OPTIMAL TRAJECTORY PLANNING OF A HUMANOID ROBOT WITH TORSO MODIFICATIONS

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Abstract- In this article, by mathematical simulation of a seven linked biped robot and regarding zero moment point criterion, several effective walking parameters are optimized to maintain the stability of the robot. In addition, torso angle changes with respect to the time to adjust the Zero Moment Position (ZMP) of the robot. Particle Swarm Optimization (PSO) is used to generate optimal parameters of the robot. Trajectory of links are generated in the offline mode. The paper focuses on optimization of fourteen walking parameters using P.S.O. and the significant effect of torso angle in adjusting the ZMP. It can be seen that this method is very effective in generating stable walk.

Index Terms- Humanoid robot, Trajectory, ZMP, Walking, Particle Swarm Optimization

I. INTRODUCTION

Biped robots are used in different tasks such as rehabilitation or working in dangerous places or performing tasks that are difficult for human. These robots are categorized by the number of their legs such as one leg biped quadruped hexapod; even numbers for the number of legs are more common. Gait generation for humanoids and humanoid walking has been the subject of many researches in robotics [1-6]. Austin and Hamon simulated a four-bar linkage robot for walking [7], and McGeer worked on passive walking [8]. Zheng and Shan worked on static walking regarding static walking methods [9]. Wu et al used neural network to generate walking for biped robots [10]. Mousavi and Bagheri presented a mathematical simulation of a biped robot on ramp, and adjusted some walking parameters [11]. Mombaur et al worked on optimal control of a walking robot [12]. Cardenas-Maciel performed optimized walking by using genetic algorithm [13]. Sina et al used iteration methods to find optimum ZMP for the humanoid robot with arms and forearms [14]. Some researches focused on path planning using particle swarm optimization [15]. Liu et al studied online path planning for a robot on a ramp using Neural Networks [16]. During the walking many parameters should be considered and adjusted to reach stable walking. These parameters play important roles in the walking. Hence it is very important to select suitable parameters for optimization and calculate possible answers for these parameters. In this research fourteen walking parameters are selected and optimized to enhance stability of the humanoid robot during walking.

II. MODELING OF THE HUMANOID ROBOT

The humanoid robot is modeled by seven links. Polynomials are used to generate trajectory with respect to the break points. Then, the path for ankle and hip is generated and, by inverse kinematics, the trajectories of related links are calculated. Also the torso angle changes and adjusts the robot stability during walking regarding ZMP criterion.

Breakpoints of foot, ankle and hip

Fig .1 illustrates the configuration of the biped robot in sagittal plane. There are various parameters in this figure, which will be presented later.

A. Foot parameters in the sagittal plane

In Fig. 1, x_a is the horizontal displacement of ankle, z_a is the vertical displacement of ankle, Tc is the time of single and double support phase, T_d is the time of double support phase, T_m is the time that the ankle joint is in maximum height. K is the step number, D_s is the length of step, q_b and q_f are angles of foot lift and contact with level ground. and H_{ao} is the maximum height of the ankle joint. Also, L_{ao} is the horizontal distance between the start point and the maximum height of ankle during walking. Eq (1) shows the breakpoints of the ankle

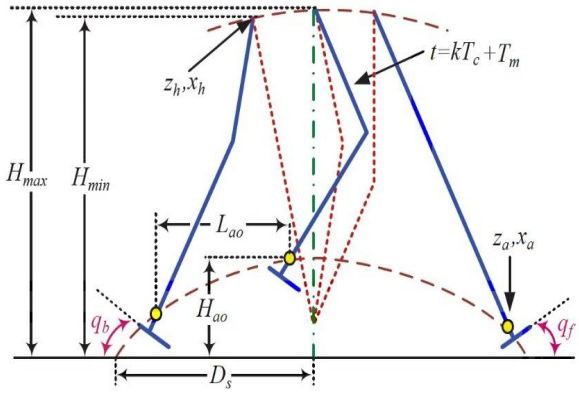


Fig. 1. Configuration of robot [14].

$$\theta_a(t)=\begin{cases}-q_{gs}; & t=kT_c\\ -q_b; & t=kT_c+T_d\\ q_f; & t=(k+1)T_c\\ q_{gf}; & t=(k+1)T_c+T_d\end{cases}$$
$$\begin{cases}\dot{\theta}(kT_c)=0\\ \dot{\theta}[(k+1)T_c+T_d]=0\end{cases}$$
(1)

