Particle-Swarm-OptimizationTechnique and many other techniques in this paper will apply Zeigler-Nichol's and genetics algorithm.

III. Methodology and Simulation

A. PID Algorithm Controller Steps

Firstly, tet the response of the open-loop system then decide which parameter needs to be enhanced, as an example use proportional gain to enhance the rise time, use the integral gain to remove the steady-state error and use the derivative gain to enhance the overshoot of the system [14]. Secondly, keep adjusting the parameters tell finding the overall desired response. Finally, the three controllers gain not always needed in the same system

PID Algorithm Parameters tuning steps:

Ziegler–Nichols Mathematical model steps for tuning the PID: In this method, firstly you need to set Ti with ∞ value and Td with 0 by Using the method of the proportional type of control only as explained in Fig. 5, then upgrading the increased value of K from 0 to Kcr critical value Kcr means the value where the system output shows sustained oscillations at the response then you can use proportional gain to enhance the rise time, use the integral gain to remove the steady-state error and use the derivative gain to enhance the overshoot of the system.

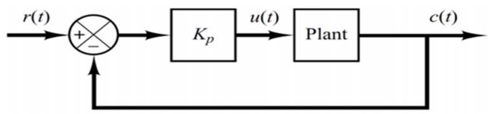

Fig. 5. How to get the kcr for the second table of Zeigler-Nichol's.

Whatever the taken Kp value this method cannot be applied If the exhibition of output response not sustained oscillations, at the moment we find the Kcr and its Pcr (the corresponding period the seconded method can be applied by using Table. 3.

Table 3. ZEIGLER-NIHOL's second method table

TYPE OF CONTROLLER	K_P	T_I	T_D
P	$0.5k_{cr}$	∞	0
PI	$0.45k_{cr}$	$\frac{1}{1.2}P_{cr}$	0
PID	$0.6\,k_{cr}$	$0.5P_{cr}$	$0.125P_{cr}$.

Genetic Algorithm:

The genetic algorithm is a random-based classical evolutionary algorithm. By random here we mean that in order to find a solution using the genetic algorithm, random changes applied to the current solutions to generate new ones. Note that genetic algorithm may be called Simple genetic algorithm (SGA) due to its simplicity compared to other evolutionary algorithms. GA is based on Darwin's theory of evolution. It is a slow gradual process that works by making changes to the making slight and slow changes. Also, genetic algorithm makes slight changes to its solutions slowly until getting the best solution. The main Structure of GA consist of five phases which are as follow:

(1) Initial population

(2) Fitness function

(3) Crossover

(4) Mutation

(5) Selection

In order to use the genetic algorithm as a tuning method for PID controller we need to study the mathematical explanation of the algorithm, the mathematical model for the algorithm can be shown as follow:

$$\text{Chromosome} = [p1, p2, p3, \ldots\ldots pn] \qquad (5)$$

where the problem elements can be defined chromosome, then we are going to encode each chromosome as Npar element array, each pi is a particular value of the ith parameter.

Then the evaluation function which in our case is PID equation:

$$c_{pid}(t) = k_p(t) + k_i \int e(t)dt + k_d \frac{de(t)}{dt} \qquad (6)$$

It will be used as our fitness function since our function is variable of 3 variables Pn=3.

We define our population size N of chromosomes, the mutation rate, and the number of iterations, the initial population is generated randomly, the parameters can be any real number between 0 and 10 instead of just 1 or 0 if the result is not good you can increase the number of iterations. The probability that the chromosome in nth place will be given by the parents using this equation:

$$P_n = \frac{N-n+1}{\sum_{I=1}^{N} I} \qquad (7)$$

Where N is the highest ranking of the surviving population.

Once we have two parent chromosomes m= [Xm, Ym] and d= [Xd, Yd], we first randomly select one of the parameters to be the point of crossover X or Y. If x is the crossover point for a particular m and d. Then we introduce a random value between 0 and 1 represented by β, and the x-values in the offspring are offspring1 is equal to [X=Xnew1, Ym], and offspring2 is equal to [Xnew2, Yd

B. Simulation steps:

As explained before the PID controller will be subjected to two tuning methods in this section each method will be discussed in detail and the steps of implementing each method:

1) Change the CAD model into the Simulink model it can de be done as the following steps:

(1) How to import the CAD file to the MATLAB software? You have to open your model by your CAD software, for example, Solidworks then export the assembly file to XML format to do that you should consider choosing the simmechanics generation you use on your computer 1st or 2nd generation then export the file and save it in your computer.

