International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Available at http://inpressco.com/category/ijcet

Research Article

Modeling, Simulation and Control of Prosthetic Hand using SimMechanics

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Received 01 Jan 2018, Accepted 01 March 2018, Available online 03 March 2018, **Vol.8, No.2 (March/April 2018)**

Abstract

In recent years, researches about design and control of prosthetic, orthotics devices have been developed rapidly. Modeling and testing process of these devices requires long time. Matlab/SimMechanics Toolbox is a very effective and easy for modeling and analyzing of mechanical system. This paper presents the multi body simulation, analysis and control of 15 DoF prosthetic hand. Prosthetic hand 3D model is designed using SolidWorks, according to structural of the adult human hand. Hand pattern are demonstrated via MATLAB SimMechanics toolbox. PID controller response for each joints of fingers are presented.

Keywords: *Prosthetic hand, analysis, simulation, control, SimMechanics*

1. Introduction

People may lose limbs because of injuries, accidents, medical conditions, or congenital hereditary disorders. The prosthetic hand takes the place of the missing limb and imitates its function when the people lose your own hand because of these situations (C. L. Taylor *et al*, 1955).

The complexity and motion types number increase in direct proportion to the number of joints in a limb. For this reason, biological hand movement is quite complex (L. Ungureanu *et al*, 2005). Human hand has got countless patterns such as hand-off, hand-on, thumb-index finger touch, thumb-middle finger touch, point an object, gripping big object such as a bottle, grip a card with two fingers etc. The prosthetic imitating the movements of the human hand must also possess these abilities. Three main factors enable the functional and visual prosthetics to be used like a biological hand:

1) Human- Prosthetic hand cognitive interaction (A. O.I Mohammadreza *et al*, 2007; M.I. Ibrahimy *el al*, 2012; E Scheme *et al*, 2011; M. Khezri *et al*, 2011; W. M. B. W. Daud *et al*, 2013; X. Chen *et al*, 2013; P. Manimegalai *et al*, 2013).
2) Prosthetic hand mechanical design and modeling (H.Rakibul *et al*, 2013; R., Hasan *et al*, 2013) and
3) Perform the position and speed controls of each joint efficiently and precisely (W. Widhiada *et al*, 2011; K. Englehart *et al*, 2003; M. Asghari Oskoei et. al, 2007; J. Chu *et al*, 2005).

In literature generally Surface Electromyography (sEMG) signals are used to recognize of human motion desire. EMG is used extensively to obtain valuable information about neuromuscular activities and to determine human motion intended. Cognitive interaction networks between human and prosthetic device is first step of control strategy.

Recording, pre-processing, feature extraction and classification steps of EMG signals part of the studies within our project are explained in detail (B Taşar *et al*, 2017). In this article; mechanical design, modelling and position control of prosthetic hand issues were presented. Research concerning the design, modeling, and control of prosthetic hands is increasing day by day. The dynamic and kinematic analyses of the hand are one of the basic steps for the design and control of a prosthetic. Hand modeling is a set of mathematical expressions that describe the kinematic and dynamic behavior of the hand.

In order to evaluate performances of a mechanical system is used kinematical and dynamic analysis which is one of classical methods. But kinematical and dynamic analysis is too hard because of establishing of the mathematical solution for hand which occur five fingers and each finger has three dof. Analysis based on simulation are easier than mathematical solution of kinematics and dynamics (V. Fedák *et al*, 2014; The MathWorks Comp. 2007). SimMechanics, which is a block diagram method for simulation and modeling mechanism by bodies and joints, solve this mathematical solution problem easily via Newtonian dynamics of torques and forces (V. Fedák *et al*, 2014). The kinematical analyses using SimMechanics are independent from kinematic equations of mechanic

