Robust Controller Design with Particle Swarm Optimization for Nonlinear Prosthetic Hand System

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***Abstract*—The recent trend of a prosthetic hand is gradually importance due to its capability to replace amputee's hand that is lost caused by various factors. However, precision control of prosthetic hand is challenging task especially dealing with its high precision response and functionality. Apart of comprehensive modelling, the controller is another essential part that playing a vital role in the enhancement of the prosthetic hand performance. In this paper, a Sliding Mode Control (SMC) has been designed and integrated with the prosthetic hand, which parameters have been obtained through try and error technique, followed by an optimization technique using Particle Swarm Optimization (PSO) algorithm. The finding shows that the SMC, which is optimized using PSO algorithm outperforms the conventional SMC and proportional-integral-derivative (PID) controllers. Therefore, it can be inferred that appropriate controller with proper tuning technique is essential to achieve high precision performance for a prosthetic hand.**

***Index Terms*—prosthetic hand, nonlinear, sliding mode control, particle swarm optimization**

I. Introduction

Prosthetics hands have been widely produced to replace the human hands that are unable to accomplish daily tasks normally, which are lost or damaged caused by war, trauma, accident or congenital anomalies. A design of prosthetic hand, which is according to the real human hand conditions must taking every detail into consideration such as force, movement, and functionality at a fingertip, which will able to hold an object and grasp it with an adequate amount of force.

A healthy human's hand is known to be capable of accomplished daily tasks including writing, carrying, playing, holding, and texting [1]. The prosthetic hand can be separated into three finger parts, which consists of one dimension that can be related with the compound pendulum. The Lagrangian dynamic equation can be used to model the movement of the human's finger, which considering the linearity that related to the compound pendulum.

In the past several years, numerous works conducted by engineers and researchers to develop a prosthetics hand that is similar to a human hand have been reported [2-3]. However, a survey has been carried out in [4] reported that up to 50% of the upper extremity amputees is not using their prosthetics hand frequently. The defect remonstrated by these subjects including limited controllability, poor cosmetic appearance, and reduced functionality. In order to conduct more daily routine activities, these subjects would like to improve the grasping functions capability. Furthermore, subjects also required sensory feedback function to be able to feel their prosthetic hand as a part of their own body.

Furthermore, numerous control approaches have been suggested in the recent years to enhance the capabilities of the prosthetic hand. These control strategies may be loosely classified into linear control, nonlinear control, and intelligent control strategies [5]. These control approaches implemented to the prosthetic hand system including proportional-integral-derivative (PID) [6-9], proportional-integral (PI) [10], Linear Quadratic Gaussian (LQG) [11], Model Reference Adaptive Control (MRAC) [12], Fuzzy Logic Controller [13-14], Artificial Neural Network (ANN) [15-16], Sliding Mode Control (SMC) [17-19], even hybrid control approaches [20-22].

In the control engineering field, the SMC nonlinear control approach is well known to be preserved to ensure the stability of different classes of engineering systems, which are commonly exposed to uncertainties in real-time [23]. Thus, the SMC has been widely applied to different applications including electro-hydraulic system [24], electrical system [25], mobile robot [26], aero jet missile [27], power steering system [27], and ship's manoeuvring system [28].

It is well known that the performance of an engineering application is very much affected by the material used to fabricating the physical model of that particular application including prosthetic design [29]. Consequently, apart from the consideration of the physical model, a number of studies have shifted to the design of an appropriate control approach. However, a design of a quality control strategy is a challenging task which must taking into account various possible factors including a proper design of a prosthetic model [30].

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Therefore, a nonlinear modelling of a prosthetic hand has been carried out in [31] and discussed in this study. Besides that, in order to improve the performance of the designed prosthetic hand, the SMC control strategy has been implemented to enhance the grasping capability considered as the contribution of this study. The design of the sliding surface, which is based on the model order of the prosthetic hand system has been presented in this paper. By integrating the cost effective and efficient Particle Swarm Optimization (PSO) computational algorithm, the performance of the prosthetic hand has been significantly improved, which behave as another contribution to this study and produced an alternative in tuning the parameters of SMC. On the other hand, the Proportional, Integral and Derivative (PID) control has been employed, which behave as a benchmark in the control analysis in order to illustrate the improvement of the proposed control approach.

The paper is organized as below. Section 2 describes the development of nonlinear mathematical modelling of a prosthetic finger. The proposed SMC control strategy integrated into the prosthetic model is carried out in Section 3. In section 4, the PSO tuning technique employed to the proposed control method is discussed. The comparison of the performance for the proposed control strategy with the conventional PID controller is presented in Section 5. Finally, the conclusion of the study is explained in Section 6.

