JOURNAL OF THEORETICAL
AND APPLIED MECHANICS
**58**, 4, pp. 841-851, Warsaw 2020
DOI: 10.15632/jtam-pl/125505

# COMPARISON OF Z-N AND PSO BASED TUNING METHODS IN THE CONTROL STRATEGY OF PROSTHETIC LIMBS APPLICATION

Ma Ashmi
*Electrical and Electronics Department, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, Tamilnadu, India*
*e-mail: ashmi_mi@yahoo.co.in*

M. Anila
*Electronics and Instrumentation Department, Federal Institute of Science And Technology, Ernakulam, Kerala, India*

K.S. Sivanandan
*Biomedical Engineering Department, Manipal Institute of Technology, Karnataka, India*

S. Jayaraj
*Mechanical Engineering Department, National Institute of Technology Calicut, Kerala, India*

The aim of the study is to compare Ziegler-Nichols (Z-N) and Particle Swarm Optimization (PSO) based tuning methods for controller tuning in the driving mechanism of prosthetic limbs. By adopting suitable control strategies like P, PI and PID in the driving system, the positioning of knee and hip joints can be attained in the ideal time of 1.4s for completing one locomotion cycle. The gain constants ($K_P$, $K_I$, and $K_D$) of the controllers were tuned manually and also using Z-N and PSO; thereby appropriate constants were determined so that the joints could be moved to the desired position. The performance of P, PI, and PID controllers were compared and PID was identified as the ideal control strategy which exhibited least error and good stability. It was observed that the conventional Z-N method produced a big overshoot, and so a modern approach called PSO was employed to enhance its capability. The PSO based PID controller optimization resulted in less overshoot as well as it helped in optimizing the gain constants so as to improve the stability of the system when compared to the classical method.

*Keywords:* Z-N, PSO, PID, DC motors, ATmega328 microcontrollers

## 1. Introduction

The development of the limb prosthesis attained tremendous improvement in the medical and biomechanics fields. Artificial walking aids compensate physical limitations experienced by handicapped persons and help them to reduce their dependence on others. Moreover, these devices can provide assistance to aged persons to overcome their physical limitations, which arise naturally in the old age. Any supporting device designed should help the users to do their routine activities in a safe manner and also must have provisions for knee locking during the stance phase while allowing free knee extension in the swing phase. The above knee (AK) prostheses should be designed in such a way that it supports the knee during stance phase and provides damping to the knee during its swing phase; but most of them do not provide these features.

Kaufman *et al.* (1996) developed knee-ankle-foot orthosis (KAFO), which unlocked and locked the knee during swing and stance phases of human gait. The major issue faced with KAFO was unrestricted knee movements in the swing phase. Yakimovich *et al.* (2009), Irby (1994) and Malcolm *et al.* (1980) developed an improved version of KAFO by providing an articulated knee joint system that reduced metabolic energy requirements during human gait.

Many of the prosthetic limbs suggested in literature like Otto Bock Free Walk, Becker Orthopedic 9001 E-knee, Horton Stance Control Orthosis, Fillauer swing phase lock lack stability and are costly, bulky and lock the knee only in extension. The challenge associated with gait analysis and control is the uncertainty in tracking the human locomotion within a gait cycle.

In a typical proportional-integral-derivative (PID) control strategy, the controller compares the values of desired input and measured output. Mamdani's fuzzy logic methodology proposed by Moosavi *et al.* (2013) was employed to solve non-linear uncertainties of a second order system. A modified version of a PID hybrid fuzzy controller was implemented, which partially controlled the non-linear dynamics of a robot manipulator. For control of parallel robotic manipulators, ANFIS-PID tuning provided less settling time, low steady state error and a good response (Al-Saedi *et al.*, 2013). The accurate positioning of the arm was attained using PID controllers which replaced the fuzzy logic controller providing less error (Lee and Gonzalez, 2008). The Ziegler-Nichols (Z-N) method was used to tune the transfer function of the limb in both paraplegic and fatigue conditions (Schröder *et al.*, 2003) where a higher gain constant resulted in a better response. Further, particle swarm optimization (PSO) tuning was added for improving the efficiency of the limb, and this technique proved to be more effective than the Z-N method (Neogi *et al.*, 2011).

The movement of the limb was achieved by implementing controllers in the driving mechanism. The gain constants in the controller should be tuned to improve the accurate positioning of the limb. The actuator in an orthotic limb was controlled using PID strategy and different tuning methods (Internal Model Control (IMC), Closed Loop Ziegler-Nichols (CLZN), Open Loop Ziegler-Nichols (OLZN) and Tyreus-Luyben (T-L) were tested (Dutta *et al.*, 2014). The popularity of the IMC method was due to its favorable framework for determining PID parameters and also it considered the system uncertainty. The time consuming closed loop tuning method, CLZN gave a rough estimation about the basic parameters of the plant. The OLZN tuning method proved to be effective for a system with time-delay and first-order characteristics. T-L method, a modified form of the Z-N tuning technique depended on the ultimate gain (Ku) and oscillation period (Pu). The IMC method proved to be efficient due to its good response, less settling time and overshoot in completion of a gait cycle.