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DOI: https://doi.org/10.14741/ijcet/v.8.2.2

system. Graphical represent method can be used easily for mechanical systems by connected block diagrams.
To get a better grasp of objects, multi-fingered prosthetic handles have begun to be developed. Mechanical design and modeling are of utmost importance for deciding the shape and size of the prosthetic hand, which will make the best possible gripping movement. Simulation is important in terms of making pre-fabrication analyzes and optimizing the design (W.F.B.W. Tarmizi *et al*, 2010). Analysis of the kinematics and dynamics of the mechanical model is easily accomplished by block modeling without the need for mathematical modeling with the SimMechanic ToolBox. Kinematic analysis performs the position and orientation of the mechanism resulting from the motion. Dynamic Analysis describes the relationship between a particular forces or moment effect and the velocity of motion, acceleration of the mechanism (H. Bruyninckx 2005). There are many studies in the literature to increase the gripping ability of multi-finger robots. Mahdi *et al*. performed kinematic modeling and simulation of SCARA robot using Matlab / Simulink (M. S. Alshamasin 2009). Y. Yavin (2000), involved in the study of the kinematic and dynamic analysis results of three graduated manipulators using computer simulation environment.. Machomad Ariato *et al*. were focus on developing of low cost anthropomorphic prosthetic hand and they designed 14 Dof prosthetic hand via SimMechanics first generation (M. Ariyanto *et al*, 2016 (a); M. Ariyanto *et al* 2016 (b); M. Ariyanto *et al* 2016 (c)). Asif Mahmood Mughal (2017) was presented analytical modeling of hand via SimMechanics and PID controller response of five finger. Roshan Kumar Hota *et al*. (2016) developed a robotic prosthetic hand capable of producing ten grip patterns and simulated hand pattern via SimMechanics in their study.

In this study; fifteen degree of freedom prosthetic hand is modeled according to structural characteristics of an adult human hand using SolidWorks. Then motion analysis of hand simulated via SimMechanics. Positions of each prosthetic finger are controlled PID controller. Also PID controller is designed to content the performance criteria for track of the reference. PID controller performance is tested with five hand motion pattern, which are hand on, hand off, thumb-index touch, thumb, middle touch, thumb-ring touch and thumb-little touch motions.

2. 3D Modelling of the prosthetic hand using SolidWorks

The human hand has high functionality and modeling is a very complex mechanism. The reason for this is the high degree of freedom. In other words, Human hand has a large number of joints that act independently of one another. As shown in Figure 1, each finger is made up of three small bones and connected joints. These small bones are called "Proximal phalanx", "Middle phalanx". "Distal phalanx" respectively. The distal interphalangeal (DIP) and proximal interphalangeal (PIP) joints have 1 DOF owing to rotational movement and metacarpophalangeal (MCP) joint has 2 DOF owing to adduction-abduction and rotational motions. Kinematics and dynamics features of Index, middle, ring and little fingers are similar. But thumb is the most complex physical structure compared to others and thumb has 5 DOF (W.F.B.W. Tarmizi *et al*, 2009; J. K Salisbury *et al*, 1985; S.C. Jacobsen *et al*, 1986).

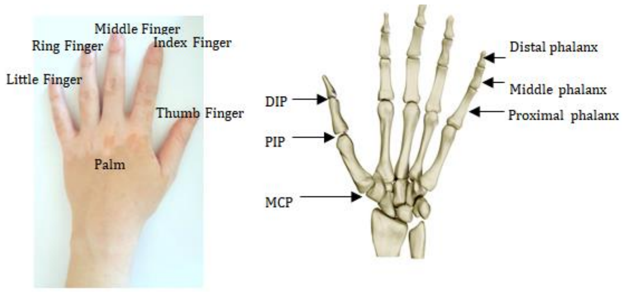

Figure 1 Structure of human hand

Physical model development of a multifunctional prosthetic hand starts by identifying its parameters: structural characteristics of the human hand like length and width of all fingers and hand palm, number of individual joints of each finger etc. Firstly an adult man hand characteristics are obtained as given in Table 1.