II. Modelling of Prosthetic Finger

A. Dynamic Model of Prosthetic Finger

Fig. 1 illustrates the general structure of a prosthetic finger.

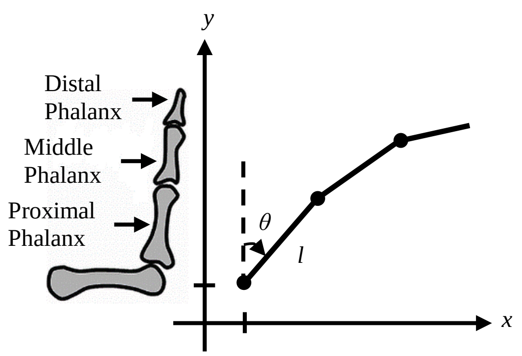

Figure 1. General structure of prosthetic finger with flexion of angle for one finger

By employing the Lagrange method, the dynamic model of this system has been derived, which is purposely to measure the torque produced by the prosthetic finger [32]. The parameters and symbol used for one Degree of Freedom (DOF) prosthetic finger are tabulated in Table I.

From the studies of the literature, the Lagrange equation will be commonly used to model the prosthetic hand system. Generally, the Lagrange equation can be expressed as:

$$L = T - V \tag{1}$$

where, the kinetic energy is denoted as T, and the potential energy is represented by V.

The velocity of centre mass for the prosthetic finger can be archived by using Euler Lagrange as presented in equations (2) and (3).

$$\dot{x} = -\left(\frac{1}{2} l \sin\dot{\theta}\right) \tag{2}$$

$$\dot{y} = \frac{1}{2} l \cos\dot{\theta} \tag{3}$$

TABLE I. Dynamic Model of Prosthetic Finger

Parameters	Symbol	Values
Resistance	R	2.6Ω
Constant torque	K_t	0.007NmA^{-1}
Constant electric	K_e	0.007Vsrad^{-1}
Gear ratio	z	15
Radius pulley	rp	0.02m
Length	l	0.75
Mass	m	1kg
Gravity	g	9.81ms^{-1}
Friction	B	12.32

Therefore, the linear velocity of the finger can be obtained as:

$$V_l = \dot{x}^2 + \dot{y}^2 \tag{4}$$

$$V_l = \frac{1}{4} l^2 \dot{\theta}^2 \tag{5}$$

For the overall prosthetic finger, the kinetic energy and the potential energy can be obtained in the equation (6) and (7) respectively.

$$T = \frac{1}{2}\dot{\theta}^2 \left(\frac{1}{4} ml + 1\right) \tag{6}$$

$$V = \frac{1}{2}(mgl \sin\theta) \tag{7}$$

Thus, $L = \frac{1}{2}\dot{\theta}^2 \left(\frac{1}{4} ml + 1\right) - \frac{1}{2}(mgl \sin\theta)$ (8)

B. Expression of DC Motor

By using the Lagrange-Euler formulation, the equation of motion for 1-DOF prosthetic finger can be written as:

$$\left(\frac{l^2 \ddot{\theta} m}{4} + l\ddot{\theta}\right) - \frac{(mgl\cos\theta)}{2} = F \tag{9}$$

An electrical and mechanical part of the DC motor that connected to the prosthetic finger can be expressed by,

$$\left(\frac{l^2 \ddot{\theta} m}{4} + l\ddot{\theta}\right) - \frac{(mgl\cos\theta)}{2} + B\dot{x} = F \tag{10}$$

Instead of feeding the current directly to the motor, an electrical field that composed of the input voltage, V was varied to manipulate the speed of the DC motor. The total force produced can be expressed in equation (11).

$$F = \frac{VKtz}{R} - \frac{KeKtz^2}{R}\dot{x} \tag{11}$$

By substitute the electrical and mechanical parts in equation (10) to the DC motor on the prosthetic finger in equation (11), the following equation can be obtained.

$$\left(\frac{l^2\ddot{\theta}m}{4} + l\ddot{\theta}\right) - \frac{(mgl\cos\theta)}{2} + B\dot{x} = \frac{VKtz}{R} - \frac{KeKtz^2}{R}\dot{x} \tag{12}$$

where, $V = \left[\frac{R}{Ktz}\right]\left(\frac{l^2\ddot{\theta}m}{4}\right) + \left[\frac{R}{Ktz}\right]\left(l\ddot{\theta}\right) - \cdots$

$$\left[\frac{R}{Ktz}\right]\left(\frac{mgl\cos\theta}{2}\right) + \left[\frac{RB}{Ktz} - Kez\right]\dot{x} \tag{13}$$