An optimal PID controller for a DC motor speed control based on the Z-N and modified Z-N method was proposed (Meshram and Kanojiya, 2012). The two methods were compared on the basis of the output response, minimum rise time, minimum overshoot and minimum settling time. The results implied that the performance of the PID controller using a modified Z-N technique was better than the traditional Z-N. The performance analysis of a DC motor with a PID controller was attained with the parameters such as maximum overshoot, settling time and rise time. The PID controller gave the best response among all other controllers (Dubey and Srivastava, 2013). Overall, a well tuned PI/PID controller indicated a good system response in terms of robustness and predictability. The peak overshoot was reduced by a fuzzy logic controller (FLC) and it required no tuning. However, the response of FLC was sluggish and it needed to be optimized (Rajanwal *et al.*, 2014).

The conventional tuning techniques like Z-N produced overshoot and so PSO was employed to enhance the capability. The classical method gave a set of desired gain constants, and to optimize the best solution PSO was carried out (Johnson, 1993). Also, a substantial improvement in the time domain specification in terms of lesser rise time, peak time, settling time as well as overshoot was proved. The PSO can be applied to any higher order system and proved to be more effective than the existing tuning techniques (Solihin *et al.*, 2011). Also, the PSO approach is well-known to solve large scale nonlinear optimization problems in many areas of biomedical research. A stable, robust and controlled system with a high quality solution and better computational efficiency was obtained by fast tuning of the PID controller using PSO. By changing the gain constants ($K_P$, $K_I$ and $K_D$), the response of the system was improved, resulting in reduction of the rise time, settling time and peak overshoot (Giriraj Kumar *et al.*, 2010).

The recent research works addressed in literature utilized the PSO technique for tuning controllers. In this study, the gait of healthy subjects was analyzed for the development of a driving mechanism in an assistive limb. The PID controller was incorporated in the driving system to achieve accurate positioning of the knee and hip joints. The parameters of the controller were determined by a modern heuristic approach named PSO, and its performance was compared with manual tuning and Z-N tuning. To obtain the optimal solution in PSO, a fitness function was designed for the performance evaluation of different combination of PID parameters. This optimization technique resulted in less overshoot and better stability. The optimal gain constants are helpful in designing a driving mechanism for people with lesser afflictions.

## 2. Methodology

### 2.1. Data collection

The gait analysis using video camera was conducted on 30 healthy subjects along a horizontal track of length, 50 m. The subjects were made to move normally (neither slow nor fast) with a speed of 1.15 m/s. This average walking speed for steady gait was used by other researchers as well (Kutilek *et al.*, 2013). The video analysis was conducted on subjects of 20 to 30 years with average height of 158 cm. The videos were captured with a 16.1 mega pixel camera with 10x optical zoom. The camera was positioned perpendicularly to the plane in which the subjects moved. The videos were processed using Frameshot® software, and the time interval selected between each frame was 0.05 s. The angle measurement of the knee and hip joints were performed using MB Ruler® software. The knee joint was locked and unlocked in 400 ms and 1000 ms, respectively. It was observed that one gait cycle was completed in 1.4 s which covered 28 frames (Ashmi *et al.*, 2016b).

### 2.2. Experimental setup

The mechanical structure of the limb is driven by suitable actuators and drivers, properly synchronized, sequentialized and controlled. For successful working of the assistive limb, a proper driving circuit is required. The recorded joint angle data obtained from the video analysis of human locomotion was used as the reference for fixing the input to the driving system. The driving system to mimic human locomotion is achieved by controlling 6 DC motors for locking and unlocking the knee and rotation of the hips. As one leg starts its motion, the knee rotates in the clockwise direction whereas the hip in counter-clockwise direction. While one leg is moving, the other leg locks itself so as to balance the person. The driving circuit is implemented using Mitsumi DC motors with encoder (6 No.s), ATmega328 microcontrollers (4 No.s), motor drivers, LCD and keypad. The DC motors used in this study operates on 10-32 V DC, load current of 3 A and 4000 rpm at no load. ATmega328 is an 8-bit microcontroller with operating frequency of 20 MHz and operating voltage of 1.8-5.5 V.

The system designed in this work is presented in Fig. 1. It can be executed in either PC or keypad mode. There is a master control module (ATmega328) and three slave control modules which are interconnected by $I^2C$ communication. The user can enter the desired setpoint and the gain constants of the controller through keypad or in real time. The control signals received at the motor driver (L293D) drives the DC motors to the respective position of knee and hip joints. The output pulses corresponding to motor rotation are sensed by the inbuilt encoder in the DC motor. If there is a difference between the desired and actual position, the error signal is generated and passed to the microcontroller (respective Slave module) which takes the appropriate control action (P/PI/PID) so as to minimize the error and drive the motors to the desired position. The knee and hip joint data is captured in real-time using VB 6®. The detailed explanation of the control modules and the components used are elaborated in the previous research work (Ashmi *et al.*, 2016a).

