

Research Article

Modeling and Analysis of the Control System Drive in an Artificial Limb

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Abstract

This study is an effort towards developing a linear mathematical model of the control system drive in an artificial limb using average value based approach. The design of the driving circuit is based on data's obtained from video analysis of human locomotion. The user can enter the desired angle for actuating the driving circuit through the client module and the master controller helps in driving the DC series motors. The speed of the motors is controlled by Pulse Width Modulation (PWM) technique and is achieved with the help of 555 timer and potentiometer. The video analysis of the developed driving circuit was performed in the same manner as that of video locomotion analysis of subjects. The knee angle and hip angle dynamics involved in human locomotion is modeled by calculating the base average and the variational components. The developed mathematical model will be capable in designing the artificial limb having similar driving characteristics.

Keywords: Average value based approach; PWM; 555 timer; Locomotion.

1. Introduction

In recent years there has been increasing enthusiasm to research human gait which is a complex bio-mechanical process. The gait cycle describes the motions from initial placement of the supporting heel on the ground to when the same heel contacts the ground for a second time. A very important feature of gait analysis is the exploration of the kinetics of human body segments from kinematics data or vice versa (N Jamshidi *et al*, 2009). The movements of the lower limb during walking on a level surface may be divided into alternating swing and stance phases. The stance phase begins with heel strike, when the heel strikes the ground and begins to assume the body's full weight, and ends with push-off from the forefoot. The swing phase begins after push-off, when the toes leave the ground and ends when the heel strikes the ground. The swing phase occupies approximately 40% of the walking cycle and the stance phase, 60% (K Tong *et al*, 1999). The four joints with the most movement during walking are hip, knee, ankle and big toe (Fig.1). There are many human locomotion analyzing techniques such as gyroscopes, opto electronic systems, inertial systems, EEG, EMG, video cameras, etc. The use of video recording for locomotion analysis can be performed with or without markers on the subject (WA David, 1990). Two-dimensional analysis requires only one camera positioned perpendicular to the plane of

movement of interest, but the results can be affected by out-of-plane motion. Three-dimensional analysis looks at the movement in all planes of motion and this requires more than one camera (Clayton *et al*, 2001). To get the movement information of the leg 3D motion analysis system can be employed, using cameras the pictures are taken when people are walking and then information of the leg is obtained through image processing technology.

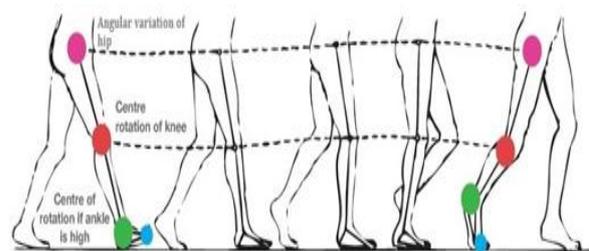


Fig. 1 Phases of human gait

Nowadays different artificial limb models have been developed to prove that a person with an above or below knee amputation can perform different types of motions. It requires power in knee and ankle joints with hydraulic units whose weight and overall dimensions would not interfere with the comfort of the prosthesis user (D Remzo *et al*, 2011). Knee-ankle-foot orthosis (KAFO) locks the knee during stance and allows free-knee motion during the swing phase of human locomotion and thereby provided complete

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stability in stance phase and unrestricted knee movements in swing phase (RK Kenton *et al*, 1996). The walking controllers have the power for upslope walking of 5°, 8°, and 10° slopes by adjusting knee flexion (AV Huseyin *et al*, 2011). The variation in forces and torques at the knee, at the hip and ankle during walking can be analyzed to study the dynamic characteristics at different plantar interfaces during human locomotion (ZH Hao *et al*, 2005). A biologically inspired motor control scheme based on sensory-motor interaction within the central nervous system was developed to control the single joint limb segment actuated by pneumatic muscles (S Eskiizmirililer *et al*, 2001).

In the field of bio-mechanics, simple mathematical models have been widely used to reveal the basic principles of human locomotion. Mathematical models were developed to simulate the stance phase of human locomotion and the proposed control methods could effectively decrease the net external mechanical work performed by legs (L Long-won *et al*, 2013). The biped model of leg is capable of dynamic walking gaits and is restricted to stop in three cases, including falling down, running and shank releasing but the optimal foot ratio is still larger than that of the human foot (W Qining *et al*, 2010). Even though these literatures cited many mathematical models for human gait, a synchronized methodical approach towards the development of control aspects and characteristics of the driving system which can assist people with afflicted human locomotion is not specifically seen. The objective of the work is to develop an empirical mathematical model for the observed knee and hip angle variation in the control system drive of the assistive device.

