Modelling and Control of Robotic Leg as Assistive Device

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Abstract. The ageing population (people older than 60 years old) is expected to constitute 21.8% of global population by year 2050. When human ages, bodily function including locomotors will deteriorate. Besides, there are hundreds of thousands of victims who suffer from multiple health conditions worldwide that leads to gait impairment. A promising solution will be the lower limb powered-exoskeleton. This study is to be a start-up platform to design a lower limb powered-exoskeleton for a normal Malaysian male, by designing and simulating the dynamic model of a 2-links robotic leg to observe its behaviour under different input conditions with and without a PID controller. Simulink in MATLAB software is used as the dynamic modelling and simulation software for this study. It is observed that the 2-links robotic leg behaved differently under different input conditions, and perform the best when it is constrained and controlled by PID controller. Simulink model is formed as a foundation for the upcoming researches and can be modified and utilised by the future researchers.

1. Introduction

Due to development of human civilisation, improvement in the area of nutrition, medical advancement, health care, sanitation, education and economic well-being people are able to live longer than ever[1], resulting in the increasing number of ageing population with the ageing symptoms on them which could reduce their mobility. On top of that, various health conditions such as multiple sclerosis, cerebral palsy, stroke or injury of spinal cord could also lead to acute or chronic impairment in human’s locomotors. The wheelchairs or wheeled type robots would face difficulty climbing an obstacle with the height more than half of the diameter of the wheel, yet a leg-type robot would be able to do so easily[2]. Hence, a promising solution for this problem will be a robotic assistive device for the lower limbs. The main function of a lower-extremity exoskeleton in locomotion assistance is to provide external torque at the respective positions of human joints to replace the deficient motor function of the patients[3].

This study is to provide a start-up platform for the basic understanding towards the dynamic modelling of a lower limb powered-exoskeleton. By developing the dynamic model of the proposed lower limb powered-exoskeleton, the coordinates of the different critical points of the link could be determined so that they could be managed and controlled correctly. This study is to provide the elderlylies, patients, and victims who are suffering from the gait impairment with a new hope of standing up again, which in turn will benefit the overall population of the earth.

A group of researchers from Sun Yat-sen University came out with a mathematical model for their 3-links exoskeleton by using Euler-Lagrangean approach. They incorporated the kinematic model, together with friction model and motor model into their dynamic model. The kinematic model is about
the exoskeleton and ideal joint torque, the friction model describes the compensation for the friction in the servo-system, and the motor model presents the conversion of electrical energy to kinetic energy[4].

The existing powered exoskeletons employ different control strategies. Berkeley Lower Extremity Exoskeleton (BLEEX) employs a mixture of position control for stance-leg and positive feedback based sensitivity amplification controller for the swing leg. Lower Extremity Powered Exoskeleton (LOPES) has 3 different modes of choice, namely “patient-in-charge” mode, “robot-in-charge” mode, and “therapist-in-charge” mode. For Active Leg Exoskeleton (ALEX), 2 force-torque sensors are mounted at the shank segment and thigh segment respectively[3]. The force-field controller employed receives the feedback of force and torque to assist-as-needed. MoonWalker uses 3 pressure sensors under each foot. As for KIT-EXO-1, it utilises the interaction forces acting in between the user’s body and the exoskeleton as the input for the controller, which is used to predict the upcoming motion. The forces are collected using sensors attached at different part of the exoskeleton, especially at the knee joints[5].

Proportional-integral-derivative (PID) controllers are said to be the most adopted controllers in industrial settings due to its relative ease of use and the satisfactory performance in different processes. A PID controller consists of the 3 different control actions, the proportional part, the integral part, and the derivative part. PID controller has to be tuned to provide the best optimised performance for a mechanical control system either by traditional rule-based tuning methods or automated tuning.