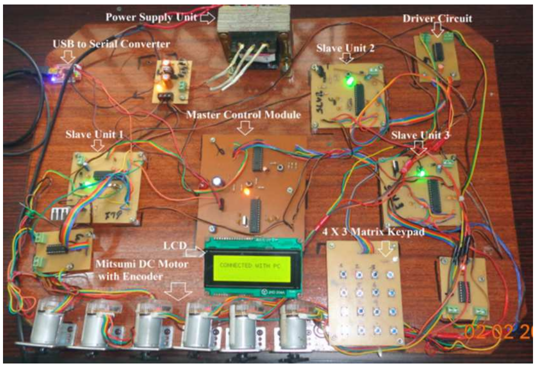


Fig. 1. Setup of the closed loop control system drive

As the gait cycle begins, the knee and hip motor ($M_1$, $M_2$) of the right leg operates simultaneously followed by the locking and unlocking motors of both legs ($M_3$, $M_6$), and then the knee and hip motor ($M_4$, $M_5$) of the left leg operates concurrently. So in the driving system, for an angular input of 45°, each of the three operations mentioned above should be completed in 0.46 s (setpoint). The average time taken for the completion of gait is 1.4 s (Ashmi *et al.*, 2016b). During human gait, the locking of knee/hip angle corresponds to 180° (stance phase) and any other joint angle results in the unlocking of the motors (swing phase). The designed circuit is a replica of healthy human gait and the aim of the locking and unlocking motors is to balance the motion of the subject. Human gait is noncyclical and it is not necessary that the right leg movement should precede the left leg. The operational characteristics of the driving system explained above can be modified as per the user's decision.

Under no load condition, the gain constants were tuned to achieve the optimum response. Different control strategies (P, PI, PD and PID) were tested, and PID controller got the best response when $K_P = K_I = 0.5$ and $K_D = 0.05$ with the least settling time (0.45 s). In Table 1, the settling time $T_s$ and the desired position of the motor ($\theta_{RK}$ – right knee angle, $\theta_{RH}$ – right hip angle, $\theta_{LK}$ – left knee angle and $\theta_{LH}$ – left hip angle) to reach the setpoint is stated and the best responses obtained for different controllers are highlighted. The angular velocity estimated for different controllers was found to be in the range of 124.813°/s and 162.570°/s for the best response.

### 2.3. Estimation of transfer function

The modeling of the DC motor is performed using the basic equivalent circuit with armature resistance $R_a$, armature inductance $L_a$ and voltage source $V(t)$. The motor transfer function is given as

$$\frac{\theta_m(s)}{V_a(s)} = \frac{\frac{K_t}{R_a B}}{s[(1+sT_a)(1+sT_m)+K_t K_b]} \tag{2.1}$$

The electrical time constant, $T_a = L_a/R_a$ and mechanical time constant $T_m = J/B$. The armature resistance and inductance is determined using an RCL meter and is found to be 4 Ω and 11.67 mH, respectively. The torque constant $K_t$ and back-emf constant $K_b$ are 26.67 Nm/A and 1.26 V/rad/s. The rotor inertia $J$ and viscous-friction coefficient $B$ are found to be 0.005823 kg m$^2$ and 0.006158 Nm/rad/s.

Substituting the motor parameters into equation (2.1), the transfer function of the open loop system becomes

$$\frac{\theta_m(s)}{V_a(s)} = \frac{1083}{0.002918s^3 + 1.002971s^2 + 34.6042s} \tag{2.2}$$

The closed loop transfer function of the system by applying PID algorithm is

$$\frac{C(s)}{R(s)} = \frac{1083K_Ds^2 + 1083K_Ps + 1083K_I}{0.002918s^4 + 1.002971s^3 + (1083K_D + 34.6042)s^2 + 1083K_Ps + 1083K_I} \tag{2.3}$$

This transfer function was used in Matlab® for Z-N and PSO tuning.

**Table 1.** Response obtained by manual tuning of gain constants for both legs

| SETPOINT: 45° | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Right leg | | | | Left leg | | | |
| $K_P$ | $K_I$ | $K_D$ | $T_s$ [s] | $\theta_{RK}$ [deg] | $T_s$ [s] | $\theta_{RH}$ [deg] | $T_s$ [s] | $\theta_{LK}$ [deg] | $T_s$ [s] | $\theta_{LH}$ [deg] |
| 10 | 0 | 0 | 0.555 | 41.4 | 0.51 | 44.28 | 0.555 | 42.3 | 0.525 | 44.12 |
| 1 | 0 | 0 | 0.6 | 32.3 | 0.615 | 35.4 | 0.585 | 31.76 | 0.63 | 34.56 |
| 0.5 | 0.5 | 0 | 0.525 | 42.12 | 0.525 | 41.62 | 0.54 | 42.08 | 0.525 | 41.5 |
| 0.5 | 0.05 | 0 | 0.48 | 42.23 | 0.48 | 43.45 | 0.495 | 42.35 | 0.465 | 43.13 |
| 0.5 | 0.5 | 0.05 | 0.45 | 43.74 | 0.45 | 42.12 | 0.45 | 43.52 | 0.465 | 43.27 |
| 0.5 | 0.5 | 1 | 0.51 | 50.25 | 0.525 | 52.32 | 0.54 | 51.75 | 0.555 | 50.65 |

