Control Techniques of Multi-Fingered Hand for Rehabilitation

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Abstract. The use of the robotic hand today has been widely studied. So many ideas from robot designers to create different types of robots and have their functionality. Today the use of robots has been widely used everywhere such as factories, hospitals, homes, offices and others. Several factors are contributing to the increase in hand robot construction in hospitals due to the high demand in hand rehabilitation for stroke patients. In this study, there are four controllers used namely PID controller, Fuzzy Logic controller, Fuzzy-PID controller, and PID-PSO controller to find the best system response for hand applications. Appropriate control schemes should be set with various methods and parameters to enhance the system response to human hand rehabilitation.

1. Introduction

Stroke is a major cause of severe disability in adults. It is estimated that 40 000 people stroke every year in Malaysia (National Stroke Association Malaysia, 2011). According to the 2015 National Health Commission, there are almost 4.7 million adults in the United States who find it "extremely difficult or unable to understand or handle small objects" [1]. Hand injuries are normally observed in neurological and musculoskeletal diseases such as arthritis, Cerebral Palsy, Parkinson's disease, and stroke. Therefore, physical recovery has been used for motor recovery through repeated repetitive movements [2-5]. This is largely due to neuroplasticity - the ability of the brain to regenerate by establishing new neural connections. Physical therapists are now seeking to take advantage of neuroplasticity to regenerate motor functions in the brain through repeated training. However, to date, there has been no consensus on the best modes and doses to facilitate neuroplasticity [6]. Also, the success of recovery depends on the ability of the patient to attend therapy in terms of therapeutic practice, time allocation to therapy or therapeutic cost barriers. Robot hands can increase access to repeat exercises. Therefore, a special organization was established to assist the disabled and the disadvantaged to provide additional therapy to restore patient access, agreement, and subsequent recovery efforts. A summary of the designs by comparing the different methods will help in the expansion of these tools in the future. Today the use of robots has been widely used everywhere such as factories, hospitals, homes, offices, and more. However, the use of robot hands in hospitals is also less widely used than in factories or industries. Various factors lead to increased demand in hospitals when a high demand for people with hand injuries. Rana and Aggarwal (7) proposed that robot arms...
are controlled using EMG signals obtained from electrodes attached to human arms. EMG signals are learned from three different muscle groups in the upper arm. Minas et al. (2014) proposed an Electromyography-based interface (EMG) used to control robot hand movements. First, it is used to control the robot’s fingers involving EMG signals in human arm muscles and then record intact finger/finger movements and predict prosthesis movements using synergistic behavior. Body power interfaces are used for those who want to achieve lower costs, with a robust intuitive process [8].

2. Methodology
The human hand is a very important structure in the reaction of an object. The function of human hands is based on the higher degrees of freedom (DOF). Normally, human hands consist of 23 DOF and 17 joints [9]. The degree of freedom in the human hand increased to 29 DOF when its movement was three-dimensional due to rotation differences. Figure 1 shows the human hand structure that is divided into multiple joints.

![Figure 1: Human Hand [6]](image)

The phalanges are the small bones that constitute the skeleton of the fingers and thumb. The phalange close to the hand is called the "proximal" phalange and the tip of the finger is called the "distal" phalange. Between the proximal and the distal is known as the "middle" phalange. The joint between the proximal phalange and the arm is metacarpophalangeal (MCP) with 2 DOFs. The other joints represent 1 DOF. Unless the thumb has 5 DOFs. The other fingers are index, middle, ring and small fingers whose structure is very similar in kinematic and dynamic characteristics. Thumb is a very complex physical structure between the fingers and differs from the finger which contains only two phalanges and has 5 DOFs [9].

| Table 1: Fingered Hand Parameter |
|----------------------------------|
| Variables | Values | Descriptions |
|----------|--------|--------------|
| L1       | 0.0605m| Link1        |
| L2       | 0.0375m| Link2        |
| L3       | 0.0245m| Link3        |
| m1       | 0.0100728kg | Mass1 |
| m2       | 0.00397876kg | Mass2 |
| m3       | 0.00208544kg | Mass3 |
| g        | 0.98 1Nm³   | Gravity      |
Each joint finger movement is controlled by the dc motor. This study is focused on one motor control position dc based on one finger that refers to the parameter of the motor dc given in Table 2.