Table 1 Dimensions of parts of the hand

Dimensions of parts of the hand	Dimensions of First link		Dimensions of Second link		Dimensions of Third link	
	Length (mm)	Width (mm)	Length (mm)	Width (mm)	Length (mm)	Width (mm)
Thumb	70	30	45	30	40	30
Index Finger	55	30	40	25	30	25
Middle Finger	55	30	50	26	40	26
Ring Finger	55	30	40	25	30	25
Pinky	30	30	40	25	30	25
Palm	130	120				

Then a suitable prosthetic hand 3D model is designed using SolidWorks program presented in Fig. 2 base on this information table.

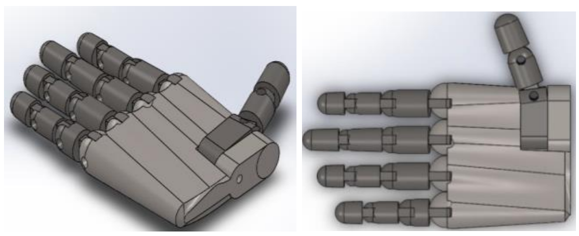

Figure 2 Visualization of the multifunctional prosthetic hand imported from the 3D model into the SolidWorks program

3. Simulation and analysis of prosthetic hand using SimMechanics

SimMechanics ™ is a simulation package that enables three-dimensional modeling of mechanical systems. This package, running in the Simulink environment, extends the Simulink environment with multi body mechanical modeling with its extensive function library. SimMechanics toolbox contains real system components, which bodies, joints, constraints, transform, forces and torques to design real mechanical system dynamics [31-36] (Y. Shaoqiang *et al*, 2008; I. Kakadiaris *et al*, 2000; C. Yang *et al*, 2010; W. Deng, *et al*, 2009; D. Gao *et al*,2006; L. T. Dung *et al*,2010).

The 15-dof prosthetic hand was modeled in the first generation of SimMechanics. When the 3D physical hand model, which is developed in the SolidWorks program, is exported into the SimMechanics, each finger is automatically shaped individually and formed as a mechanic chain strip mounted on the palm area. Shape of the prosthetic hand parts are shown in Figure 3 with exported SimMechanics scheme because of better understanding.

Movement of one part relative to the other (rotation or translation) is determined in the joint module. A rotary joint was chosen for the connection of the finger bones. There are three revolute joints on each finger, namely a total of 15 joints (degrees of freedom). The model can be input using input, force, seed or moment module.