### 2.4. Ziegler-Nichols tuning

Ziegler and Nichols proposed a heuristic method for tuning the PID controller. Basically, this approach improves the system response, steady state error and decreases overshoot of the system (Johnson, 1993). The drawback of the Z-N method is that, sometimes, it drives the system to instability. The tuning is performed as follows.

1. Firstly, the integral and derivative actions are reduced to their minimum effect.
2. Gradually $K_P$ is increased until the system response oscillates with a constant amplitude and that gain value is recorded as $K_u$ (ultimate gain).
3. Then the oscillation period is calculated and recorded as $P_u$ (ultimate period).
4. Finally, the parameters are tuned as per the values in Table 2 where $K_I = K_P/\tau_I$ and $K_D = K_P\tau_D$, where $\tau_I$, $\tau_D$ are time constants.

**Table 2.** Ziegler-Nichols parameters

| Type of controller | $K_P$ | $\tau_I$ | $\tau_D$ |
|---|---|---|---|
| P | $0.5K_u$ | – | – |
| PI | $0.45K_u$ | $P_u/1.2$ | – |
| PID | $0.6K_u$ | $P_u/2$ | $P_u/8$ |

### 2.5. PSO-based tuning of PID controller

Particle swarm optimization (PSO) is a population based computational approach for solving nonlinear problems. PSO algorithm functions with a swarm of particles moving in search space. Each particle movement is influenced by its local best known position which directs the movement of swarm towards the best solutions. The process is repeated, and by doing so, it is expected that a suitable solution will steadily be discovered (Solihin *et al.*, 2011; Mančić *et al.*, 2016). To obtain the best solution in PSO, a fitness function should be defined. During the optimization, the fitness of the best particle progresses with time and tends to diminish towards the end. Ultimately, stagnation of the process leads to detection of the global optimum (Giriraj Kumar *et al.*, 2010; Madić and Radovanović, 2014). A scale factor is introduced along with other parameters of the fitness function to obtain the best point where it reaches the minimal value. The chosen fitness function is

$$F_{PSO} = [1 - \exp(-\beta)](M_p + E_{ss}) + \exp(-\beta)(T_s - T_r) \tag{2.4}$$

where $F_{PSO}$ is the fitness function, $M_p$ is the peak overshoot, $T_s$ is the settling time, $T_r$ is the rise time, $\beta$ is the scaling factor and $E_{ss}$ is the steady state error.

The scaling factor is $\beta = 1$ in this PSO design. A fitness function which involves PID parameters as input values and which returns the fitness value as its output is defined in Matlab® library.

The fitness function is described as

$$\text{Function } [F] = \text{ fitness } (K_P, K_I, K_D)$$

The above defined fitness function has been used for evaluating performance of various combinations of PID parameters in the search space.

## 3. Results

### 3.1. Response of Z-N tuning

The developed driving system for the assistive limb was tuned manually to obtain the optimal values of gain constants. The transfer function of the developed system (as explained in Section 2.3) was used for Z-N tuning in Matlab®. The Ziegler-Nichols tuning was performed for knee and hip angle variation from 30° to 90°. The proportional gain varies from 0.5 to 0.9; integral gain ranges from 0.44 to 0.57, whereas the derivative gain is almost negligible (0.0000527). From the analysis of human locomotion data, the knee and hip angle varies from 30° to 45°, and for easiness the tuned response of controllers for 45° alone is illustrated in Fig. 2. It was observed that the values of $K_P$, $K_I$ and $K_D$ in manual tuning fall in the range of the values obtained in Z-N tuning. The time domain specifications (peak time, rise time and settling time) were obtained as 1.11 s, 0.0729 s and 1.07 s, respectively. The Z-N tuning produced overshoot in the order of 10.8% and so PSO was carried out for better response.

### 3.2. Response of PSO tuning

For the PSO approach, the number of iterations was varied from 0 to 50 and the population of the swarm constant was fixed at 50. Performance comparison was conducted to find the initial global best position from a class of randomly initialized swarm particles. After the application of PSO algorithm, the final global best position was achieved by conducting 49 iterations. The best response was obtained in 50-th iteration as shown in Fig. 4a. The PID controller was tuned based upon the respective parameters for 50 iterations. Hence, the global best solution was selected for the test of parameters which had the minimum error. Table 3 shows the variation of gain constants for different iterations where the optimal best fitness function is highlighted, and Fig. 3 shows the simulation results for the same.