Table 2: Parameter of Dc Motor for Fingered Hand

| Variables | Values          | Description             |
|-----------|-----------------|-------------------------|
| J         | 0.05g.m2        | Moment of inertia       |
| B         | 0.03mN.ms       | Friction coefficient    |
| Ke        | 0.705mN.m^-1    | Back EMF (constant)     |
| Kt        | 6.73mNmA        | Torque (constant)       |
| R         | 95ohms          | Values of resistance    |
| L         | 310310μH        | Values of inductance    |

Here, the transfer function used to find the position of the dc motor:

$$\theta(s) = \frac{Kt}{(J * L)s^2 + (J * R + L * B)s + (Kt * Ke)}$$

(1)

2.1. Kinematic of Multi-Fingered Robot Hand (MFRH)

Multi-fingered robot hands (MFRH) are developed and used as a starting point for kinematic equation derivation. The kinematic equation of the MFRH is implemented to find the movement and rotation. Figure 2 shows the Cad Model of MFRH is based on the actual human hand which consists of the index, middle, ring and small fingers as shown in Figure 3. Normally, the human finger has 4 joints consisted of 1 normal join and 3 active joints The DIP joint is connected to the PIP joint. The thumb has 5 joints with 5 DOF. The extension of the thumb, the yaw axis is connected with the MCP which are capable of the rotation and reflection. The number of DOF is defined by the frame of each joint.
The basic parameter for assignment to find the frame $x_iy_iz_i$ to the link is given below [10]:
- The $z_i$ axis lies along the motion axis of the rotary to the joint $j+1$.
- The $x_i$ axis is normal to both $z_{i-1}$ and $z_i$ axes and points away from the $z_{i-1}$ axis.
- The $y_i$ axis is set to form a right-handed frame $x_iy_iz_i$.

Here, the Denavit Hartenberg (DH) parameter of the frame for each joint and link are described [10]:
- $\theta_i$ is a joint angle where an angle from $x_{i-1}$ and $x_i$ measured about $z_{i-1}$.
- $d_i$ is link offset where the distance from $x_{i-1}$ and $x_i$ measured along $z_{i-1}$.
- $a_i$ is link offset where the distance from $z_{i-1}$ and $z_i$ measured along $x_i$.
- $\alpha_i$ is a joint angle where an angle from $z_{i-1}$ and $z_i$ measured about $x_i$.

In the study, the equation of the forward kinematic uses the DH parameter. The equation of the forward kinematic for finger hand will be assigned using a homogeneous transformation matrix [8]. The parameter of the fingers hand is given in Table 3.

| $i$ | $\theta_i$ | $d_i$ | $a_{i-1}$ | $\alpha_{i-1}$ |
|-----|------------|-------|-----------|----------------|
| 1   | $\theta_1$ | 0     | 0         | 0              |
| 2   | $\theta_2$ | 0     | $l_1$ (MCP) | 0              |
| 3   | $\theta_3$ | 0     | $l_2$ (PIP) | 0              |
| 4   | 0          | 0     | $l_3$ (DIP) | 0              |

Here, the homogenous formula for finger hand with 4 links:

$$H_{i=0}^i = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & s\alpha_{i-1} & s\alpha_{i-1}d_i \\ c\theta_i s\alpha_{i-1} & -c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1}d_i \\ 0 & 0 & 1 & 1 \end{bmatrix}$$ (2)

$$H_0^n = [H^n_0 H^n_1 H^n_2 H^n_3]$$ (3)
\[
\begin{bmatrix}
C_{123} & -S_{123} & 0 & l_1C_1 + l_2C_{12} + l_3C_{123} \\
S_{123} & C_{123} & 0 & l_1S_1 + l_2S_{12} + l_2S_{123} \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} = \left[
\begin{bmatrix}
C_{123} & -S_{123} & 0 & l_1C_1 + l_2C_{12} + l_3C_{123} \\
S_{123} & C_{123} & 0 & l_1S_1 + l_2S_{12} + l_2S_{123} \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}\right]
\]

(4)

2.2 Control Scheme

There are two parameters of the Ziegler Nichols method which are \( L \) time delay and \( T \) constant time as shown in Figure 4. The variable of \( \alpha \) is called tangent where it can determine the system response at the point of reflection and recording its trajectory with the steady-state values and time axis and the equations are depending the \( k \) values are maximum benefits.

![Figure 4: Time response of the Ziegler Nichols method](image)

Figure 4 illustrates the time system response of the Ziegler Nichols (Z-N). This parameter is use-values of \( L \) and \( \alpha \) to determine the gains of the PID controller as shown in Table 4.

| Control Type | \( K_P \) | \( T_i \) | \( T_d \) |
|--------------|----------|----------|----------|
| P           | \( \frac{1}{a} \) | -        | -        |
| PI          | \( \frac{0.9}{a} \) | 3L       | -        |
| PID         | \( \frac{1.2}{a} \) | 2L       | \( \frac{L}{2} \) |

2.2.1 PID Controller

Proportional Integral Derivative (PID) is normally used in an industrial control system that generic control feedback mechanism (controller) is shown in Figure 5. The PID controller is a traditional controller where some of the researchers use the Ziegler Nichols method for turning the PID controller. Ziegler - Nichols has been proposed by John G. Ziegler and Nathaniel B. Nichols. In the research, the Ziegler Nichols is used as a reference controller to compare with another controller [11].
2.2.2 Fuzzy Controller

Fuzzy logic controllers have been successfully used for non-linear systems due to their linear structural features based on their knowledge. Fuzzy logic controllers based on theoretical of the fuzzy logic. It uses the mathematical principles of representation of the knowledge of the membership level instead of the sharp familiarity of classical binary logic [12].