(2) Open MATLAB and import the file to your software by writing this command on the command window of [siminput ("file name.xml ")].

(3) Then you can see your file opened in sim-mechanics as Simulink model you just need to adjust some parameters in the model such as the stiffness and some other parameters.

(4) Then as explained before in the same section there is a needed step before using the classified motion from the pattern recognition as input signals to the control system, this step is transferring the classified label into position function. this can be done by written code in MATLAB function embedded into the Simulink system in Fig. 6.

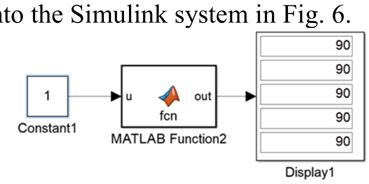

Fig. 6. Written function to transfer the classified label into the position signal input

2) Calculating the overall transfer function of the system by using system identification parameter tool that provided by MATLAB by generating a relationship between the voltage needed to reach a different specific angle by using the block of

Simulink (to workspace) to record the data to workspace this can be done by the following steps:

(1) Starting the system identification tool by typing in command window "system identification" then you can find a window where you can load the data and choose the type of your data for this research was (time-domain data) then click on "data view" then import as in Fig. 7.

(2) Choosing the number of zeros and poles

(3) Input your data that has been saved to the workspace before and choose the type of data that you will inter you can call the data file by input (@ filename) in the workspace.

(4) after that click estimate, you will see your result will be the transfer function as shown in Fig. 8.

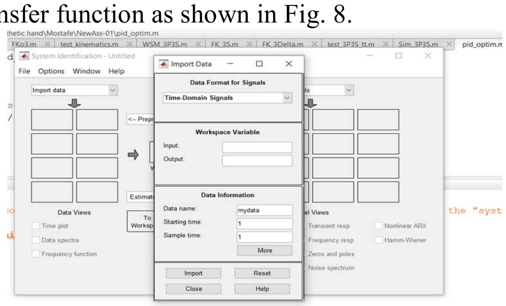

Fig. 7. The process of importing the data to system identification tool

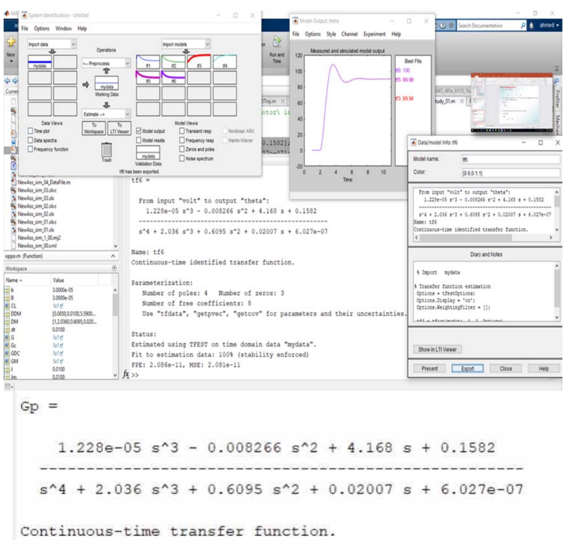

Fig. 8. Show where you can find the resultant transfer function

3) After these two steps the system can work and can be simulated on the sim-mechanics environment, and we can check the response of the system.

(1) Then after checking the system output and the response was not good as the system was overshooting and the rise time was so high witch mean the system needs a long time to perform the input orders so the system that will lead us to the need of the system to controller to enhance the system properties like rising time and the overshooting the settling time so a PID model will add to the system and the response of the system will be checked if it fulfills the target or not and we find that the system response still needs for more improvement so we decided to tune the PID model.