As a result, the nonlinear equation of angle can be computed as:

$$\ddot{\theta} = \frac{V + \frac{Rmgl\cos\theta}{2Ktz} - \frac{RB\dot{x}}{Ktz} - Kez\dot{x}}{\frac{Rl^2m}{4Ktz} + \frac{Rl}{Ktz}} \tag{14}$$

III. Prosthetic Hand Based on Sliding Mode Control

Generally, the structure of sliding mode control consists of switching control, U_{sw} and equivalent control, U_{eq} denoted as [33]:

$$U_{smc} = U_{sw} + U_{eq} \tag{15}$$

The sliding surface for the SMC design implemented into a second order prosthetic hand can be indicated by using the following equation:

$$\dot{s} = C_1\ddot{\theta} + C_2\dot{\theta} \tag{16}$$

By integrating the prosthetic hand into the SMC, following derivation can be obtained:

$$\dot{s} = C_1\left[\frac{V + \frac{Rmgl\cos\theta}{2Ktz} - \frac{RB\dot{\theta}}{Ktz} - Kez\dot{\theta}}{\frac{Rl^2mKtz + 4RlKtz}{4Kt^2z^2}}\right] + C_2\dot{\theta} \tag{17}$$

For the reaching phase control, the U_{sw} can be determined by applying the signum function to the sliding surface.

$$U_{sw} = -ksign(s) \tag{18}$$

When the control phase is reached the sliding surface, where $\dot{s}(t) = 0$, following equation can be achieved.

$$\frac{C_1 4Kt^2z^2V}{4Kt^2z^2} = \frac{-2RmglKtz\cos\theta + 4RB\dot{\theta}Ktz + \cdots}{4Kt^2z^2}$$
$$\frac{4Kt^2z^2Ke\dot{\theta} - C2\dot{\theta}Rl^2mKtz - \cdots}{4Kt^2z^2} \tag{19}$$
$$\frac{4C^2\theta RlKtz}{4Kt^2z^2}$$

where, U_{eq} is represented by the voltage U_V that drive the DC motor expressed as:

$$U_V = \frac{-2RmglKtz\cos\theta + 4RB\dot{\theta}Ktz + \cdots}{4Kt^2z^2C_1}$$
$$\frac{4Kt^2z^2Ke\dot{\theta} - C2\dot{\theta}Rl^2mKtz - \cdots}{4Kt^2z^2C_1} \tag{20}$$
$$\frac{4C^2\theta RlKtz}{4Kt^2z^2C_1}$$

IV. Optimization of SMC Based on PSO Algorithm

The general process of the proposed method is illustrated in the flow chart and block diagram in Fig. 2. The PSO is an algorithm based on the inspiration of a swarming behaviour of insects, animals, or even humans, which was introduced by James Kennedy and Russell C. Eberhart, who is a social psychologist and an electrical engineer at America in 1995 [34]. A group of agents known as particles, which are the composition of insects like ants, animal like birds, or humans that randomly walking around the wide range area to looking for food, treasure, or resources supposedly. The searching activity will always start from random search, then these creatures will communicate and share their current best information among each other. Finally, the summarized or computed current best information will be formed into a global best information, which will usually end up with a quality global best information.

Two important operators that will manipulate in the searching process are the velocity and position update. During the searching process, each of the current particles will accelerate to the new position or searching point, by according to the velocity value that composed of previous velocity and position information. The general velocity and position update have a formation of the equations as denoted below [35]:

$$v_{id}^{k+1} = v_{id}^{k} + c_1 rand_1^k (pbest_{id}^k - s_{id}^k) + \cdots$$
$$c_2 rand_2^k (gbest_{id}^k - s_{id}^k) \tag{21}$$

$$s_{id}^{k+1} = s_{id}^{k} + v_{id}^{k+1} \tag{22}$$

where i denotes the value of the particle or known as agent, d is the dimension of the problem, k represents the iteration of the particle, k+1 is the future iteration of particle, v represents the velocity of the algorithm, s is the searching point of the algorithm, c_1 denotes the self-coefficient, while c_2 is the group or known as swarm-coefficient, rand represents the random number assigned for each particle, *pbest* is the particle's self or personal best value, while *gbest* represents the particle's group or global best value.

