Genetic Algorithm Based PID tuning for Controlling Paraplegic Humanoid Walking Movement

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Abstract: Genetic Algorithm (GA) is a very useful tool to search and optimize many engineering and scientific problems. In this paper, a real time enhanced biomedical model of humanoid structure is developed in MSC visual Nastran to assist the paraplegic patient. The complexity of the model is driven by the needs that the model parameters must be estimated for an eventual individual with disability. After the development of humanoid structure an inverse model is designed to estimate the joint torques. The reference trajectories of the humanoid model are obtained from MSC visual Nastran.The controllers are designed in Matlab/ Simulink for four joints which are manually tuned simultaneously to obtain the results. Afterwards, GA is used to tune the PID controllers to find the optimal solutions which are compared with manually tuned PIDs. The results are shown and hence it is proved that GA has given a better optimized control system.

Keywords: Genetic Algorithm, PID, Inverted Pendulum, Optimization, Walking Movement.

1. Introduction

Paraplegia is a disease caused by the spinal cord injury (SCI) paralyzing lower body of the patient. Patients suffering from this disease are known as paraplegics. Paraplegics experience immobility or lack of activity in lower body part. Recently, a lot of work has been done in this area. Due to the large varieties of humanoid structure it is not possible to apply a general control method to all humanoid models. Intelligent control techniques like Neural Networks, Fuzzy control, Genetic Algorithm (GA) etc., have been used to control humanoid models due to their evolutionary learning, faster convergence and good tolerance of uncertainty and imprecision [1]. As these intelligent techniques are independent of model in optimization, and only depends upon the feedback from the system to improve performance. As the precise dynamic model of humanoid is not available due to the complex mechanical structure and high degree of freedom, so the evolutionary techniques are useful in humanoid control.

Humanoid walking is a hot issue in many research publications but this issue is still unsolved or addressed, because of its dependency on certain other issues like 3-D walking, impact of effects between humanoid robot and ground plane [2]. Pratt et al. have developed “RoboKnee” [3] to support the knee motion during walking or climbing up stairs. Johnson et al have developed a support system using pneumatic muscles by compressed gas not for a healthy person but for the paralyzed, amputee and spastic patient [4]. One of the aims of this work was to solve problems about weight, power, endurance and cost of the actuators. Many authors have investigated control of muscle force by either computer simulation or experiment. Optimal control of an antagonistic muscle pair has been discussed in [5-6] and implementations of closed-loop control of a single muscle have been also reported [7-10]. However, since their works were restricted to single -input single-output systems, it is very difficult to understand how to control multiple muscles in order to regulate a multi joint body movement. In humanoid research field, many researchers have used GA as an optimization tool [11-13]. A GA based trajectory generation method for a prismatic joint humanoid robot has been presented by Capi et al [11]. Hasegawa et al [12] has presented a hierarchical evolutionary algorithm to generate a natural walking motion on the slope surface to minimize total energy. Cheng and Lin [13] have used GA to investigate a control design to search a suitable control and parameters of trajectory based on the robustness measure developed from the liberalized Poincare map. However, all of them have not considered 3-D humanoid walking and restricted to the motion to a single plane independently.

In this paper, a simpler technique and not like passive dynamic walk but an electrically controlled system on a humanoid model is used. The development of the real time humanoid model is being done in MSC visual Nastran 4-D to obtain the reference trajectories. Matlab/ Simulink is used to implement the controllers for the disabled lower parts of the body to initiate walking movement and the controllers are tuned both manually and GA based to follow the reference trajectories for four joints obtained from MSC visual Nastran 4-D.

This paper is organized as follows. Section 2 presents the development of the humanoid model, humanoid walking gait and its phases. Section 3 covers the design of controller structure. A brief review of GA and the proposed GA based tuned PID controller is described in section 4. The results are discussed in section 5.Finally the conclusion is given in section 7.