The analysis based on the number of iterations gives better results for the design of a PID controller using the PSO technique when compared to the traditional Z-N method. The results

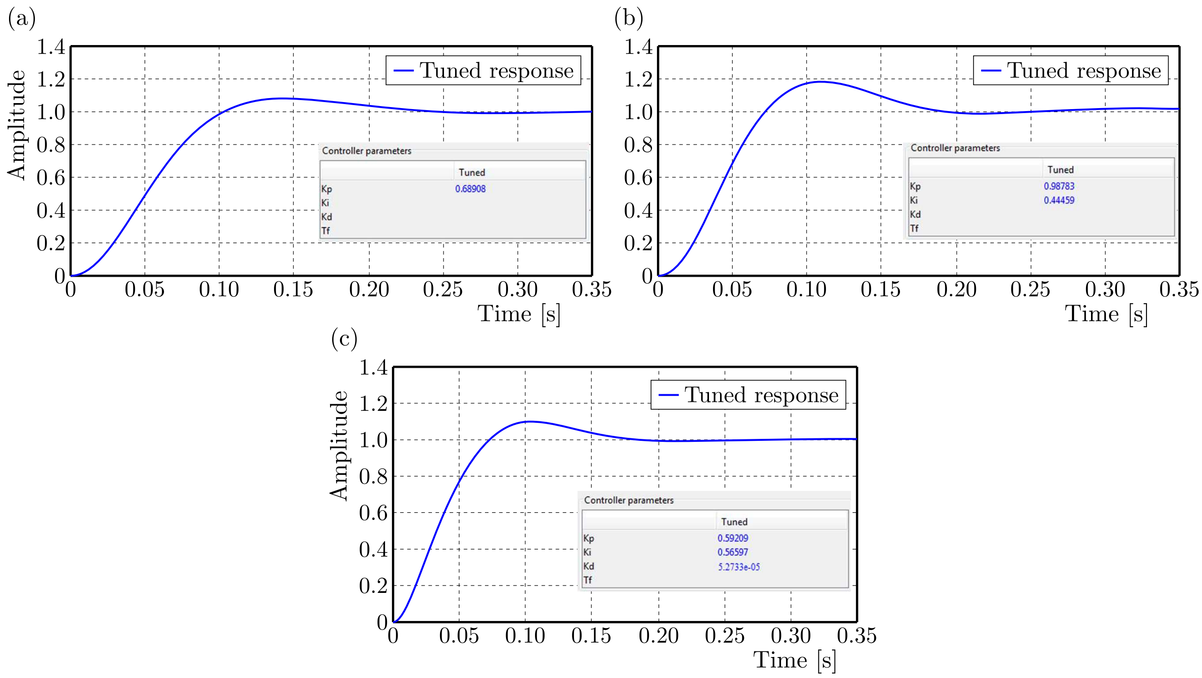


Fig. 2. The response of different controllers using Z-N tuning: (a) P controller, (b) PI controller, (c) PID controller