2. Mathematical model, Simulink model, and parameters

2.1 Mathematical Model

2.1.1 Robotic leg. Lagrange equation is used to derive the equations of the model and the equation of kinetic and potential energy are substituted in. Torque of Motor 1, \( T_1 \) and Torque of Motor 2, \( T_2 \) will be

\[
T_1 = A\dot{\theta}_1 + B\dot{\theta}_2 - D\dot{\theta}_1^2 - 2D\dot{\theta}_1\dot{\theta}_2 + G_1
\]

\[
T_2 = C\dot{\theta}_2 - B\dot{\theta}_1 + D\dot{\theta}_2^2 + G_2
\]

where:

\[
A = m_l l_1^2 + I_1 + m_2\left(l_2^2 + l_{12}^2 + 2l_1 l_2 \cos \theta_2\right) + I_2
\]

\[
B = m_2\left(l_1^2 + l_{12} \cos \theta_2\right) + I_1
\]

\[
C = m_2 l_2^2 + I_2
\]

\[
D = m_2 l_{12} \sin \theta_2
\]

\[
G_1 = m_g l_1 \sin \theta_1 + m_g \left[l_1 \sin \theta_1 + l_2 \sin (\theta_1 + \theta_2)\right]
\]

\[
G_2 = m_2 g l_{12} \sin (\theta_1 + \theta_2)
\]
2.1.2 *Robotic Leg Dimension.* The average height of Malaysian male is 165 cm[6]. From a height estimation formulae list[7], the normal length of a femur, tibia, and fibula can be estimated by reverse calculation. Thus, for the height of 165cm, the length of femur is 44.01 cm, while the length for tibia and fibula is 35.76 cm and 35.85 cm respectively. The dimension are adapted as followed:

| Link            | Length [cm] | Diameter [cm] |
|-----------------|-------------|---------------|
| 1 (Femur)       | 44          | 2.2           |
| 2 (Tibia+Fibula)| 36          | 1.8           |

2.1.3 *DC motor.* From the study of previous researchers[4], the DC motor can be modelled accordingly. The output torque of DC motor is proportional to the current. The voltage of the DC motor could be obtained from differentiating the output torque with respect to time and incorporating Kirchhoff law. Combining the output torque of DC motor with the voltage of the DC motor, the equation of DC motor will be:

\[
T_m = \frac{K_m V_m}{R} - \frac{d(T_m)}{dt}L_m - K_v K_m \omega
\]

where \(T_m\) = DC motor output torque, \(K_m\) = DC motor torque sensitivity, \(V_m\) = DC motor voltage, \(L_m\) = DC motor armature’s inductance, \(K_v\) = Back-EMF constant, \(\omega\) = DC motor output angular velocity, \(R\) = DC motor armature’s resistance

2.2 *Simulink Model of Subsystems*  
The robotic leg, DC motor, and the system are modelled in Simulink according to equation (1) to (11). The overall Simulink model of the robotic leg is shown in Figure 2.

![Figure-2: Full Simulink model of the robotic leg](image)

2.3 *Parameters of simulation*  
The parameters for the simulation condition is shown in Table 2.
Table-2: Parameters of the variables for simulation

| Variable                  | Value          | Variable                  | Value          |
|---------------------------|----------------|---------------------------|----------------|
| Mass 1, m1                | 0.46832 [kg]   | Torque sensitivity of motor, K_m | 4.32 [N m/A] |
| Mass 2, m2                | 0.2565 [kg]    | Armature’s inductance of motor, L_m | 0.0025 [H]   |
| Length of link 1, l1      | 0.44 [m]       | Back-EMF constant, K_e    | 0.287 [v/rad s^-1] |
| Length of link 2, l2      | 0.36 [m]       | Armature’s resistance of motor, R | 4 [Ω]         |
| Gravitational acceleration, g | 9.81 [m/s^2] | Torque sensitivity of motor, K_m | 4.32 [N m/A] |

3. Results

3.1 Simulation Conditions

Table-3 and Table-4 shows the conditions for the simulation of the cases.