2. Humanoid Model

2.1 Humanoid Structure

The development of an accurate humanoid model is extremely important. Designing an accurate controller to perform walking movement is not possible until and unless there is an accurate model. Because of the high degree of freedom and complex mechanical structure it is hard to precisely model the dynamics of humanoid. To build an accurate model a computer aided design tool is required that can simulate the designed model in real time. This model is created in AutoCAD and is imported to MSC visual Nastran software. It can be easily connected with Matlab/ Simulink so that a suitable controller can be designed for making the model to move. The complete development of the humanoid model includes all the body segments and measurements of their length and weights. The main focus of this paper is on the left hip, left knee, right hip, and right knee while the rest of the body movement is ignored. Revolute motors are being used on these specified joints to obtain the reference trajectories in terms of instantaneous angles for a normal human walking as shown in figure 1.

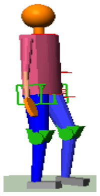

Fig.1 Humanoid Model Developed.

2.2 Walking Gait

A unique feature of locomotion analysis is that unpredictable human behavior must be taken into account when the control system is designed [14]. The main difficulty lies in balancing the body, reducing the contact force between the feet and steps and avoiding "slipping" of the feet in the support phase. To balance the body and to avoid foot "slipping", the weight acceptance (moving centre of mass forward) is essential. The above developed model is moved in MSC visual Nastran to obtain the instantaneous positions of left hip, left knee, right hip and right knee in terms of angles for a time interval of three seconds as shown in figure 2.

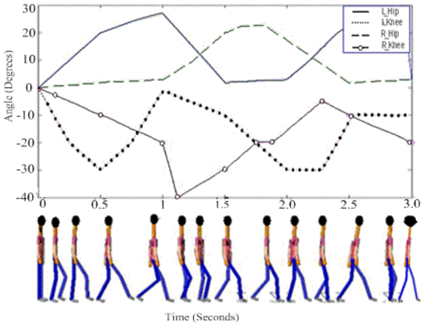

Fig.2 Walking gait with reference trajectories.

2.3 Phases of Walking

The first phase is the initiation phase. During this phase the forward momentum is generated. The forward momentum generation is necessary in order to transfer weight from the still position to a moving position. The beginning of this phase corresponds to fast changes in the anterior-posterior component of the ground reaction force. The initial phase for a normal walking movement can be considered as a ballistic movement. Table 1 shows the left and right foot complete 2-steps cycle.

S.No	Phase	Activity	Cycle
1	Initial Phase	Trunk movement with still legs	10%
2	First Step/Left foot	Forward Acceleration	10%-40%
3	Back to initial position	Deceleration/Balancing Body	40%-50%
4	Second Step/Right foot	Forward Acceleration	50%-80%
5	Final phase	Back to still position	80%-100%

Table 1: Phases of the walking movement

3. Controller Structure Design

To design a controller that will control the movement of the humanoid model according to the obtained reference trajectories. The PID controllers are used to track the reference trajectories of the revolute motors used for each left hip, left knee, right hip, and right knee. In this design, the voluntary upper body effort has been taken as a disturbance.

3.1 Multivariable PID Control System

To achieve satisfactory performance, multivariable control methods must be used. This is a strong motivation to derive effective yet simple methods for tuning PID controllers used within a multivariable controller. Consider the case of 4×4-square system.

3.1.1 Matrix Vector Expression

The system can be modeled as:

$$y = f(\theta)\, u \tag{1}$$

where output and control vectors satisfying $y,u \in \Re^4$ and 4 ×4-square matrix of system transfer function $f(\theta) \in \Re^{4\times 4}$

The error can be written as:

$$e_{\begin{bmatrix} l-h \\ l-k \\ r-h \\ r-k \end{bmatrix}} = r_{\begin{bmatrix} l-h \\ l-k \\ r-h \\ r-k \end{bmatrix}} - y_{\begin{bmatrix} l-h \\ l-k \\ r-h \\ r-k \end{bmatrix}} \qquad (2)$$

where error, reference and output vectors satisfying $e,r,y \in \Re^4$

and the controller of the system will be :

$$u_{\begin{bmatrix} l-h \\ l-k \\ r-h \\ r-k \end{bmatrix}} = G_c(s) - e_{\begin{bmatrix} l-h \\ l-k \\ r-h \\ r-k \end{bmatrix}} \qquad (3)$$

where control and error vectors satisfying $e,u \in \Re^4$ and 4-sqaure matrix of controller transfer function satisfying $G_c(s) \in \Re^{4\times 4}$

