Comparison of PID and fuzzy logic to control the motions of robotic prosthetic limbs

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Abstract. Prosthetic limbs are one of the tools that can be used for people with lower limb disabilities. The bionic leg is one of the breakthroughs in which its movements can be regulated by the implementation of a control system on the microcontroller. Testing is done by interfacing with Matlab / Simulink on the prototype using the PID control system and the Fuzzy Logic control system with a time of 10s at a reference angle of 90°. The PID control system design is done by auto-tuning to get the required parameters, kp, ki, and kd while the Fuzzy Logic control system by determining the input and output parameters and its rules. The PID parameters obtained were 2 KP, 18 KI, and 0.5 KD while the Fuzzy Logic is the reference signal input and voltage of the DC motor as the output. The motion data obtained from the transient response is the maximum overshoot, percentage error, and settling time from both of the control systems, as for the PID 6.90%, 3.69%, and 0.877s respectively and 3.31%, 3.46%, and 0.610s respectively for the Fuzzy Logic control system. The prototype performance with the Fuzzy Logic control system is better than using the PID control system.

1. Introduction
Now several companies are producing bionic robot systems to solve some problems the limitations of wheelchair mobility, by returning the user's ability to walk[1]. For example, ReWalk is Bionic robot leg, produced by Israeli company Argo Medical Technologies Ltd and the Rex bionic robot leg from New Zealand.

Disability is a condition where a person has physical or intellectual deficiencies or sensory experiences for a long time. Disability is a general term, which includes disorders, activity limitations, and restrictions on participation. Persons with disabilities in Indonesia have a large number. Based on a survey conducted on 14 (out of 33) provinces in Indonesia, there were 1,167,111 people with disabilities. Disability can be caused by several things, including congenital, perinatal conditions, illness and accidents. One example of disability is lower limb disability.

Prosthetic limbs are one of the important devices or elements of functional restoration. Significant improvement in the study of prosthetic has highly accelerated during the past few decades [2]. However prosthetic limbs in Indonesia have a relatively cheaper price and are easily manufactured, generally, the users still have some trouble and spend a lot of energy to move it. It has become an important challenge for society and the government to rehabilitate these people with disabilities [3]. These problems can be
reduced by making bionic legs or robotic prosthetic limbs.

Bionic legs can be used as an alternative tool for persons with lower limb disabilities to facilitate the movement of the person in carrying out activities. Bionic is a study about replacing anatomic structures or physiological processes with electronic and mechanical components. Bionic is a term that refers to the flow of ideas from biology to engineering and vice versa [4]. The application of bionic aims to replace or repair the function of organs or parts of the body with a mechanical approach. Bionic limbs have progressed greatly today, shown in a previous study, a review has been made to discuss how main functions of the human hand are replicated artificially and the key areas of research that could conduct to vast advancement in bionic limbs functionality [5].

Bionic legs movements can be regulated by the implementation of a control system on the microcontroller. The control system is a tool to control and regulate the condition of a system so that the movement is more optimal. The complication of the dynamic system makes it urgent to develop process control technology [6]. Recently, a study shows that using microprocessor-controlled systems allows dynamic controls of the flexion and extension behavior of the knee joint, resulting in potential benefit to the amputee [7]. Researchers focus on four elements through improving prosthetic limbs: mechanisms, actuators, sensing, and control [8].

In a previous study conducted by HualongXie, bionic legs with a PID control system could produce normal human movements using a trial and error method [9]. Another study shows that the implementation using fuzzy logic on a prosthetic hand’s thumb offers flexibility in the hand movement and is similar to the movement of an actual human hand [10]. The real-time implementation on non-linear PID controller was developed to control the servomechanism drive system based on MATLAB/Simulink [11].

In this study, a PID and Fuzzy Logic control system was designed in MATLAB/Simulink based bionic leg to be compared to determine the optimal and accurate bionic leg prototype movements and fast response. The bionic leg’s characteristic is shown in the transient response control. One of the most important requirements for every control system is a good transient response [12]. The desired result is done by reducing signal errors, maximum overshoot and settling time.