B. Ankle parameters

Foot configuration is illustrated in Fig. 2. In addition, horizontal and vertical displacements of swing leg are presented in (2).

$$x_a(t)=\begin{cases}kD_s; & t=kT_c\\ kD_s+l_{an}\sin q_b+l_{af}(1-\cos q_b); & t=kT_c+T_d\\ kD_s+l_{ao}; & t=kT_c+T_m\\ (k+2)D_s-l_{an}\sin q_f-l_{ab}(1-\cos q_f); & t=(k+1)T_c\\ (k+2)D_s; & t=(k+1)T_c+T_d\end{cases}$$
(2)

C. **Foot configuration is illustrated in Fig. 2.** In addition, horizontal and vertical displacements of swing leg are presented in (3-5)

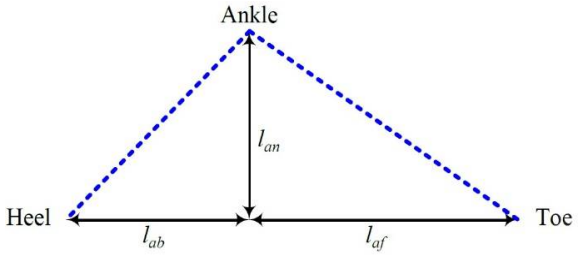


Fig. 2. Foot configuration [14].

$$x_a(t)=\begin{cases}kD_s; & t=kT_c\\ kD_s+l_{an}\sin q_b+l_{af}(1-\cos q_b); & t=kT_c+T_d\\ kD_s+l_{ao}; & t=kT_c+T_m\\ (k+2)D_s-l_{an}\sin q_f-l_{ab}(1-\cos q_f); & t=(k+1)T_c\\ (k+2)D_s; & t=(k+1)T_c+T_d\end{cases}$$

$$z_{ahor}=\begin{cases}l_{an}; & t=kT_c\\ l_{af}\sin q_b+l_{an}\cos q_b; & t=kT_c+T_d\\ H_{ao}; & t=kT_c+T_m\\ l_{ab}\sin q_f+l_{an}\cos q_f; & t=(k+1)T_c\\ l_{an}; & t=(k+1)T_c+T_d\end{cases}$$
(4)

The horizontal and vertical velocity of the ankle joint are

$$\begin{cases}\dot{x}_a(kT_c)=0\\ \dot{x}_a[(k+1)T_c+T_d]=0\\ \dot{z}_a(kT_c)=0\\ \dot{z}_a[(k+1)T_c+T_d]=0\end{cases}$$ (5)

Hip parameters in the sagittal plane

Parameter x_{sd} is the distance between the ankle of the support leg and hip horizontally in the beginning of the double support. Parameter x_{ed} is the distance between the hip and ankle joints horizontally at the end of the double support phase. These parameters are shown in Fig. 3.

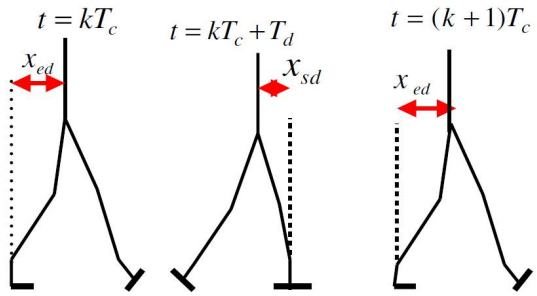


Fig. 3. Parameters of hip: xed, xsd [11].