2. Data Acquisition

The gait analysis was conducted on 30 subjects at self-selected walking speed in barefoot for level walking along a horizontal walkway with the aid of video cameras. The tested group is women of 20 to 30 years having height 150cm to 165cm and the video analysis was conducted without placing markers on the subject. The video camera used is a 16.1 mega pixels model with 10x optical zoom and 25mm wide lens. The camera was placed perpendicular to the plane of movement. The human mean walking speed was 1.15 m/s. The video processing was done using Frameshot® software and the videos were split into different frames and the time interval chosen between each frame was 0.025s. In one second 40 frames were covered so each frame is 25ms and from each snap, knee joint and hip angle is measured using MBRuler® software.

3. The Proposed System

The suitable hardware setup was developed for amputees based on the gait analysis. The working of the driver circuit resembles the actual human locomotion. When one leg moves forward, the knees of

that leg rotate in clockwise direction whereas the hips rotate in the anti-clockwise direction and while one leg is moving, the other leg locks itself.

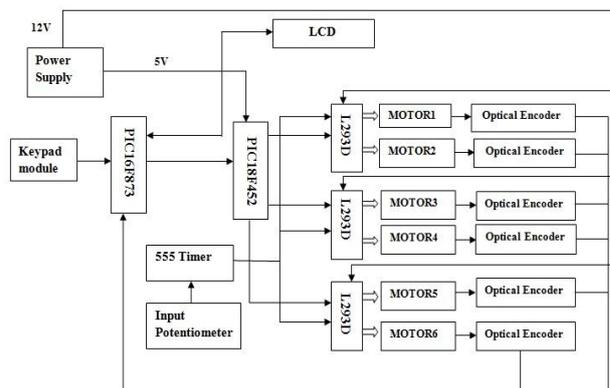


Fig. 2 Block diagram of the control setup

This movement can be achieved by using six DC series motors imitating the various movements of the knees, hips and the locking of the legs (Fig. 2). The user can enter desired input angle (0 to 99°) to PIC16F by keypad interfacing technique and thereby it sends the input pulses to PIC18F micro-controller through serial communication. The PIC18F gives the signals to the driver (L293D) which in turn drives the motors: M1 (Knee) clockwise, M2 (Hip) anticlockwise and M3 (Knee) is LOCKED, M6 (Knee) is UNLOCKED followed by M4 (Knee) clockwise, M5 (Hip) anticlockwise and vice-versa. All LCDs will then display corresponding motor direction (clockwise / anticlockwise) and motor state (Locked/ Unlocked). Wheel encoders are attached to the shaft of each DC series motors and the feedback pulses corresponding to rotation of motors are attained with the help of optical encoders. The PIC16F microcontroller is programmed in such a manner that, based on the error obtained it will proportionally increase or decrease the output. The modified pulses are then sent to the Master controller for driving the motors. The speed of the motors is controlled by Pulse Width Modulation (PWM) technique and is achieved with the help of 555 timer and potentiometer. The microcontroller programming was done in MPLAB® and the system was simulated using Proteus® software.

PIC18F452 micro-controller which has a clock frequency of 40MHz acts as the master controller and is used to control and drive the 6 DC series motors of 12V, 10Nm torque each for locking and unlocking the knees and hip for both legs involved in the human locomotion. PIC16F873 micro-controller integrated along with the keypad acts as the client module and has an operating voltage of 2V to 5.5V. The wheel encoders are fixed to the shaft of the DC motor and have number of transparent slots within its design (30 slots in our design). As the disc rotates with the speed of the shaft, each slot passes by the sensor in turn producing an output pulse representing logic "1" or logic "0". In this work we have used MOC7811 infrared based optical