2. Methodology of Research
2.1. Description of Research
At the beginning of the research, a 3D model design as simulation and visualization of the bionic leg system is needed. The 3D model of the bionic foot system is drawn using software Inventor-Auto Desk. The measurement of the bionic foot system is matched with one side of the prosthesis. Matlab/Simulink the software provides the facility to export the 3D model in Inventor to the XML file in Matlab/Simulink. To avoid being upset with the design of the robot, it must first be simulated with a control system. Figure 1 shows the bionic robot leg. The bionic robot leg has one degree of freedom with installed a dc motor as an actuator of this robot. The DC motor used is the DC motor of car wiper with 12 Voltage, 85 ± 25 rpm, current ≤ 3 A and torque 30 kg.cm.

Other components used are Arduino Mega 2560, L298N motor driver, Myoware sensor and potentiometer. DC motors that have been installed as actuators are connected to the L298N motor driver which is connected to the Arduino Mega 2560 and battery. Arduino functions as a microcontroller to adjust the rotating speed and direction of rotation of a DC motor. The L298N motor driver is used so that the DC motor can be adjusted like a servo motor. The potentiometer and Myoware sensor are connected to the Arduino Mega as an analog input. Myoware sensor is used as input of muscle movements and potentiometers are used as feedback and output in the form of angles. The problems are how to increase the power of the EMG signal when the muscle in the fatigue condition. The signal of EMG was collected muscle of biceps to perform flexion and extension [13].
Testing is done by interface with Matlab / Simulink on the prototype using the PID control system and Fuzzy Logic control system with a time of 10s at a reference angle of 90° as a comparison. The results obtained in the form of the transient response to the bionic leg prototype motion to get signal error parameters and maximum overshoot of less than 5% and settling time is less than 1s. These parameters will be the point of reference for comparing the two control systems.

2.2. Testing with PID Control
PID tuning can adjust dynamic system gain parameters quickly and precisely to get the robust design with ideal response time and can be used on single and multi-loop PID tuning methods [14]. In a simple way that is by adjusting the response time and behavior time, the response time will change according to the wishes as shown. In the testing, the input reference is a angular angle at 90°. By using the auto tuning which is available in MATLAB/Simulink program that is given easier for the user to determine the parameter of proportional (Kp), integral (Ki) and derivative (Kd) gains. The PID control system is created by determining the values of Kp, Kd, and Ki by auto-tuning the simulation. Simulation is made with actual DC motor parameters. MATLAB software will identify the plant that has been made and determines the values of Kp, Kd, and Ki according to the plant. From the simulation is obtained the parameter of Kp = 2 KP, Ki = 18 KI and Kd = 0.5 KD. The parameter values that have been obtained in the simulation are inserted into the actual control system. The block diagram is shown in Figure 2. Block diagram of this robot is created by using the support package Arduino AT Mega which is available in Simulink Toolbox. There are three of output indicators should be achieved such as minimum overshoot signal, minimum error signal and faster to achieve the stability control.
2.3. Testing of Fuzzy Logic Control System (FLCS)

The FLCS model used in this study is Mamdani. The process of FLCS uses a Linguistic Variable as Input. This input is obtained from sensor readings at sampling k (Sk). After processing through fuzzy stages based on the predetermined rule base, Crips Output is obtained as a deviation value for setting the PWM on the dc motor. This is shown in Figure 3.

The FLCS is used to determine motor rotation. Users can map the voltage entering the DC motor and enter tolerance from the angle of motion of the joint. Motor rotation will be regulated by voltage regulation. The FLCS uses an error signal of angular displacement as an input which is the difference from the reference input and angle of the potentiometer. The membership functions of input and output are shown in Figure 4 and 5.
The Fuzzy Logic control system is created by determining the input, output, and the rules.

Input (Error signal) Parameters:
- Zero : [0 0 0]
- Small : [0 0.4 0.8 1.2]
- Med : [0.6 1.4 2.2]
- Large : [1.4 2.2 3]
- XLarge: [2.5 3 5 10]

Output (Voltage) Parameters:
- Zero : [10 10 10]
- Small : [10 10.5 10.89 11.5]
- Med : [10.8 11.6 12.4]
- Large : [11.6 12.6 13.3]
- XLarge : [12.75 14 15.5 17]

Fuzzy Logic Rules:
1.) IF (error is zero) then (volt is zero) (1)
2.) IF (error is s) then (volt is s) (1)
3.) IF (error is m) then (volt is m) (1)
4.) IF (error is xl) then (volt is xl) (1)

The form of building of block diagram of FLCS for robot bionic leg is nearly similar with PID control system. Matlab/Simulink has provided the support package Arduino AT Mega. It contains some of block which related to the robot application program. This block diagram of FLCS is shown in Figure 6.