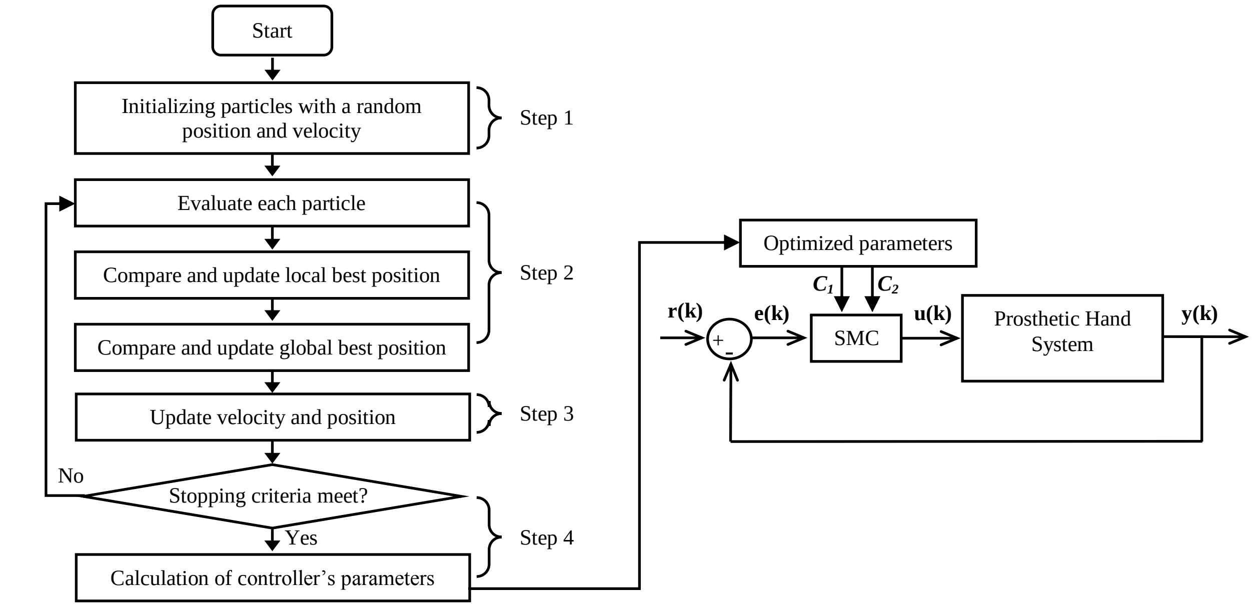

Figure 2. Flow chart and block diagram of proposed control strategies

After the SMC is successfully designed, the PSO algorithm will be utilized to searching for optimal parameters. In the searching process, the generation of the random variable for the particle's position and velocity based on the problem dimension of the SMC, which are C_1 and C_2 will be executed as illustrated in Step 1. Then, followed by the evaluation process after the random variables are distributed to all particles. The best parameter obtained by these particles will be set to current local best position or also known as *pbest*. The substitution process will be always existed by referring to the best variables obtained in each iteration. The best parameter obtained within the *pbest* will be assigned as a global best or usually known as *gbest* position as indicated in Step 2.

In the step number 3, the searching point of these particles will be changed according to the general velocity and position algorithm as discussed in [36]. The parameter obtained in the searching process is according to the objective function that depends on our plant. In this study, the objective function of Integral Time Square Error (ITSE) is applied to searching for the minimum error in each random parameter distributed to the particle. In the last stage, the termination of the searching process will be performed. The termination criteria for instance, minimum error has been achieved and maximum iterations have been reached. The searching process will be executed and repeated to the Step number 2 until the stopping criteria have been met.

V. Results and Discussion

In the evaluation of the controller response, step input reference signal has been fed into the prosthetic hand system. The controller variables as tabulated in Table II for the PID and the SMC, obtained through different tuning technique, where the tuning technique including auto tuning, try and error, and PSO tuning techniques have been utilized to obtain the parameter of the controller. It can be observed from the simulation results as depicted in Fig. 3, the response generated by the PID controller is very poor.