3.1.2 Element wise Matrix Vector Definition

The system equation $y_{\begin{bmatrix} l-h \\ l-k \\ r-h \\ r-k \end{bmatrix}} = f(\theta)\, u_{\begin{bmatrix} l-h \\ l-k \\ r-h \\ r-k \end{bmatrix}}$ is given the element wise description.

$$\begin{bmatrix} y_{l-h} \\ y_{l-k} \\ y_{r-h} \\ y_{r-k} \end{bmatrix} = \left[f(\theta) \right] \begin{bmatrix} u_{l-h} \\ u_{l-k} \\ u_{r-h} \\ u_{r-k} \end{bmatrix} \qquad (4)$$

where output and control components are:

$y_{l-h}, y_{l-k}, y_{r-h}, y_{r-k}, u_{l-h}, u_{l-k}, u_{r-h}, u_{r-k} \in \Re(s)$,

The error equation $e_{\begin{bmatrix} l-h \\ l-k \\ r-h \\ r-k \end{bmatrix}} = r_{\begin{bmatrix} l-h \\ l-k \\ r-h \\ r-k \end{bmatrix}} - y_{\begin{bmatrix} l-h \\ l-k \\ r-h \\ r-k \end{bmatrix}}$ is given by the element wise description.

$$\begin{bmatrix} e_{l-h} \\ e_{l-k} \\ e_{r-h} \\ e_{r-k} \end{bmatrix} = \begin{bmatrix} r_{l-h} \\ r_{l-k} \\ r_{r-h} \\ r_{r-k} \end{bmatrix} - \begin{bmatrix} y_{l-h} \\ y_{l-k} \\ y_{r-h} \\ y_{r-k} \end{bmatrix} \qquad (5)$$

where error, reference and output vector elements satisfying:

$e_{l-h}, e_{l-k}, e_{r-h}, e_{r-k}, r_{l-h}, r_{l-k}, r_{r-h}, r_{r-k}, y_{l-h}, y_{l-k}, y_{r-h}, y_{r-k} \in \Re^4$

Finally the controller equation $u_{\begin{bmatrix} l-h \\ l-k \\ r-h \\ r-k \end{bmatrix}} = G_c(s)\, e_{\begin{bmatrix} l-h \\ l-k \\ r-h \\ r-k \end{bmatrix}}$ is given the element wise description.

$$\begin{bmatrix} u_{l-h} \\ u_{l-k} \\ u_{r-h} \\ u_{r-k} \end{bmatrix} = \begin{bmatrix} g_{l-h} & 0 & 0 & 0 \\ 0 & g_{l-k} & 0 & 0 \\ 0 & 0 & g_{r-h} & 0 \\ 0 & 0 & 0 & g_{r-k} \end{bmatrix} \begin{bmatrix} e_{l-h} \\ e_{l-k} \\ e_{r-h} \\ e_{r-k} \end{bmatrix} \qquad (6)$$

where the error and control vector elements satisfy:

$e_{l-h}, e_{l-k}, e_{r-h}, e_{r-k}, u_{l-h}, u_{l-k}, u_{r-h}, u_{r-k} \in \Re^4$

Figure 3 shows the control system for multivariable model.