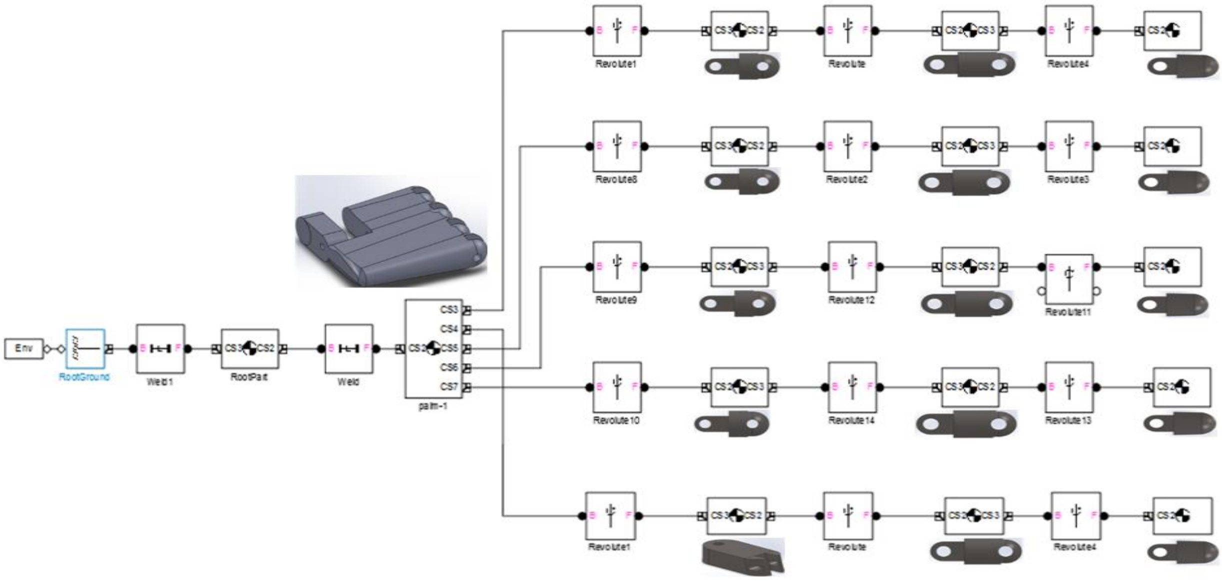

Figure 3 Program scheme of the 15-DOF multifunctional prosthetic hand in SimMechanics

Table 2 Reference angle value of finger for six hand pattern

Hand Pattern and Joint Rotation Angle Table		Index Finger			Middle Finger			Ring Finger			Little Finger			Thumb Finger		
		θ_1	θ_2	θ_3	θ_1	θ_2	θ_3	θ_1	θ_2	θ_3	θ_1	θ_2	θ_3	θ_1	θ_2	θ_3
1	Hand off	90	90	90	90	90	90	90	90	90	90	90	90	90	35	35
2	Thumb-Index Touch	90	30	25	0	0	0	0	0	0	0	0	0	60	10	0
3	Thumb-Middle Touch	0	0	0	90	30	25	0	0	0	0	0	0	80	10	0
4	Thumb-Ring Touch	0	0	0	0	0	0	90	35	0	0	0	0	100	20	0
5	Thumb-Little Touch	0	0	0	0	0	0	0	0	0	90	35	0	115	20	0

3.1. Hand Pattern Input

For the purpose the prosthetic hand to perform five selected hand pattern, the reference angle value for each finger joint is transmitted to joint actuators. As the hand reaches the desired pattern, the position, velocity and acceleration of each finger were measured. The reference of finger positions is show in Table 2 above.

3.2. Model parameters

The weight of the prosthetic hand is 200 gr, which is added to consider the effect of inertia. The hand characteristics of an adult individual in Table 3 are taken as reference in the selection of the dynamic model parameters.

Table 3 Parameters of Finger

L1	0.057 m	J3	0.00000155 kgm^2
L2	0.062 m	k1	0 Nm/rad
L3	0.051 m	k2	0 Nm/rad
m1	0.01852416 kg	k3	0 Nm/rad
m2	0.01468982 kg	c1	0.005 Nms/rad
m3	0.01492950 kg	c2	0.002 Nms/rad
J1	0.00000189 kgm^2	c3	0.005 Nms/rad
J2	0.00000101 kgm^2	g	9.18 m/s^2

3.3. Position Control of Hand

There are many studies and method about position control of prosthetic device (P. J. Keyberd *et al*, 1995; H. Rakibul *et al.*, 2013; R. Hasan *et al*, 2013; W. Widhiada, 2011; R. Gorez 1994). The positions of the joints in the finger are controlled by a Proportional, Integral and Derivative (PID) controller. The values of the controller's gains K_P, K_I and K_D are determined by the Zeigler Nicholson method to ensure that the system reaches steady state quickly without overshooting, as shown in Table 4. The PID control input-output relationship is written as Eq. (1) [42-46] (F. Vatansever *et al*, 2013; J. K. Astrom *et al*, 1995; S. Bennett *et al*,1993; E. Köse *et al*,2011)

$$u(t) = K_p \cdot e(t) + K_i \cdot \int_0^t e(t) \cdot dt + Kd \cdot \frac{de(t)}{dt} \quad (1)$$

Two suitable constant gain values for PID control of the prosthetic hand finger used in the simulation are given in Table 4.

Table 4 Gains used in simulation

Constant Gain	K_P	K_I	K_D
Thumb –Index-Middle –Ring And Little	5	0.05	0.005

SimMechanics block diagram of one finger with three joints is shown in Figure 4. The PID motor diagram control is illustrated in Figure 5.