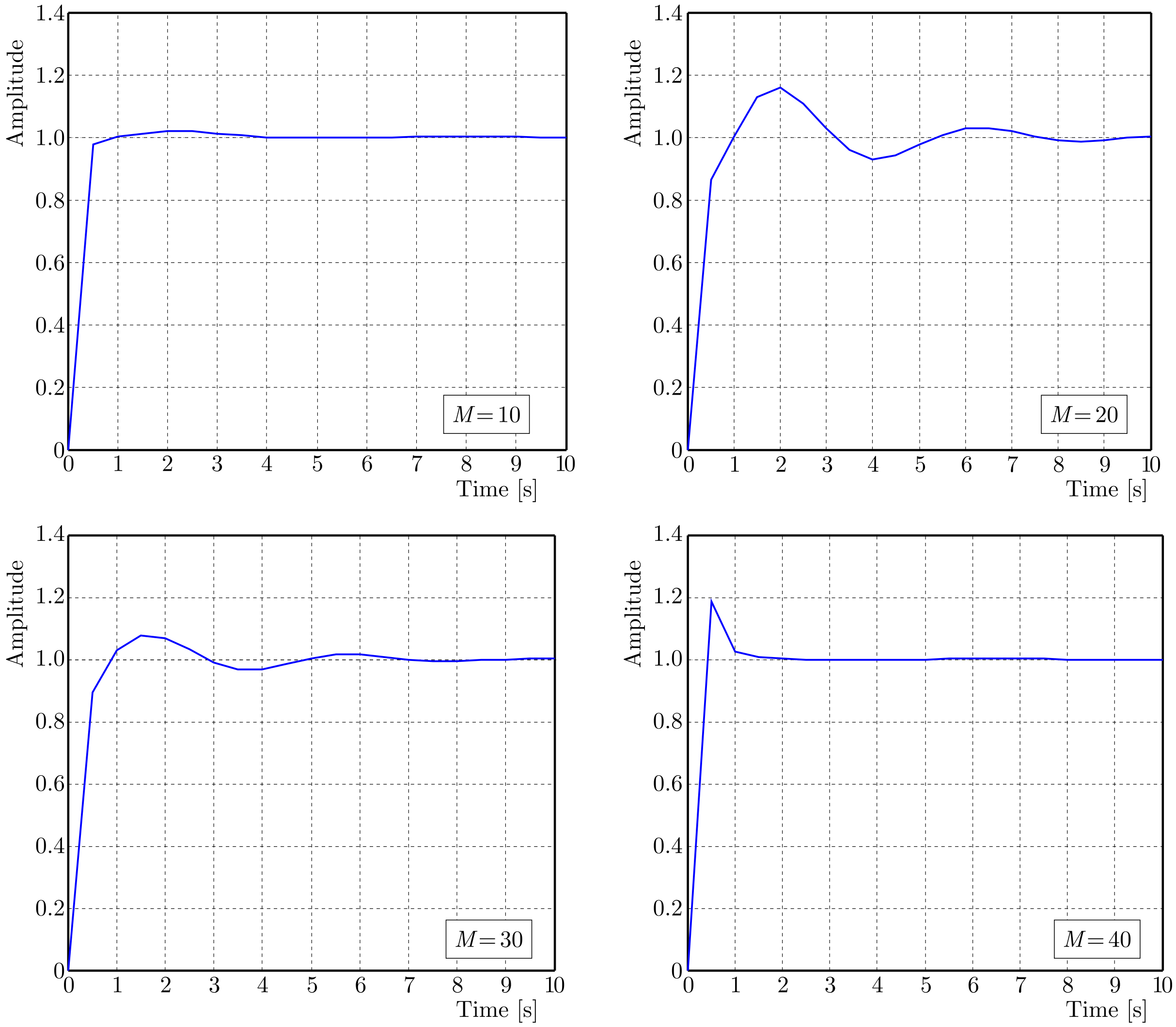


Fig. 3. Simulation results with different number of iterations

indicate improved system performance with the progressing number of iterations but after 50-th iteration the response of the system started deviating (ie. the $K_P$, $K_I$ and $K_D$ constants were not matching with the real time tuned constants and the overshoot was present too) as illustrated in Fig. 4b.

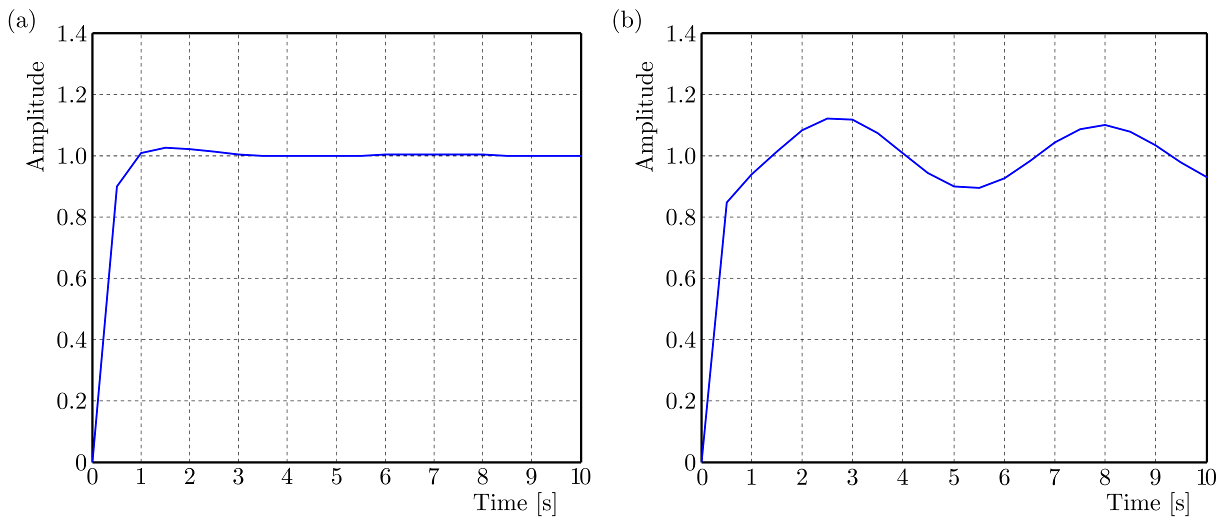


Fig. 4. (a) Best response at 50-th iteration, (b) response after 50-th iteration

**Table 3.** Results obtained for various iterations

| Number of iterations | Optimal best fitness function | Optimal best point [$K_P$,$K_I$,$K_D$] |
|---|---|---|
| 5 | 0.6716 | [0.1270, 0.6324, 0.8147] |
| 10 | 0.4299 | [0.8370, 0.4720, 0.7672] |
| 15 | 0.6743 | [0.0885, 0.9167, 0.7372] |
| 20 | 0.5397 | [0.2103, 0.6540, 0.0399] |
| 25 | 0.4499 | [0.1352, 0.2269, 0.4532] |
| 30 | 0.7133 | [0.3349, 0.6864, 0.3781] |
| 35 | 0.5533 | [0.6009, 0.1812, 0.2840] |
| 40 | 0.5081 | [0.2872, 0.2830, 0.1903] |
| 45 | 0.4574 | [0.6682, 0.2417, 0.0309] |
| 50 | 0.3374 | [0.7990, 0.1799, 0.0720] |
| 51 | 0.4583 | [0.1366, 0.5004, 0.9960] |
| 52 | 0.4951 | [0.7386, 0.6342, 0.7303] |