Figure 6. Block diagram of FLCS

3. Results and Discussion
Figure 7 shows the research testing for the transient response of the bionic leg prototype using PID control.
The black line shows the reference angle and the red line shows the actual bionic leg response with the PID control system. The transient response graph shows that the motion of a DC motor with a PID control system is stable and doesn’t oscillate. Figure 6 shows the actual motion of a DC motor is slightly overshot. The time needed to reach the reference angle is 0.689s and reaches stable at 0.877s with an angle of 89.73°. The maximum overshoot is 95.36°, which is 6.90%. The maximum overshoot value exceeds the predetermined value (below than 5%).

Figure 8 shows the difference in output and input prototype with the PID control system. The error signal angular displacement value is 3.341° and the maximum error value obtained is worth 90.54° so that the percentage error value is 3.69%. The error value generated by the prototype with the PID control system does not exceed the predetermined limit.

The transient response of the bionic leg prototype using Fuzzy Logic control system is shown in Figure 9.

The black line shows the reference angle as an input and the red line shows the actual response of the bionic leg with the fuzzy logic control system. The time needed to reach stable is faster than using the PID control system which is 0.610 seconds with an angle of 88.9°. The maximum overshoot reaches 91.88°,
which is 3.31%. The maximum value of overshoot obtained is lower than using the PID control system and does not exceed the specified value (below 5%).

Figure 10 shows the error signal of the bionic leg prototype with a fuzzy control system. In the graph shows the output difference and input prototype with the fuzzy control system. The value of the error that occurred was 3.13° and the maximum error angular displacement value obtained was 90.27°. The percentage error value was 3.46%. The error value produced by a prototype with a fuzzy control system has a lower value compared to using a PID control system. The error value is below the specified value (below 5%).

Table 1. Transient Response Result

| Transient Response of bionic leg prototype | PID       | Fuzzy Logic |
|------------------------------------------|-----------|-------------|
| Error signal (%)                        | 3.69      | 3.46        |
| Max. Overshoot (%)                      | 6.90      | 0.31        |
| Settling time (s)                       | 0.877     | 0.610       |

Table 1 shows the transient response to the results of bionic leg testing with a PID dan Fuzzy Logic control system. There are 3 things to consider, which are error and a maximum overshoot of less than 5% and a settling time of less than 1s.

The PID control system has the maximum overshoot, error percentage, and settling time values of 6.90%, 3.69%, and 0.877s respectively. The maximum overshoot of the PID control system still exceeds the determined value, despite, that it has generated a smooth motion that does not oscillate. This is due to the kp parameter that applies as an amplifier (gain) which gives a direct effect on the error, where the greater the error, the greater the control signal produced by the controller. The ki parameter serves to correct the steady-state so that the transient response graph with the PID control system is more stable. The kd parameter serves to set the speed or rate of the error, where the feedback is given proportional to the speed of the error change to the time so that the controller can anticipate the error that occurs.

From the research testing shows the Fuzzy Logic has a slightly better performance than using PID control because the error signal with fuzzy logic control is small percentage than using PID control, the maximum overshoot signal is small than using PID control and settling time to get stability response more faster than using PID control.

4. Conclusion
The paper describes the comparison of the robotic prosthetic leg using PID and Fuzzy Logic control systems. The PID parameters obtained were 2 KP, 18 KI, and 0.5 KD while the Fuzzy Logic is the reference signal input and voltage of the DC motor as the output. The motion data obtained from the transient response is the maximum overshoot, percentage error, and settling time from both of the control systems, as for the PID 6.90%, 3.69%, and 0.877s respectively and 3.31%, 3.46%, and 0.610s respectively for the Fuzzy Logic control system. The Fuzzy Logic has a slightly better performance compared to the PID control system. The prototype performance is more accurate than the PID and the time needed to reach the reference angle is faster than the PID control system. Fuzzy Logic functions to map voltage for motor motion from input error. In addition, the fuzzy Logic control has a slightly better performance than PID control because the error signal is the smallest.
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