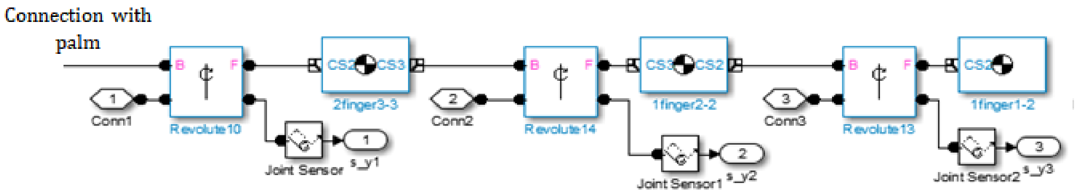

Figure 4 SimMechanics block of one finger with joint sensor and joint actuator

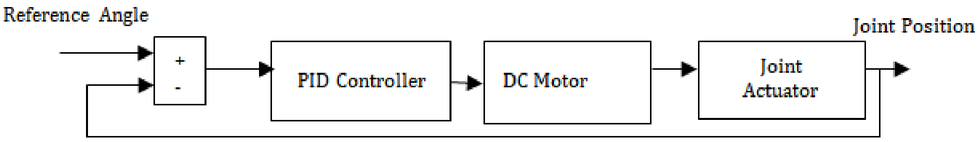

Figure 5 Designed PID controller for each joint of hand

3.3 Results

The joints of prosthetic hand SimMechanics model were transmitted and simulated in the following order respectively: 1) the reference signals for hand-off, 2) thumb-index finger touch, 3) thumb-to-middle finger touch, 4) thumb-to-ring finger touch, 5) thumb-to-little finger touch motions. In order to better observe the transient response obtained from the dynamic model, the change that occurred in the first 0.1 sec is given. The five finger endpoint position changes and PID responses are shown in Figure 6 to 10 respectively for five fingers. And also Simulation images of prosthetic hand for five motions (hand-off, Thumb-Index touch, Thumb-Middle touch, Thumb-Ring touch, Thumb-Little touch) are presented.

When the hand is in the open position, the reference angle values for then hand-off movements are transmitted to the prosthetic hand model, and the angular movements that are performed by the endpoints of the five fingers are shown in Figure 6. All fingers except thumb reached steady state angle in 0.0812 sec. steady state time with 5.44 degree overshoots, and 0.01 degree steady state error values. And also thumb finger reached steady state angle in 0.0613 sec. steady state time with 1.807 degree overshoots, and 0.001 degree steady state error values.

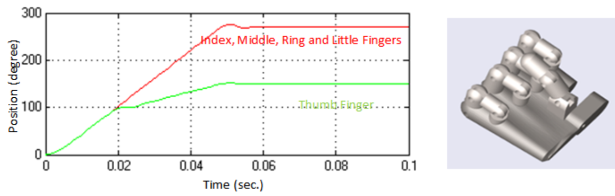

Figure 6 Hand-off motion (a) PID response of all fingers (b) Simulation Images of hand

When the hand is in the open position, the reference angle values for then thumb-index touch movements are transmitted to the prosthetic hand model, and the angular movements that are performed by the endpoints of the thumb and index fingers are shown in Figure 7.

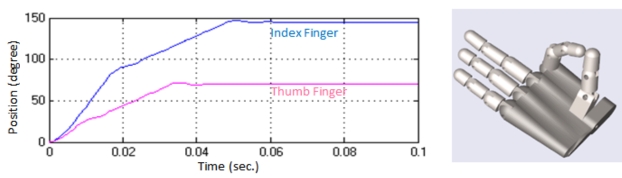

Figure 7 Thumb-Index finger touch motion (a) PID response of thumb and ındex fingers (b) Simulation Images of hand

Index and thumb fingers reached steady state angle respectively in {0.0914, 0.0698} sec steady state time with {1.814, 1.8424} degree overshoots, and {0.0025, 0.0038} degree steady state error values.