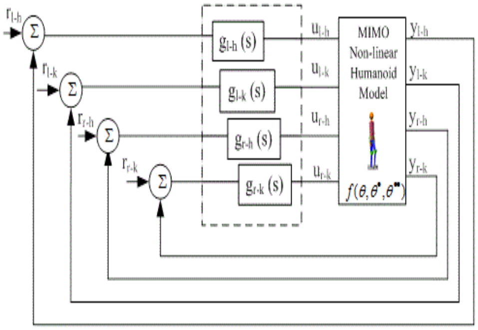

Fig. 3 Multivariable PID Control System

The integration of Matlab/ Simulink with MSC visual Nastran makes it possible for Simulink to send signals to MSC visual Nastran and to receive signals from it in real time. In this way the two software environments work together. Therefore, a control system in Matlab/ Simulink is essential to enable the joints angular displacement, angular velocity, angular acceleration and torques to track the desired trajectories and the humanoid model to perform walking in MSC visual Nastran. As there are various components of the system which are dynamically strongly coupled, slight change in any joint causes disturbance and variation in the trajectories of all other segments. Hence, it is not easy to construct a precise mathematical model that describes the dynamic behavior of the humanoid model. A closed loop control system has been designed to achieve the desired trajectory.

4. Problem Formulation

In order to move the humanoid model to walk under the control of PID controllers the reference trajectories are needed, which should be followed for the balance motion of the model. First of all the reference trajectories are generated in MSC visual Nastran for normal human walking and then PID controllers are used to move the model according to the reference trajectories. To tune the PID controllers so that the model follows the reference trajectories is a very time consuming process and also it cannot guarantee good walking performance.

In the proposed method, a multi-criteria GA is used to search optimal value for the parameters of the PID controller which will guarantee to follow the reference trajectories. So the objective function can be defined in terms of errors and PIDs are tuned using GA to minimize the error.

4.1 Objective Function

To design the four GA based PID controllers so that it will follow the reference trajectories given by the visual Nastran 4-D. The objective function can be defined as:

$$J = w_{l-h}\left(\int_0^3 e\,dt\right)_{LeftHip} + w_{l-k}\left(\int_0^3 e\,dt\right)_{LeftKnee} + w_{r-h}\left(\int_0^3 e\,dt\right)_{RightHip} + w_{r-k}\left(\int_0^3 e\,dt\right)_{RightKnee} \quad (7)$$

$$e_{\begin{bmatrix} l-h \\ l-k \\ r-h \\ r-k \end{bmatrix}} = r_{\begin{bmatrix} l-h \\ l-k \\ r-h \\ r-k \end{bmatrix}} - y_{\begin{bmatrix} l-h \\ l-k \\ r-h \\ r-k \end{bmatrix}} \quad (8)$$

where e is the error, r is the reference trajectory and y is the current output of the plant and $w_{l-h} = w_{l-k} = w_{r-h} = w_{r-k} = 1$.

4.2 Optimization Problem

In this study, minimization of the objective function J is used. The constraints are the coefficients of the PID controller.

Minimize J

Subjected to:

$$K_{P,i}^{\min} \le K_{P,i} \le K_{P,i}^{\max}$$

$$K_{I,i}^{\min} \le K_{I,i} \le K_{I,i}^{\max}$$

$$K_{D,i}^{\min} \le K_{D,i} \le K_{D,i}^{\max}$$

where $i \in [1,2,3,4]$. The proposed design is optimized through GA to search the optimal controller parameters. Table 2 gives the details of the parameters with their bounds to be optimized by GA.

S.No	Parameters	Min	Max
1	K_{P1}	0	50
2	K_{I1}	0	50
3	K_{D1}	0	50
4	K_{P2}	0	50
5	K_{I2}	0	50
6	K_{D2}	0	50
7	K_{P3}	0	50
8	K_{I3}	0	50
9	K_{D3}	0	50
10	K_{P4}	0	50
11	K_{I4}	0	50
12	K_{D4}	0	50

Table 2: The parameter bounds for optimization

In Table 3 the parameter values of GA based tuned PIDs are given.

S.No	Parameter	Value
1	Maximum Generations	100
2	Population Size	20
3	Crossover Probability	0.6
4	Mutation Probability	0.1

Table 3: GA parameters

5. Humanoid Walking using GA based Control System

The genetic algorithm is an optimization algorithm which simulates the natural evolution process to search the optimal solution of the optimization problem. It depends entirely on responses from its environment and evolution operators (i.e., reproduction, crossover and mutation) to arrive at the best solution. By starting at several independent points and searching in parallel, the algorithm avoids local minima and converging to sub optimal solutions.