(2) Usually, PID tuning has a famous technique which called Zeigler-Nichol's so we decided to use it for tuning to which mean use it to get the best gains (k parameters) that can make the systems fulfill the target response

4) After that, we decided to use one of the artificial intelligence techniques because of its known properties in training and choosing the best parameters so we choose to use the genetics algorithm that can be done as the following steps:

(1) By using genetics algorithm in optimization tool by calling the function by typing "optimal" in MATLAB command window and then typing the number of variables in this case and call the function by its name in the workspace and then click start to start evaluating the value of the optimum there parameters shown in Fig. 9. After getting the optimum values for the parameter we can upgrade it manually then check your target specification.

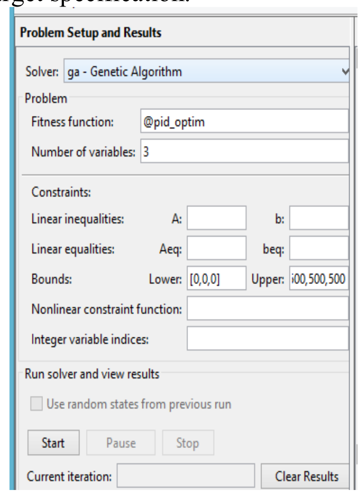

Fig. 9. Shows the setup of the genetics algorithm on optimizing tools in MATLAB.

IV. Result and Discussion

From Fig. 10 you can see the system response is unstable at all which leads us to use a controller that can provide the system with proper stability and enhanced the system response as you can see from Fig. 11. PID using Zeigler-Nichol's second method for tuning have stabilized and controlled the system with improvement in the rise time by minimizing it to 0.414 sec which will make the system response faster and active at the same time the settling time has decreased to 6.47 sec which means that the required time to that system error to fall within 2% of y final has minimized to be 6.47 sec, from Fig. 12. That describes the response of the controlled system using genetics algorithm as the PID controller gives the system the desired stability GA has been used just to provide the system with best tuning values for the k parameter that can improve the system response and it's obvious that the GA has also succeeded in achieving this task because after applying the parameter of GA tuning the rise time has decreased to 0.1579 sec and the settling time has decreased also to 0.7181 sec witch was less than the rise and the settling time that achieved by Zeigler-Nichol's also GA has eliminate the overshoot so from the results GA was the best choice for tuning the PID as it gives a proper solution of the high rise time, settling time and the overshoot of the system as shown in the Table. 4.

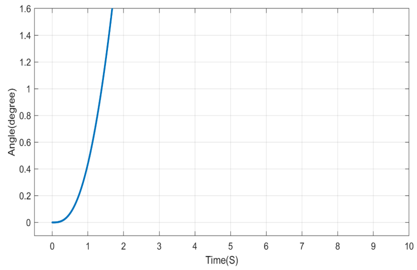

Fig. 10. The response of the system without applying the control system.

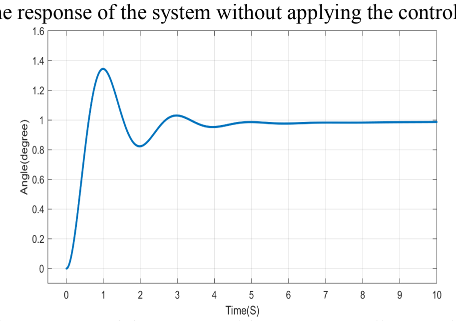

Fig. 11. The response of the system with a PID controller tuned by Zeigler-Nichol's second method

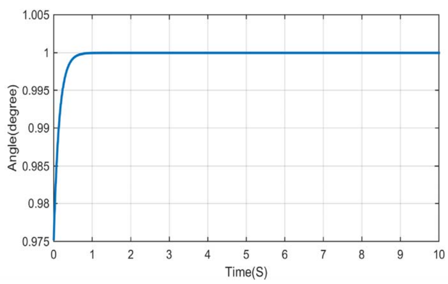

Fig. 12. The response of the system with a PID controller tuned by genetics Algorithm

Table 4. The table shows the different parameters of the system during the different research steps

SYSTEM PROPERTIES	ZEIGLER-NICHOL'S	GENETIC ALGORITHM
RISE TIME	0.41448659	0.1579
SETTLINGTIME	6.47706168	0.7181
OVERSHOOT	0.342835	0
UNDERSHOOT	NA	NA

V. CONCLUSION

For controlling the position of fingers of the prosthetic hand, a PID controller was successfully investigated and applied. The result of the simulation work on the plant demonstrates that the PID controller is a good choice to suppress the rise time and the settling time of the system. The Genetic-based PID control method was implemented and simulated, compared to traditional Zeigler-Nichol's algorithm the genetic algorithm had proved to be better by decreasing the rise time, improving the settling time and eliminating the overshoot in the system. In the end, an EMG-based prosthesis control simulation system was established. The EMG decoding combined with the controller was realized to perform the desired four-hand movement with delay time less than 160 ms.