When the hand is in the open position, the reference angle values for then thumb-middle touch movements are transmitted to the prosthetic hand model, and the angular movements that are performed by the endpoints of the thumb and middle fingers are shown in Figure 8. Middle and thumb fingers reached steady state angle respectively in {0.0914, 0.0908} sec steady state time with {1.814, 1.816} degree overshoots, and {0.001, 0.001} degree steady state error values.

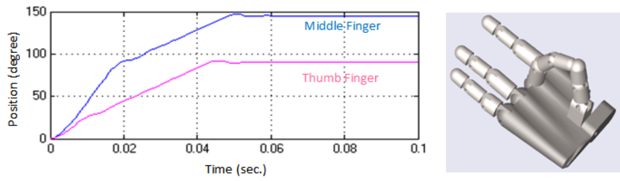

Figure 8 Thumb-Middle finger touch motion (a) PID response of thumb and middle fingers (b) Simulation Images of hand

When the hand is in the open position, the reference angle values for then thumb-ring touch movements are transmitted to the prosthetic hand model, and the angular movements that are performed by the endpoints of the thumb and ring fingers are shown in Figure 9. Ring and thumb fingers reached steady state angle respectively in {0.0682, 0.0693} sec steady state time with {1.795, 1.815} degree overshoots, and {0.002, 0.0046} degree steady state error values.

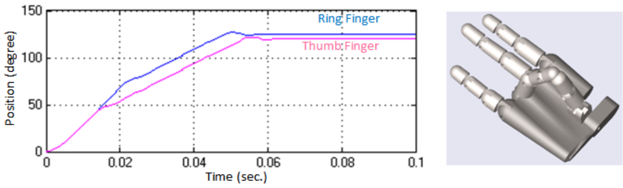

Figure 9 Thumb-Ring finger touch motion (a) PID response of thumb and ring fingers (b) Simulation Images of hand

When the hand is in the open position, the reference angle values for then thumb-little touch movements are transmitted to the prosthetic hand model, and the angular movements that are performed by the endpoints of the little and thumb fingers are shown in Figure 10.

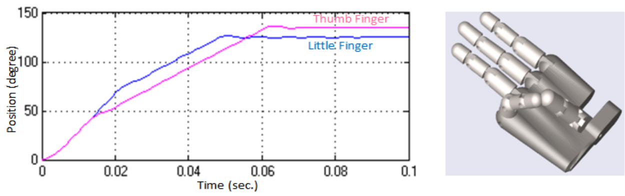

Figure 10 Thumb-Little finger touch motion (a) PID response of thumb and little fingers (b) Simulation Images of hand

Little and thumb fingers reached steady state angle respectively in {0.068, 0.0813} sec steady state time with {1.795, 1.7982} degree overshoots, and {0.001, 0.008} degree steady state error values.

Conclusion

The complexity of human limb movements, the number of independent movement, is increased proportion to the number of joints in the limb. If the wrist joints are ignored, human hand has got fifteen independent joints with three joint of each finger. For this reason, dynamic and kinematic analysis of hand is quite complex. Kinematics and dynamics analysis based on simulation is easier than mathematical solution. The kinematical analyses using SimMechanics are independent from differential equations of mechanic system. The simulation results have been demonstrated that finger motion control with PID control is achieved in a very fast, smooth and stable. Clearly, SimMechanics is effective way for analyzing of mechanical systems with its intuitive, easy, and high accuracy rate typical. It is benefit for analyzing mechatronic systems.

Acknowledgements

The subject of this article, which is Beyda TAŞAR's doctoral thesis, was supported by TÜBİTAK under the Domestic Doctoral Scholarship Program for Priority Areas in 2211 C. In addition, the study was supported by Fırat University Scientific Research Projects Management Unit within the scope of PhD Thesis Project number MF-14.25.

Funding information

There isn't used any funding source for this study.

Conflict of interest

There isn't any conflict between authors.

Author contributions

Oguz YAKUT and Beyda TAŞAR carried out the modeling and simulation of hand via Matlab and PID Controller design for pattern control. Arif GULTEN participated in its design and coordination and helped to draft the manuscript. All authors read and approved the final manuscript.

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