The Fuzzy logic controller consists of one output and two inputs. The inputs are error change and position error. The output is the torque of the dc motor. Input and output are determined by the Fuzzy logic controller proficiency function. The Fuzzy logic controller is tested by 2x2 membership functions, 3x3 membership functions, 5x5 membership functions, and 7x7 membership functions. The best tuning for the system response is to use 5x5 membership functions.

2.2.3 Fuzzy PID Controller

Figure 7 illustrates the block diagram of the Fuzzy PID controller. Fuzzy-PID controllers have been implemented to produce better response systems. The combination of the Fuzzy controller and the PID controller is to enhance the system response of the finger hand.
2.2.4 PID PSO Controller

Figure 8 illustrates the block diagram of the PID-PSO Controller. PID-PSO controller combines the PID controller with the Particle Swarm Optimization algorithm (PSO). The combination of the controller is to find a better system response.

2.3 Particle Swarm algorithm

The PSO algorithm is a social search algorithm developed by Kennedy in 1995 for segment behavior and introduced as an optimization method. By using methods that inspire the collective movement of birds to find food in groups. Accuracy classification and length of the selected feature vector is considered as the evaluation criteria for particle movement. In the method of the PSO, the particle flow in the search space. In this study, the PSO was combined with the PID controller to turning the system response [14].

3. Results and Discussion

The simulation uses four controllers. The first controller is PID controller as a reference. Then other controllers are Fuzzy Logic controller, Fuzzy PID controller and PID-PSO controller as shown in Figure 9 until Figure 12. The best tuning is depending a good system response. It is based on five criteria which are the rise time (Tr), settling time (Ts), maximum amplitude (C max), steady-state error(Error), percent overshoot (%OS) where %OS = (C max - C final) x 100 and final amplitude (C...
Final) is the value of the amplitude goes to stable. In Figure 9, the results using PID Controller is shown the rise time = 2.13, settling time = 8.25 and percent overshoot = 38% and steady-state error = 0.38 and maximum amplitude = 1.38 and final value = 1.0. Figure 10 shows the results using Fuzzy Controller where the rise time = 2.82, Settling time = 7.25 and Percent Overshoot = 1.02% and Error = 0, maximum amplitude = 1.01 and final value = 1. The result of the Fuzzy controller is leading than the PID controller in terms of settling time with 2.82 although the rise time is still lagging with 7.25. In Figure 11, the results using Fuzzy-PID is shown the rise time = 4.98, settling time = 6.5 and Percent Overshoot = 0% and Error = 0, maximum amplitude = 1.0 and final amplitude = 1.0. The result of the Fuzzy PID controller has improved at the settling time with 6.25 and zero percent overshoot and no error but it still lagging at the rise time with 4.98. In Figure 12, the results using PID-PSO is shown the rise time = 2.07, settling time = 5.36 and percent overshoot = 4% and Error = 0.04 where maximum amplitude = 1.04 and final value = 1.0. The result of PSO-PID more improved than others. Detail the results are shown in Table 3.
According to Table 5, the system response of the PID-PSO controller is the best compared to that of the PID controller, the Fuzzy controller, and the Fuzzy-PID controller in terms of the rise time, the settling time and percent overshoot. By comparing with PID and Fuzzy, the fuzzy controller is greater to the PID controller with a settling time of 7.25. The Fuzzy-PID controller also improves the rise time and has no errors. However, Fuzzy-PID lags behind the others with 4.98. Therefore, PID-PSO is better than others with a solution time of 5.03. A good output impression depends on a timely solution because it is time-consuming for difficulty. According to PID for reference, Fuzzy solution time increased to 12% and Fuzzy-PID also improved to 17% PID. Then, PSO-PID is a good system response than another controller with 36%.
4. Conclusion
In this study, the results of four controllers consisting of PID controllers, fuzzy controllers, fuzzy-PID controllers, and PID-PSO controllers were performed. By using a PID, Fuzzy Logic Controller, PSO algorithm and simulation work to determine the position control FRH. Appropriate control schemes should be set with various methods and parameters to enhance the system response to human hands for recovery. Further work, research may expand the use of dissimilar methods to enhance the output responses of the fingered hand.

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