Table 1: Motor states during human gait

Time	States					
	M1	M2	M3	M4	M5	M6
0	OFF	OFF	OFF	OFF	OFF	OFF
100msec	ON +ve	ON -ve	OFF	OFF	OFF	OFF
200msec	ON +ve	ON -ve	ON +ve	OFF	OFF	ON -ve
300msec	ON +ve	ON -ve	ON +ve	ON +ve	ON -ve	ON -ve
400msec	ON +ve	ON -ve	ON +ve	ON +ve	ON -ve	ON -ve
500msec	ON +ve	ON -ve	ON +ve	ON +ve	ON -ve	ON -ve
600msec	ON +ve	ON -ve	ON +ve	ON +ve	ON -ve	ON -ve
700msec	ON -ve	ON +ve	ON +ve	ON +ve	ON -ve	ON -ve
800msec	ON -ve	ON +ve	ON -ve	ON +ve	ON -ve	ON +ve
900msec	ON -ve	ON +ve	ON -ve	ON -ve	ON +ve	ON +ve
1000msec	ON -ve	ON +ve	ON -ve	ON -ve	ON +ve	ON +ve
1100msec	ON -ve	ON +ve	ON -ve	ON -ve	ON +ve	ON +ve
1200msec	OFF	OFF	ON -ve	ON -ve	ON +ve	ON +ve
1300msec	OFF	OFF	OFF	ON -ve	ON +ve	OFF
1400msec	OFF	OFF	OFF	OFF	OFF	OFF

sensor which contains an IR emitter and receiver pair mounted facing each other. The speed control of the motors is attained with the help of input potentiometer and 555 timer (Fig. 3). In the Table below the motor states are presented where M1, M2, M3 are knee motor, hip motor and locking motor of the right leg and M4, M5, M6 are knee motor, hip motor and locking motor of the left leg. Here ON+ve stands for motor rotation in clockwise direction and ON-ve stands for motor rotation in anticlockwise direction.

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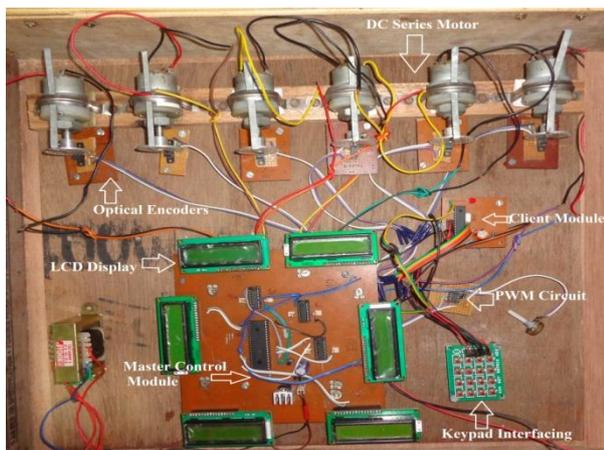


Fig. 3 Entire setup of control system drive

PIC18F452 micro-controller which has a clock frequency of 40MHz acts as the master controller and is used to control and drive the 6 DC series motors of 12V, 10Nm torque each for locking and unlocking the knees and hip for both legs involved in the human locomotion. PIC16F873 micro-controller integrated along with the keypad acts as the client module and has an operating voltage of 2V to 5.5V. The wheel encoders are fixed to the shaft of the DC motor and have number of transparent slots within its design (30 slots in our design). As the disc rotates with the speed of the shaft, each slot passes by the sensor in turn producing an output pulse representing logic "1" or logic "0". In this work we have used MOC7811 infrared based optical sensor which contains an IR emitter and receiver pair

4. Mathematical Modeling of the Control System Drive

For modeling the dynamics involved in human gait, average value based approach can be employed in an effective manner (M G Pandya *et al*, 1988). The video locomotion analysis of the developed hardware was performed in the same manner as that of video locomotion analysis of subjects. The analysis was performed by entering different angles in the hardware setup and the actual angular variation of the motor for different time intervals were measured. The locking and unlocking motors were not considered for developing the mathematical model and the knee and hip motors (M1, M2) of right leg and (M4, M5) of left leg were taken into account.

4.1 Steps Involved in Modeling

1. In this work video analysis of the control system drive was conducted for 20°, 30° and 40° and 5 gait cycles were considered for analysis.
2. The videos were split into different frames of equal duration (0.025 sec) each for Knee motor of right leg (M1), Hip Motor of right leg (M2), Knee motor of left leg (M4) and Hip Motor of left leg (M5).
3. The average value based modeling is done as per the following equation

$$C_1 (B_{avg}) + C_2 (\delta B_{avg}) + C_3 (\delta^2 B_{avg}) = r\theta_{avg} \tag{1}$$

Here $r\theta_{avg}$ is the angular distance covered by the wheel encoder and $r = 0.019m$.