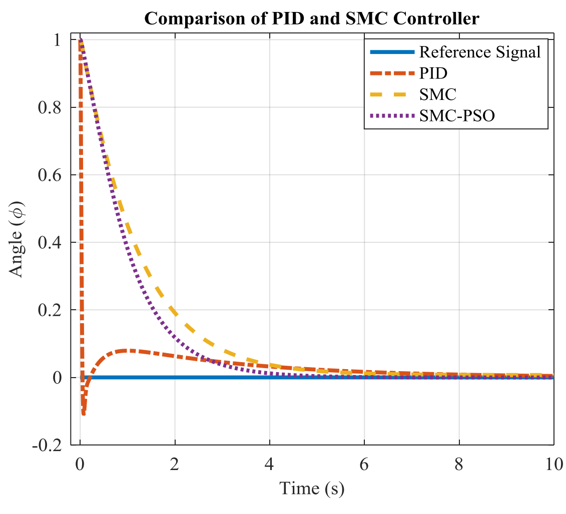

Figure 3. Comparison of different control strategies

A sudden reaction has been produced when the PID controller is employed to the prosthetic hand system. Theoretically, the high rise-time might be very harmful to the patient's finger. The high overshoot is another unwanted controller phenomenon in any engineering application, especially when the application is required to be implemented to the human object. Followed by the SMC that utilize try and error parameters. The performance indicated better response when the SMC is applied to the prosthetic finger. However, the response indicated slow settling time which clearly demonstrated the efficiency of the tuning technique. Therefore, in order to improve the efficiency of the SMC, the PSO tuning technique has been employed to the system. The results indicate significant improvement have been achieved in term of the rise time, the settling time, as well as the steady state error. As a result, it can be concluded that the robust SMC is capable of improving the performance of the prosthetic hand system. The response is even better when the cost effective and efficient PSO computational algorithm has been utilized to obtain the SMC parameters. A comprehensive transient response analysis regarding the performance produced by using different control strategies implemented to the prosthetic hand is tabulated in Table III.

TABLE II. DYNAMIC MODEL OF PROSTHETIC FINGER

Controller	Technique	Parameter		
		K_p	K_i	K_d
PID	Auto Tuning	136.90	41.74	40.76
		C_1	C_2	
SMC	Try and Error	01.0000	01.0000	
	PSO Algorithm	12.8413	15.6744	

TABLE III. TRANSIENT RESPONSE FOR THE PROSTHETIC HAND SYSTEM

Controller (Tuning Technique)	Transient Response Analysis			
	Rise Time (*s*)	**Overshoot (%)**	**Settling Time (*s*)**	**Steady-state Error (θ)**
PID (A)	0.042	10.86	5.43	0.00014
SMC (B)	2.761	0.00	4.90	0.00692
SMC (C)	2.212	0.00	3.71	0.00008

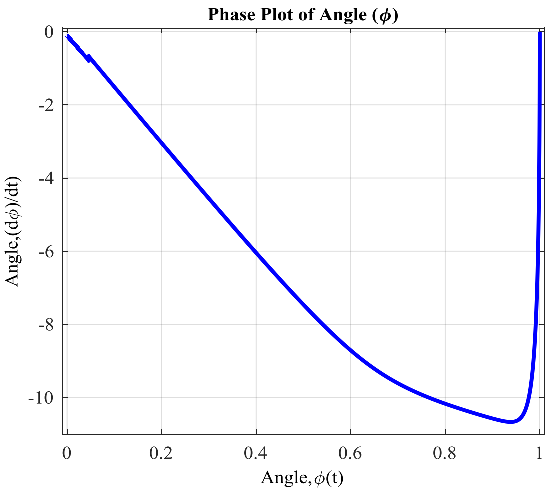

Figure 4. Phase plot of the SMC controller

Fig. 4 depicts the phase plot of the SMC. It can be seen that the angle (θ) and the derivative of the angle ($\dot{\theta}$) approaching to the zero, which indicates that the system achieved the equilibrium condition by approaching the sliding phase and remain on the surface. Fig. 4 also demonstrated the control effort produced by the controller and generating no chattering phenomenon during the control process.

VI. CONCLUSION

The nonlinear mathematical modelling of the prosthetic hand has been derived in the simulation study. In order to increase the performance of the proposed system, the PID controller has been employed and better performance has been achieved. However, the response demonstrated that the performance of the PID controller might cause injury to the patient in a real-time system. Therefore, the SMC controller has been designed based on the modelling of the prosthetic hand system. The issue emerged since there is no proper tuning technique can be utilized to obtain the SMC parameters. Thus, the well-known PSO computational algorithm has been applied to obtain the parameters of the SMC. As a result, it can be concluded that the robust SMC is capable of improving the performance of the prosthetic hand system. The response is still can be improved if an appropriate tuning technique is utilized to obtain optimal controller parameters.

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