Horizontal and vertical parameters of hip and ankle are shown in Fig. 1. In the current study, the height of hip in vertical direction is regarded constant. So, $H_{h-\min}=H_{h-\max}$. Equations (6-7) show horizontal and vertical position of hip.

$$x_h=\begin{cases}kD_s+x_{ed}; & t=kT_c\\ (k+1)D_s-x_{sd}; & t=kT_c+T_d\\ (k+1)D_s+x_{ed}; & t=(k+1)T_c\end{cases}$$ (6)

$$z_h=\begin{cases}H_{h\min}; & t=kT_c\\ H_{h\max}; & t=kT_c+0.5(T_c-T_d)\\ H_{h\min}; & t=(k+1)T_c\end{cases}$$ (7)

D. Torso angle

The torso angle is θ_7 which is shown in fig.4. In the current article it is assumed that the torso angle is not constant. Hence the torso angle is changing with respect to the time. In order to satisfy the boundary conditions of the robot during the walk, by using two separate fourth order polynomial representing the torso angle versus the time, the torso swings. One of these polynomials is used to move the torso forward and the second polynomial is used to swing the torso backward which are presented in (8).

$$\theta_{7-forward}=\begin{cases}\theta_{7-start}; & t=kT_c\\ \theta_{7-end}; & t=kT_c+0.5T_d\end{cases}$$

$$\theta_{7-backward}=\begin{cases}\theta_{7-end}; & t=kT_c+0.5T_d\\ \theta_{7-start}; & t=(k+1)T_c\end{cases}$$
(8)

E. Inverse kinematics

After generating hip and ankle trajectory, by using inverse kinematics, trajectory of the shank and thigh is generated uniquely. Fig .4 shows inverse kinematic parameters of the robot. These parameters are calculated as follows:

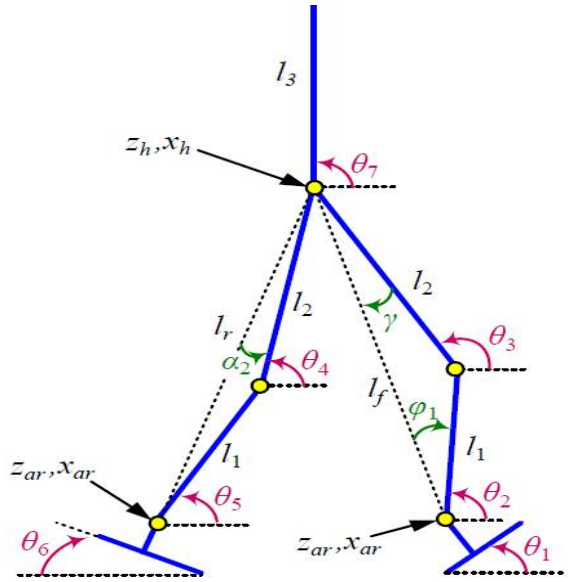


Fig. 4. Inverse kinematics parameters [14].

These parameters are calculated as follows:

$$L_f = \sqrt{(x_h - x_{af})^2 + (z_h - z_{af})^2}$$

$$L_r = \sqrt{(x_h - x_{ar})^2 + (z_h - z_{ar})^2}$$

$$\varphi_1 = \cos^{-1}\left(\frac{L_1^2 + L_f^2 - L_2^2}{2L_1L_f}\right)$$

$$\varphi_2 = \cos^{-1}\left(\frac{L_2^2 + L_f^2 - L_1^2}{2L_2L_f}\right)$$

$$\gamma = \cos^{-1}\left(\frac{x_h - x_{af}}{L_f}\right) \quad \beta = \cos^{-1}\left(\frac{x_h - x_{ar}}{L_r}\right)$$

$$\alpha_1 = \cos^{-1}\left(\frac{L_1^2 + L_r^2 - L_2^2}{2L_1L_r}\right) \quad \alpha_2 = \cos^{-1}\left(\frac{L_2^2 + L_r^2 - L_1^2}{2L_2L_r}\right)$$

$$\theta_2 = \gamma - \varphi_1,\ \theta_3 = \gamma + \varphi_2,\ \theta_4 = \beta + \alpha_2, \theta_5 = \beta - \alpha_1 \quad (9)$$

In stable walking, the ZMP is inside the polygon of supporting legs. In path planning the robot joints, four parameters are considered for optimization; x_{ed}, x_{sd}, L_{ao}, and H_{ao}. For each set of these parameters, trajectories for joints are generated. The target function is the distance between the generated ZMP and middle line of stability margins. In the present work, by using PSO algorithm, the optimum values for the mentioned parameters are calculated. Pso algorithm is a Meta heuristic algorithm, which is inspired of moving birds and particles. This algorithm was first presented by Eberhart and Kennedy in 1995 [17]. When a particle moves in the problem space, each particle has a specific position, and during movement, it may be in the best position that ever found, which is named personal-best position (P_{best}).