In this paper, GA is used to search the parameters of the PID controllers in terms of objective function minimization as shown in figure 4.

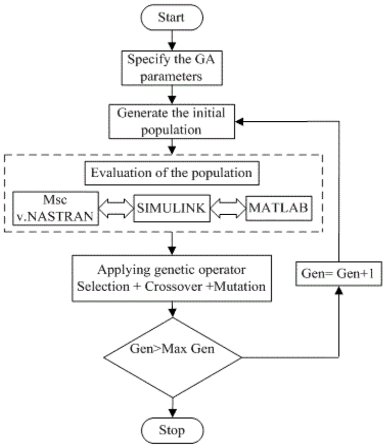

Fig.4 Flowchart of Design process

A closed loop control system is designed for humanoid model movement as shown in figure 5.

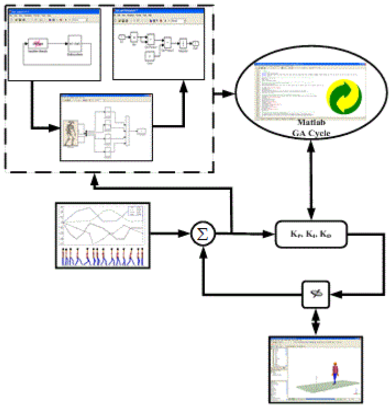

Fig.5 Interface of MSC visual Nastran with Matlab/ Simulink

In this figure it is shown that the humanoid model is moved in MSC visual Nastran and its movement is controlled by closed loop control system in Matlab/ Simulink. The parameters of the PID controllers of closed loop control system are tuned using GA implemented in Matlab.

6. Results and Simulations

The normal humanoid walk has been carried out in MSC visual Nastran for a time interval of 3 seconds to obtain the reference trajectories. Figure 6 shows the initial and final positions of the humanoid model in MSC visual Nastran.

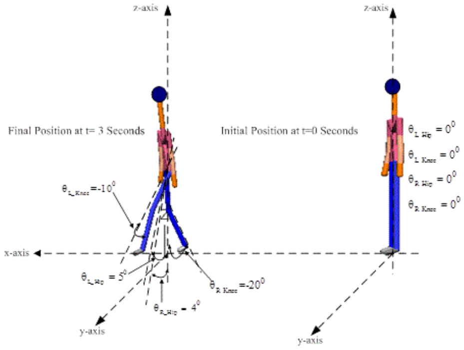

Fig.6 Initial position and final position of humanoid model in MSC visual Nastran

A closed loop control system is applied to move the model and the PID controller parameters are tuned manually and using GA. The angular displacement, angular velocity, and angular acceleration corresponding to the reference trajectories are given in figures 7, 8 and 9 respectively.