### 3.3. Comparison of the response obtained by Z-N and PSO tuning

The step response characteristics such as the rise time, peak time, settling time and peak overshoot were determined to compare the response obtained by Z-N and PSO tuning. The PSO results reduced overshoot of the Z-N method from 10.8% to 0.45% which indicates smooth response characteristics. The peak time and settling time in the Z-N method was 1.11 s and 1.07 s, whereas it got reduced in PSO. As shown in Table 4 the step response characteristics indicate that PSO tuning is superior to the Z-N method although conducting the iterations is time consuming in PSO. The PSO being a stochastic technique optimizes the gain constants of the PID controller so as to improve the stability.

**Table 4.** Comparison of the response obtained by Z-N and PSO

| Step response | Z-N | PSO |
|---|---|---|
| Peak time [s] | 1.11 | 0.52 |
| Peak overshoot [%] | 10.8 | 0.45 |
| Rise time [s] | 0.07 | 0.11 |
| Settling time [s] | 1.07 | 0.23 |

## 4. Discussion

The above knee (AK) prosthesis is incredibly valuable to afflicted human beings because it can help to restore some of the capabilities lost with the afflicted limb. The prosthetic limb achieve its stability only with the implementation of appropriate controllers. For the development of the prototype (driving system for the limbs) gait analysis was carried out using high resolution camera for normal walking on an average basis. The knee and hip joint locks for an angular rotation of 180° and it unlocks for any other angle. The right knee angle variation was from 180° to 126°, whereas the left knee angle varied from 180° to 132°. The hip angle variation of the right and left leg was in the range of 180° to 155°.

A driving system which imitates the characteristics of human locomotion was designed for the study of controller tuning and its performance. Then suitable control strategies (P, PI and PID) were experimented in the driving system and the appropriate gain constants were determined by manual tuning. The settling time and setpoint corresponding to the right knee were 0.6 s, 32.3° and 0.48 s, 42.23° for P and PI controllers, respectively. The PID controller gave better stability when compared with other controllers in attaining the settling time and setpoint (0.45 s and 43.74°). It was observed that tuning for larger values of $K_P$ leads the system to instability with a rapid response. Similarly, larger values of $K_I$ resulted in overshoot and it was eliminated by introducing $K_D$ which slowed down the transient response. The manual tuning used in the first phase of experimentation could not guarantee a satisfactory performance and thereby Z-N tuning was conducted. A suitable transfer function with the PID algorithm was developed for Z-N tuning. The performance of this approach was measured in terms of the rise time, peak time, settling time and overshoot. The peak time, settling time was greater and the presence of high percentage overshoot was some of the issues in this technique.

So the PSO technique was implemented to improve the system performance and determine the optimal value of gain constants. The peak time and settling time got reduced to a greater extent and the presence of overshoot was decreased from 10.8% to 0.45%. The reason for PSO improvement over Z-N is due to its ability to find the global best solution. From the results, it is evident that the system performance can be improved by conducting a larger number of iterations. The best response was obtained in the 50-th iteration with $K_P$ as 0.7990, $K_I$ as 0.1799 and $K_D$ as 0.0720. The optimal best fitness function obtained was 0.3374. The time domain specifications (rise time, peak time, and settling time) were noticed to be 0.1164, 0.7518 and 0.2835.

The drawback of this study is that the design and operation of the driving mechanism is based on the experimental data taken on an average basis. The characterization based on the individual experimental data is time consuming and hence the optimized gain constants do not match exactly with other individuals. The response of the driving system was also checked under loaded conditions and it was observed to be unreliable since it could not drive the motors to reach the setpoint effectively.

## 5. Conclusion

The artificial walking aids for afflicted human beings have immense significance considering the humanitarian aspects. It is also beyond doubt necessary to make the attempts to enhance the compensating abilities of such devices so as to overcome the limitations of the handicapped. In the previous work (Ashmi *et al.*, 2016a), an effort was taken to identify the best control strategy in the closed loop driving mechanism of the assistive limb. The optimum response was offered by PID controller which was excellent in driving the motors to the suitable position. The tuning was performed in real time using the developed prototype and also with the Z-N and PSO techniques. The system could not stabilize with Z-N tuning due to the presence of overshoot. However, to reduce this PSO was carried out, which reduced the overshoot from 10.8% to 0.45%. In the case of PSO implementation, the number of iterations varied from 5 to 50 and the system performance improved with the number of iterations. The optimal response obtained in the 50-th iteration was 0.3374. To implement real time algorithms for controlling different speeds of human gait is aimed in the future work.