Moreover, every particle shares data about its position with other particles. The movement of each particle depends on the current position, the best position ever found by this particle and the best position found by all particles (Global Best).

The algorithm includes the following steps.

1- Initializing
2- producing random initial positions for particles.
3- Calculation of the fitness function.
4- Calculating Pbest and Gbest.
5- Updating velocity.
6- Updating new position.
7- If stopping criteria are not satisfied, return to step 2.
8- End.

The advantages of using PSO are listed below:

1- There is no need to find the gradient of functions.
2- It is a population-based algorithm.
3- It is not a very complicated or time consuming algorithm.
4- It has relatively fast convergence.
5- By changing personal learning coefficient and global learning coefficient, it is possible to determine which one is more important, the local or the global search. Local search is related to exploitation and global search is related to exploration in the algorithm.

By performing optimization on four parameters, the optimum ZMP trajectory is found. The applied settings in the PSO algorithm are:

N_{pop} (the number of population (swarm number))=50,

the maximum number of iteration=100; The new position x_{i+1} is calculated in (10).

$$v_i = x_i + c_1 r_1 (P_{best} - x_i) + c_2 r_2 (G_{best} - x_i) + \omega v_i$$

$$x_{i+1} = x_i + v_i \quad (10)$$

C1=personal learning coefficient ,C1=2.

C2= global learning coefficient ,C2=2.

ω =inertia weight, $\omega = 1$

r_1, r_2 are uniform random numbers between 0 and 1.

The cost function is defined as the sum of the distance between the middle line of stability margins and the current ZMP. The cost function should be minimum. The cost function in the algorithm is shown in (11):

$$\text{Cost Function} = \sum_{t=0}^{t=1.8} \left| x_{zmp} - middle\ line \right| \quad (11)$$

The formulation of ZMP is presented in (12).

$$X_{zmp} = \frac{\sum_{i=1}^{n} m_i (g + \ddot{z}_i) x_i - \sum_{i=1}^{n} m_i (g + \ddot{x}_i) z_i + \sum_{i=1}^{n} I\ddot{\theta}_i}{\sum_{i=1}^{n} m_i (g + \ddot{z}_i)} \quad (12)$$

In the above formula, n is the number of links. g is the gravity acceleration, m_i is the mass of the link i, I_i is the inertia of link i, $\ddot{x}_i, \ddot{z}_i$ are the horizontal and vertical acceleration for the central mass of link i respectively, x_i is the horizontal position of link i, z_i is the vertical position of link i and $\ddot{\theta}_i$ is the angular acceleration of link i.

F. Results and discussions

The cost function is defined as the sum of the distance between the middle line of margins and ZMP. So, the cost function should be minimum. After 20 iterations and using 50 particles in the PSO algorithm, the optimum values related to the optimum ZMP are reached. The optimum values are shown in Table.1.

Table.1 The optimum values

Pramaters (m)	X_{sd}	X_{ed}	L_{ao}	H_{ao}
Optimum Values	0.229	0.230	0.400	0.155

The linear velocities of ankle and shank are shown in Fig .5. These curves are continuous, during a walking cycle, and rough. Therefore, walking is smooth. In addition, the values of velocities are not huge. Fig .6 shows the linear velocities of hip. Based on the results shown in the Fig.6, the linear velocities of the hip are continuous and rough. Thus, during walking, the robot has a smooth movement in hip. Linear acceleration of ankle and shank is shown in Fig. 7. It can be observed that these curves are smooth and this prevents the robot from jerking since jerking may cause damages in joints or actuators. Moreover, the linear acceleration of the shank in double support phase is tiny. Fig .8 shows linear acceleration of hip. The linear acceleration in hip is not huge; thus, destructive forces may not appear in the hip.