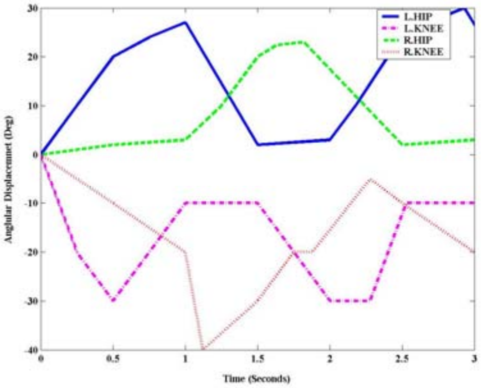

Fig.7 Angular Displacement

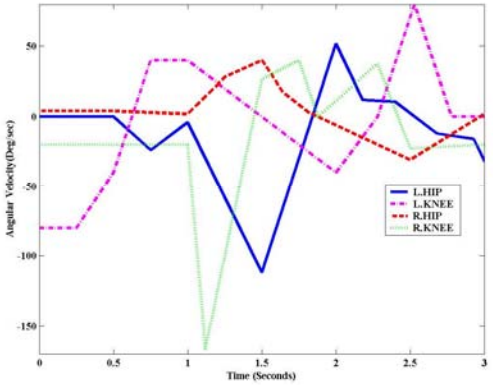

Fig.8 Angular Velocity

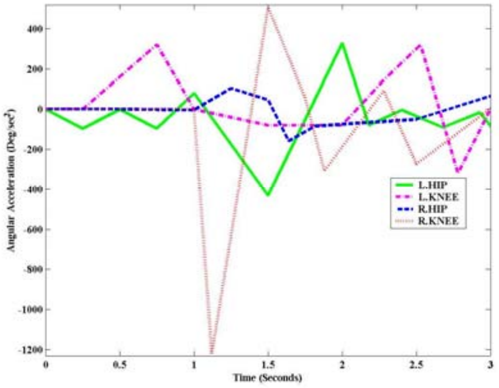

Fig.9 Angular Acceleration

In figure 10 the torques plots are given corresponding to the reference trajectories for left hip, left knee, right hip and right knee respectively.

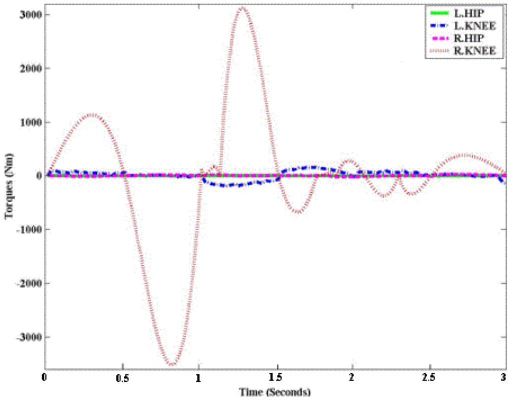

Fig.10 Torques

In this figure, the torque plots of the knees are continuous because of the fast variations at each point of humanoid walk while the torque plots of the hips are discrete because of the slow variations at each point.

6.1 Optimization Results

Both manually and GA based tuned PID controllers parameter values are given in Table 4.

S.No	Parameters	Value	
		Manually tuned	GA tuned
1	K_{P1}	42	21
2	K_{I1}	0	39
3	K_{D1}	0.7	31
4	K_{P2}	15	11.5
5	K_{I2}	1	4.6
6	K_{D2}	0.6	5
7	K_{P3}	23	5.5
8	K_{I3}	0	21
9	K_{D3}	2	30.5
10	K_{P4}	33	6
11	K_{I4}	1	1.6
12	K_{D4}	0.99	30

Table 4: Parameters values of manually tuned and GA based tuned PID controllers

Figures 11-14 show the tracked reference trajectories by manually tuned PID based control system for left hip, left knee, right hip and right knee respectively.