Table-3: Cases of applying constraint to one of the links

| Case | Input A                                      | Input B                                      |
|------|----------------------------------------------|----------------------------------------------|
| A    | Step input at t = 1s, Open-loop              | No controller                                |
| B    | Step input at t = 1s, Closed-loop            | PID controller                               |
| C    | Step input at t = 1s, Open-loop              | No controller                                |
| D    | Step input at t = 1s, Closed-loop            | PID controller                               |
| E    | Step input at t = 1s, Closed-loop            | PID controller                               |
| F    | Step input at t = 1s, Closed-loop            | No controller                                |
| G    | Step input at t = 1s, Closed-loop            | No controller                                |
| H    | Step input at t = 1s, Closed-loop            | PID controller                               |
| I    | Step input at t = 1s, Closed-loop            | No controller                                |
| J    | Step input at t = 1s, Closed-loop            | PID controller                               |
| K    | Step input at t = 1s, Closed-loop            | No controller                                |
| L    | Step input at t = 1s, Closed-loop            | PID controller                               |

Table-4: Cases of applying constraint to both links

| Case | Input A                                      | Input B                                      |
|------|----------------------------------------------|----------------------------------------------|
| M    | Ramp input                                   | Ramp input                                   |
| N    | Sine wave input                              | Sine wave input                              |

3.2 Simulation Results

Table-5 shows the overview of the simulated results from the cases of applying constraint to one of the links of the robotic legs with the supplied input and controlled input.

Table-5: Overview of results for Cases of applying constraint to one of the links

| Case | Link | Final position | Steady-state error |
|------|------|----------------|--------------------|
| A    | 1    | 0.5633 rad     | No comparison is available for an open-loop system |
| B    | 1    | 0.3588 rad     | Yes                |
| C    | 1    | π rad          | No                 |
| D    | 1    | 0.4555 rad     | No comparison is available for an open-loop system |
| E    | 1    | 0.3134 rad     | Yes                |
| F    | 1    | π rad          | No                 |
| G    | 2    | Rotate clockwise continuously. | No comparison is available for an open-loop system |
| H    | 2    | -1.2118 rad    | Yes                |
| I    | 2    | -π rad         | No                 |
| J    | 2    | Rotate clockwise continuously. | No comparison is available for an open-loop system |
| K    | 2    | -1.1826 rad (67.76°) | Yes                |
| L    | 2    | -π rad         | No                 |
In open-loop system, the links are uncontrolled and differ with different inputs. If the voltage supplied is large enough to overcome the gravitational acceleration, the link will keep rotating. For a closed-loop system, the link will eventually come to an equilibrium position but with steady-state error. In a closed-loop system and being controlled by PID controller, the link will eventually stop at the desired angle and no steady-state error is observed. Though there are some overshoot for the cases, but with proper tuning and refining of the PID controller, the problem can be reduced and minimised. Table-6 shows the simulated results from the cases of applying constraint to both links of the robotic legs.

It is observed that different types input will lead to different movement pattern of the robotic leg. When the desired angular displacement is having a ramp input, the link will rotate at a constant angular velocity defined by the magnitude of the slope of the ramp. As for sine wave input, the link will rotate to a peak angular displacement defined by the amplitude of the sine wave, and the frequency of the oscillation is according to the frequency of the sine wave input.

Table-6: Overview of results for Cases of applying constraint to both links

| Case | Link | Kinematics motion |
|------|------|-------------------|
| M    | 1    | Rotate with constant magnitude of angular velocity as specified by the inputs. |
|      | 2    |                        |
| N    | 1    | Rotate to peak of angular displacement according to the specified amplitude of sine wave inputs, with constant frequency as specified by the sine wave inputs |
|      | 2    |                        |

4. Conclusion
This study is a start up for future development of more functionable and workable powered-exoskeleton in Malaysia. Lagrangian equation is used to form the mathematical model of the 2-links robotic leg and the mathematical equation is successfully converted and transformed into the robotic leg model in the Simulink component in MATLAB software.

The simulation results show that with the application of the PID controller, the robotic leg is able to move as dictated by the desired parameters by controlling the voltage supplied to the DC motors of the robotic leg. It is desired that this platform can spearhead a future development on this topic, which can be very much beneficial to the generations to come, and to provide the underprivileged to undergo the normal human life just like the rest.

Acknowledgement
We gratefully acknowledge the financial support of the Office for Research, Innovation, Commercialization and Consultancy Management (ORICC) of UTHM under Geran Penyelidikan Pascasiswazah (GPPS) of Grant Vot No. U804.
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