VI. FUTURE WORK

In the future, the prototype experiment on the prosthetic hand will be strengthened, and the experimental results will be compared with the simulation analysis. Add more hand gestures to be recognized and controlled, and study the effect of increasing the hand gestures on the response and the delay time of the prosthetic hand.

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REFERENCES

[1] Mostafa Orban, Xiaodong Zhang, Zhufeng Lu, Yi Zhang, and Hanzhe Li. 2019. An Approach for Accurate Pattern Recognition of Four Hand Gestures Based on sEMG Signals. In Proceedings of the 2019 2nd International Conference on Control and Robot Technology (ICCRT 2019). Association for Computing Machinery, New York, NY, USA, 145–150. DOI:https://doi.org/10.1145/3387304.3387323

[2] Kobrinskiy AE. Bioelectrical control of prosthetic devices. Her Acad Sci. 1960;30:58–61.

[3] Popov B. The bio-electrically controlled prosthesis. J Bone Joint Surg Br. 1965;47:421–424

[4] McKenzie DS. The Russian myoelectric arm. J Bone Joint Surg Br. 1965;47B(3):418–420.

[5] L. J. Hargrove, B. A. Lock and A. M. Simon, "Pattern recognition control outperforms conventional myoelectric control in upper limb patients with targeted muscle reinnervation," 2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Osaka, 2013, pp. 1599-1602.

[6] Odekhe, Randolph & Zhang, Xiaodong & Mu, Xiaoqi & Kadry, Hamza. (2018). PID Control of Elderly Assistant and Walking Assistant Robot. 10.2991/amms-17.2017.92.

[7] Sailan, K., & Kuhnert, K. (2013). DC Motor Angular Position Control using PID Controller for the purpose of controlling the Hydrauli

[8] Zecca, M., Micera, S., Carrozza, M. C., and Dario, P. (2002). Control of multifunctional prosthetic hands by processing the electromyographic signal. Crit. Rev. Biomed. Eng. 30, 4–6. doi: 10.1615/CritRevBiomedEng.v30. i456.80

[9] Smith, L. H., Lock, B. A., and Hargrove, L. (2010). "Effects of window length and classification accuracy on the real-time controllability of pattern recognition myoelectric control," in Proceedings of the 18th Congress of the International Society for Electrophysiology and Kinesiology (Aalborg).

[10] Young, A. J., Smith, L. H., Rouse, E. J., and Hargrove, L. J. (2013). Classification of simultaneous movements using surface EMG pattern recognition. Biomed. Eng. IEEE Transac. 60, 1250–1258. doi: 10.1109/TBME.2012. 2232293

[11] Ortiz-Catalan, M., Hakansson, B., and Branemark, R. (2014). Real-time and simultaneous control of artificial limbs based on pattern recognition algorithms. Transac. Neural Syst. Rehabil. Eng. 22, 756–764. doi: 10.1109/TNSRE.2014.2305097

[12] Jiang, N., Rehbaum, H., Vujaklija, I., Graimann, B., and Farina, D. (2014). Intuitive, online, simultaneous, and proportional myoelectric control over two degrees of-freedom in upper limb amputees. Neural Syst. Rehabil. Eng. IEEE Trans. 22, 501–510. doi: 10.1109/TNSRE.2013.2278411

[13] Åström, K.J. & Hägglund, Tore. (2004). Revisiting the Ziegler-Nichols Step Response Method for PID Control. Journal of Process Control. 14. 635-650. 10.1016/j.jprocont.2004.01.002.

[14] The 2015 International Conference on Mechanical Engineering and Control Systems (MECS2015), Wuhan, China, 23 – 25 January 2015 https://doi.org/10.1142/9910.Edited By: Xiaolong Li.