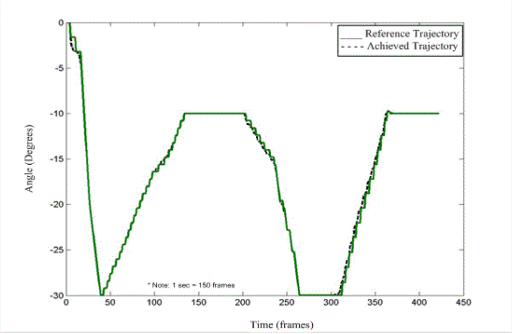

Fig.11 Reference and achieved left knee trajectory

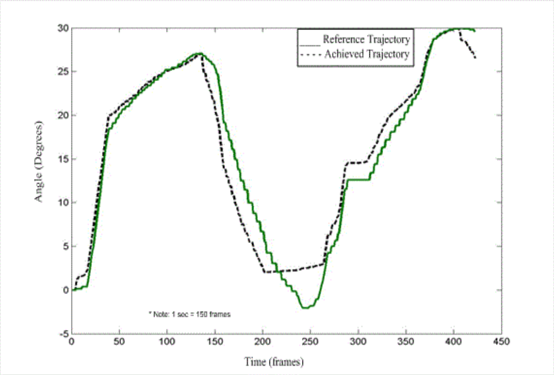

Fig.12 Reference and achieved left hip trajectory

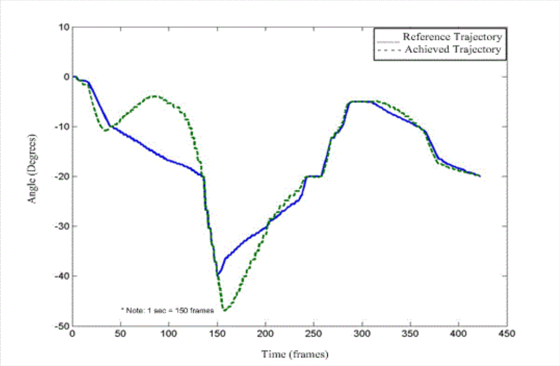

Fig.13 Reference and achieved right knee orientation trajectory

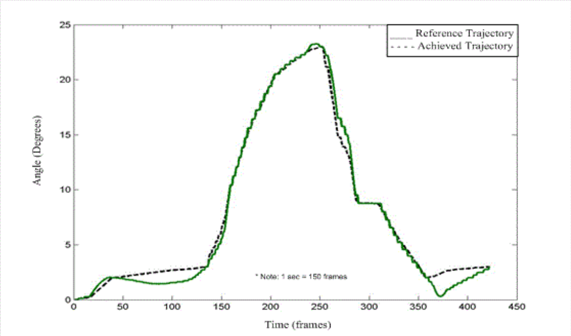

Fig.14 Reference and achieved trunk right hip trajectory

While the plots of reference trajectories following by GA based tuned PID controllers of the closed loop control system are given in figures 15-18 for left hip, left knee, right hip and right knee respectively.