The circumference of the wheel encoder is 12cm.

Table 2: Base values and variational terms

<i>Angle Entered : 20°</i>					
M1 (Knee Motor of right leg)			M2 (Hip Motor of right leg)		
Variational Terms		$r\theta_{avg}$	Variational Terms		$r\theta_{avg}$
B_{avg}	-0.083	0.1834	B_{avg}	-0.0834	0.1842
δB_{avg}	-0.0282		δB_{avg}	-0.0272	
$\delta^2 B_{avg}$	-0.089		$\delta^2 B_{avg}$	-0.0931	
B_{11avg}	0.0912	0.1506	B_{11avg}	0.0913	0.1512
δB_{11avg}	0.0533		δB_{11avg}	0.0523	
$\delta^2 B_{11avg}$	-0.0051		$\delta^2 B_{11avg}$	-0.0031	
B_{111avg}	0.1325	0.1995	B_{111avg}	0.1356	0.1998
δB_{111avg}	-0.0837		δB_{111avg}	-0.0837	
$\delta^2 B_{111avg}$	-0.0484		$\delta^2 B_{111avg}$	-0.0471	
M4 (Knee Motor of left leg)			M5 (Hip Motor of left leg)		
Variational Terms		$r\theta_{avg}$	Variational Terms		$r\theta_{avg}$
B_{avg}	0.0344	0.1997	B_{avg}	0.0343	0.1992
δB_{avg}	-0.0077		δB_{avg}	-0.0077	
$\delta^2 B_{avg}$	-0.0654		$\delta^2 B_{avg}$	-0.0646	
B_{11avg}	-0.0462	0.1652	B_{11avg}	-0.0461	0.1648
δB_{11avg}	0.0305		δB_{11avg}	0.0307	
$\delta^2 B_{11avg}$	0.0161		$\delta^2 B_{11avg}$	0.0162	
B_{111avg}	0.0279	0.2094	B_{111avg}	0.0285	0.2095
δB_{111avg}	0.0734		δB_{111avg}	0.0749	
$\delta^2 B_{111avg}$	0.0635		$\delta^2 B_{111avg}$	0.0629	

4.1.1 Procedure for Finding the Variational Terms

The output is a combination of a base average value and infinite number of hierarchically considered variational terms. These variational terms must be multiplied by the factors C_1, C_2, C_3 ..etc to attain the effect of variable structure of the input-output relationship. The variation of the system parameters is due to the structural changes occurring in the system and it is one of the main reasons for the reflected output dynamics.

(1) Procedure used to calculate first variational term (δB_{avg}):

- The whole dataset is splitted into viable number of primary sectors and its individual average is calculated.
- The primary sector is splitted into viable number of secondary sectors and its individual average is calculated.
- The difference between primary averages and secondary averages is computed.
- The average of the difference between primary and secondary sector averages is determined and this is the first variational term.

(2) Procedure used to calculate second variational term ($\delta^2 B_{avg}$):

- The secondary sectors are splitted into feasible number of tertiary sectors and its individual average is calculated.

- The difference between secondary averages and tertiary averages is computed.
 - The average of the difference between secondary and tertiary sector averages is determined and this is the second variational term.
4. The equations are formulated and the unknown coefficients (C_1, C_2 and C_3) were solved.

5. Results and Discussion

The average value based approach is a simple empirical modeling technique which helps to establish an ideal relationship desirable for the characteristics of the drive and that of natural human locomotion. M1 and M2 (Knee Motor & Hip Motor of right leg) operates from time periods of 0.025 s to 1.15 s and it will be idle till 1.425s again (it will start operating after 1.425s). M4 and M5 (Knee & Hip Motor of left leg) operates from 0.3 s to 1.35 s and it will be idle till 1.6s (again it will start operating after 1.6s). So we were able to observe that the motors were working for duration of 1.05s and were idle for 0.25s for 20°, 30° and 40°, respectively.