*Acknowledgement*

The laboratory facilities provided by National Institute of Technology Calicut, Kerala, India for conducting this research are gratefully acknowledged.

## References

1. Al-Saedi M.I., Wu H., Handroos H., 2013, ANFIS and fuzzy tuning of PID controller for trajectory tracking of a flexible hydraulically driven parallel robot machine, *Journal of Automation and Control Engineering*, **1**, 2, 70-77
2. Ashmi M., Anila M., Jayaraj S., Sivanandan K.S., 2016a, Identification of the best control strategy for the application of prosthetic limbs, *Journal of Mechanics in Medicine and Biology*, **16**, 6, 1-17
3. Ashmi M., Tintu George T., Jayaraj S., Sivanandan K.S., 2016b, A comparative study on neural network, fuzzy logic and neuro-fuzzy technique for the human locomotion angle prediction, *Journal of Medical Imaging and Health Informatics*, **6**, 3, 650-656
4. Dubey S., Srivastava S.K., 2013, A PID controlled real time analysis of DC motor, *International Journal of Innovative Research in Computer and Communication Engineering*, **1**, 8, 1965-1973
5. Dutta R., Kumar N., Pankaj D., 2014, PID control for ambulatory gait orthosis: application of different tuning methods, *Advances in Biomedical Engineering Research*, **2**, 44-49
6. Giriraj Kumar S.M., Jayaraj D., Kishan A.R., 2010, PSO based tuning of a PID controller for a high performance drilling machine, *International Journal of Computer Applications*, **1**, 19, 12-18
7. Irby S.E., 1994, A digital logic controlled electromechanical free knee brace, MSI Thesis, San Diego State University
8. Johnson C.D., 1993, *Process Control Instrumentation Technology*, Prentice Hall PTR
9. Kaufman K.R., Irby S.E., Mathewson J.W., Wirta B.W., Sutherland D.H., 1996, Energy-efficient knee-ankle-foot orthosis: A case study, *Journal of Prosthetics and Orthotics*, **8**, 3, 79-85
10. Kutilek P., Viteckova S., Svoboda Z., Smrcka P., 2013, The use of artificial neural networks to predict the muscle behavior, *Open Engineering* (formerly *Central European Journal of Engineering*), **3**, 3, 410-418
11. Lee C.S., Gonzalez R.V., 2008, Fuzzy logic versus a PID controller for position control of a muscle-like actuated arm, *Journal of Mechanical Science and Technology*, **22**, 8, 1475-1482

12. Madić M., Radovanović M., 2014, Possibilities of using the Monte Carlo method for solving machining optimization problems, *Facta Universitatis – Series: Mechanical Engineering*, **12**, 1, 27-36

13. Malcolm L., Sutherland D.H., Cooper L., Wyatt M., 1980, A digital logic-controlled electromechanical orthosis for free-knee gait in muscular dystrophy children, *Orthopedic Transactions*, **5**, 90, b12

14. Mančić M., Petrović E., Nikolić V., Jovanović M., Rajković P., Simonović M., 2016, Particle swarm optimization of a heat pump photovoltaic energy system, *Facta Universitatis – Series: Working and Living Environmental Protection*, **13**, 3, 165-176

15. Meshram P.M., Kanojiya R.G., 2012, Tuning of PID controller using Ziegler-Nichols method for speed control of DC motor, *IEEE International Conference on Advances in Engineering, Science and Management*, 117-122

16. Moosavi M., Eram M., Khajeh A., Mahmoudi O., Piltan F., 2013, Design new artificial intelligence base modified PID hybrid controller for highly nonlinear system, *International Journal of Advanced Science and Technology*, **57**, 5, 45-62

17. Neogi B., Darbar R., Mondal S., Gorai B., 2011, Study of proper tuning of prosthetic limb control system with paraplegia and fatigue condition, *IEEE International Conference on Emerging Applications of Information Technology*, 79-82

18. Rajanwal K., Shakya R., Patel S., Maurya R.K., 2014, Comparative analysis of PI, PID and fuzzy logic controllers for speed control of DC motor, *International Journal of Engineering Research and Technology*, **3**, 1, 1319-1324

19. Schröder J., Kawamura K., Gockel T., Dillmann R., 2003, Improved control of a humanoid arm driven by pneumatic actuators, *Industrial Applications of Informatics and Microsystems*, 1-20

20. Solihin M.I., Tack L.F., Kean M.L., 2011, Tuning of PID controller using particle swarm optimization (PSO), *International Journal of Advanced Science, Engineering and Information Technology*, **1**, 4, 458-461

21. Yakimovich T., Lemaire E.D., Kofman J., 2009, Engineering design review of stance-control knee-ankle-foot orthosis, *Journal of Rehabilitation Research and Development*, **46**, 2, 257-267

*Manuscript received October 25, 2018; accepted for print January 15, 2020*