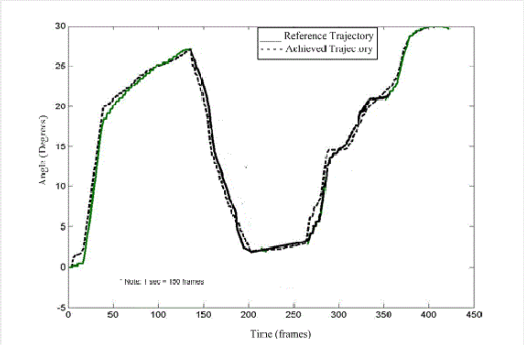

Fig.15 Reference and achieved left hip trajectory

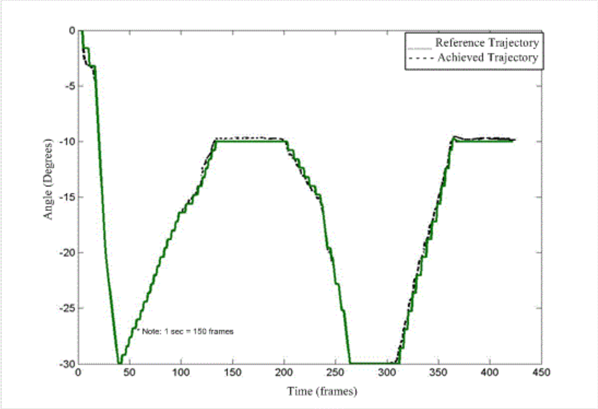

Fig.16 Reference and achieved left knee trajectory

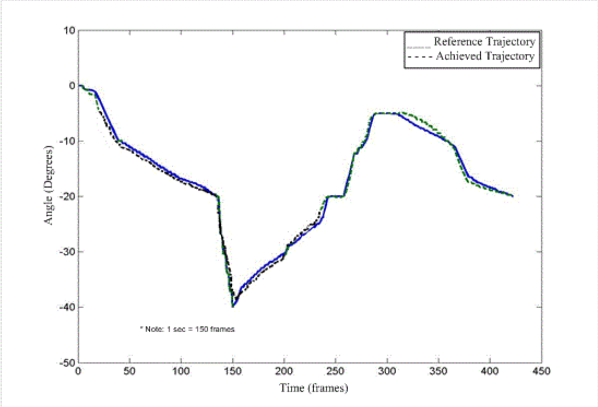

Fig.17 Reference and achieved right knee trajectory

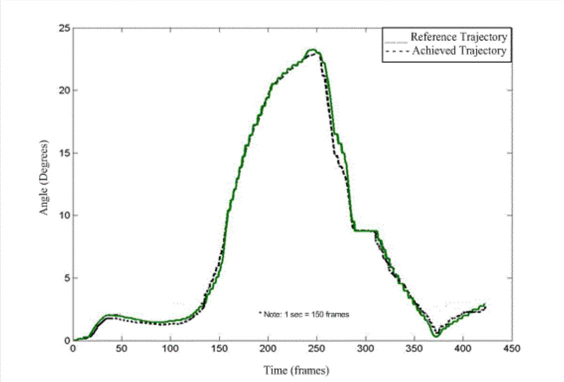

Fig.18 Reference and achieved right hip trajectory

The static and dynamic performance of both manually and GA based tuned PID controllers can easily be depicted through the IAE and ITAE as described from equations below:

$$\text{IAE :} \quad \int_0^3 |e|^2 \, dt$$

$$\text{ITAE :} \quad \int_0^3 t\,(|e|)^2 \, dt$$

Figure 19 shows the IAE value of both GA based and manually tuned PID controllers.

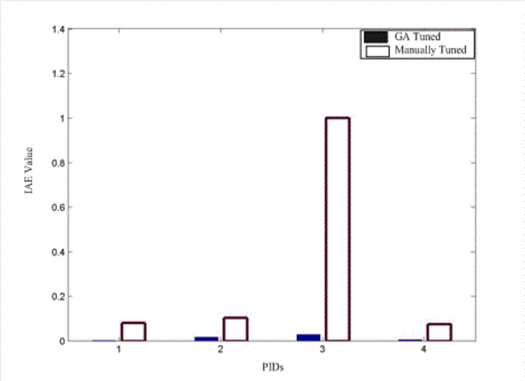

Fig.19 Comparison between the PIDs tuned manually and PIDs tuned by GA for IAE

It is observed that the IAE value of GA based tuned are less than that of manually tuned PIDs for all four joints. Figure 20 shows the ITAE value of both GA based and manually tuned PID controllers.

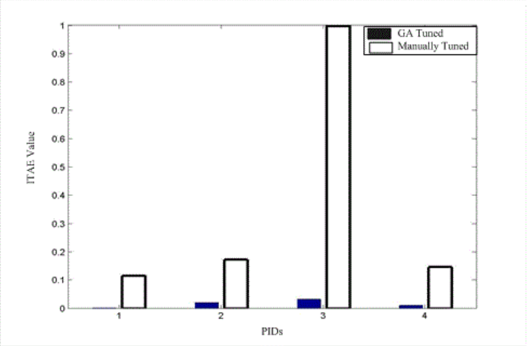

Fig.20 Comparison between the PIDs tuned manually and PIDs tuned by GA for ITAE

It is observed that the ITAE value of GA based tuned are less than that of manually tuned PIDs for all four joints. The combined IAE and ITAE values for both GA based and manually tuned of four PID controllers are given in figure 21.

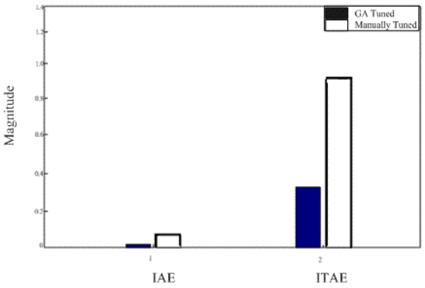

Figure 21: Comparison between the combined PIDs tuned manually and PIDs tuned by GA for IAE and ITAE

7. Conclusion

In this paper, humanoid model is developed in MSC visual Nastran.The reference trajectories have been obtained from normal humanoid walk in MSC visual Nastran. A closed loop control system with PID controllers is designed in Matlab/ Simulink to control the humanoid movement in MSC visual Nastran to follow the reference trajectories by tuning the PIDs. The PIDs are tuned both manually and using GA and their respective performances are shown through the results. It is observed that GA has tuned the PIDs better than that of manually tuned by minimizing the error.

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