The developed mathematical model is validated by comparing the actual dynamics through equations 2 and 7 with the experimentally detected values from the real system. The optimum relation and the best set of numerical coefficients for the set of measured data is found using MATLAB®. The time taken to complete one gait cycle was 1400ms and the average value of the angular distance covered by wheel encoder is in the

Table 3: Calculated coefficients of the control system drive

Angle Entered	M1 (Knee motor of right leg)			M2 (Hip motor of right leg)			M4 (Knee motor of left leg)			M5 (Hip motor of left leg)		
	C ₁	C ₂	C ₃	C ₁	C ₂	C ₃	C ₁	C ₂	C ₃	C ₁	C ₂	C ₃
20°	0.928	0.932	-3.215	0.991	0.990	-3.153	-0.669	6.675	-4.131	-0.711	6.621	-4.211
30°	1.904	-0.204	-3.251	1.916	-0.275	-3.225	-0.466	4.717	-3.173	-0.594	4.689	-3.262
40°	0.769	1.585	-4.599	0.560	0.739	-3.691	-1.341	5.536	-5.295	-1.316	5.192	-4.854

range of 0.15m to 0.29m. The range of coefficients calculated is in the range of -5 to 6 while conducting the motion and dynamic analysis of various angles upto 99°. The equations formulated for M1 and M2 and the variational terms calculated (Table 2) while entering 20° is shown in equations 2-7. The equations were formed for 30° and 40° in the same manner and the coefficients were also calculated separately for knee and hip motor of both legs (Table 3).

The equations formulated for M1 (knee motor of right leg) while entering 20° for determining the coefficients (C₁, C₂, C₃) is

$$-0.083 C_1 - 0.028 C_2 - 0.089 C_3 = 0.1834 \tag{2}$$

$$0.091 C_1 + 0.053 C_2 - 0.005 C_3 = 0.1506 \tag{3}$$

$$0.132 C_1 - 0.083 C_2 - 0.048 C_3 = 0.1995 \tag{4}$$

The equations formulated for M2 (hip motor of right leg) while entering 20° for determining the coefficients (C₁, C₂, C₃) is

$$-0.083 C_1 - 0.027 C_2 - 0.093 C_3 = 0.1842 \tag{5}$$

$$0.091 C_1 + 0.052 C_2 - 0.003 C_3 = 0.1512 \tag{6}$$

$$0.135 C_1 - 0.083 C_2 - 0.047 C_3 = 0.1998 \tag{7}$$

The first 5 gait cycles were considered for determining the coefficients of knee and hip dynamics. Considering the motor M1 (knee motor of right leg) while entering 20°, the coefficients obtained are C₁=0.928, C₂=0.932 and C₃= -3.215. Then substituting the coefficients in equation (2) we get

$$-0.928 B_{avg} - 0.932 \delta B_{avg} + 3.215 \delta^2 B_{avg} = 0.1834 \tag{8}$$

Using the average value based approach the accuracy of the developed equation is checked with the remaining set of gait cycles and new coefficients were calculated. For the next gait cycle B_{avg} is 0.0575, δB_{avg} is -0.0411 and δ²B_{avg} is 0.0617. Then substituting B_{avg}, δB_{avg} and δ²B_{avg} in equation (8) it becomes

$$(-0.928 * 0.0575) - (0.932 * -0.0411) + (3.215 * 0.0617) = 0.1834 \tag{9}$$

The new coefficients obtained are in the range which was estimated earlier and this illustrates the novelty of the model. The dynamic characteristics of the developed system matches with the human locomotion and this developed model using average value can be

used for predicting the dynamics in continuous time varying systems. The limitations of the proposed method are the following.

- (i) There is no specific technique for identifying the sectors and this division is done by an approximation.
- (ii) The length of the sectors considered in each segment is also fixed arbitrarily.
- (iii) The approximation is done by assuming that the system is linear and many aspects regarding the dynamic characteristics of human gait are yet to be considered.

Conclusion

The average value based approach is used efficiently in developing the mathematical model of the driving mechanism in an artificial limb. The data regarding the angular variation of knee and hip for normal level walking is captured with the aid of cameras with a reasonable resolution. The control system drive was designed based on the data's obtained from video analysis and it is supportive to conduct the motion and dynamic analysis for various postures through keypad interfacing technique. The characteristics of the driving system such as locking and unlocking of the knees as well as the synchronized and sequential functioning of the knee and the hips have been examined. The knee and hip angle distinction in human gait is modeled from the data acquired by means of calculating the base value and the variational components and is validated successfully. A future work is aimed in implementing controllers to enhance the performance of the system and to interface the existing hardware with PC so that the hip and knee angle variation can be monitored in real time.

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