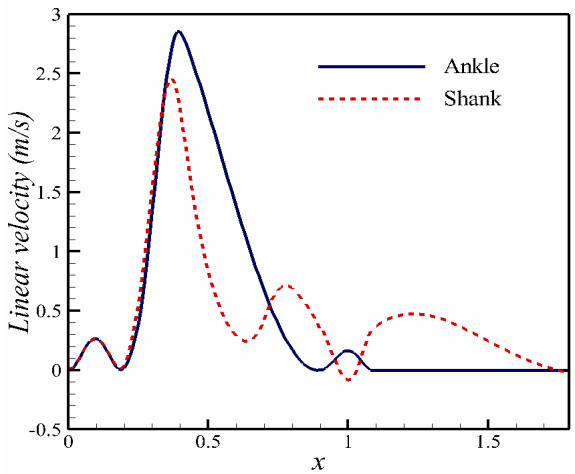


Fig.5 Linear velocities of ankle and shaft

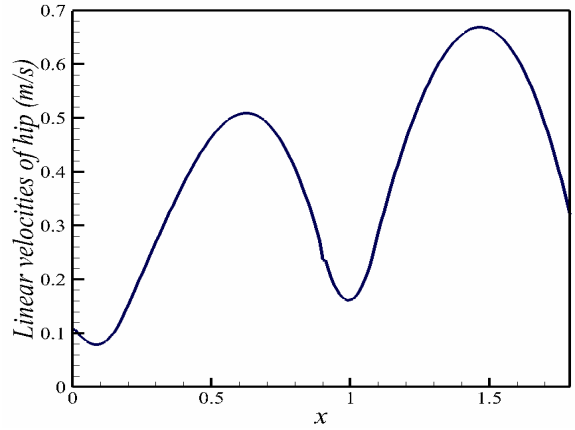


Fig .6. Linear velocity of hip

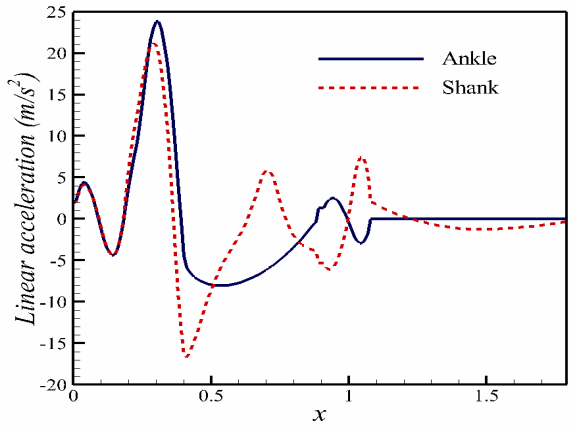


Fig.7 Linear acceleration of ankle and shank

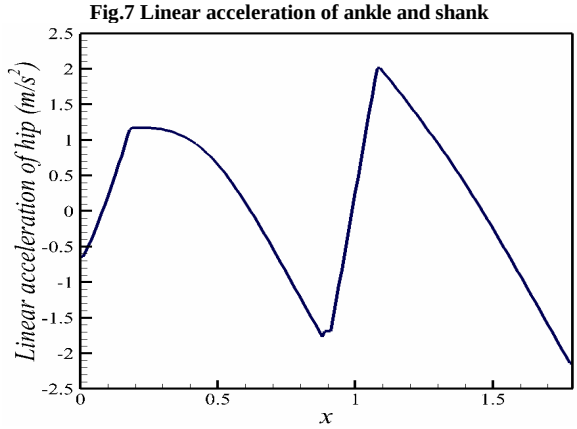


Fig .8. Linear acceleration of hip

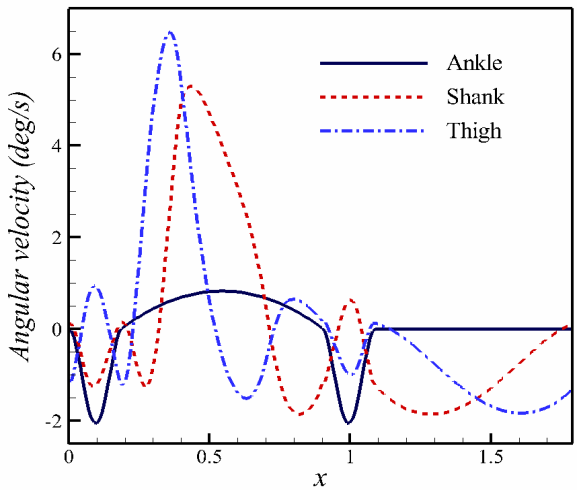


Fig .9. Angular velocities.

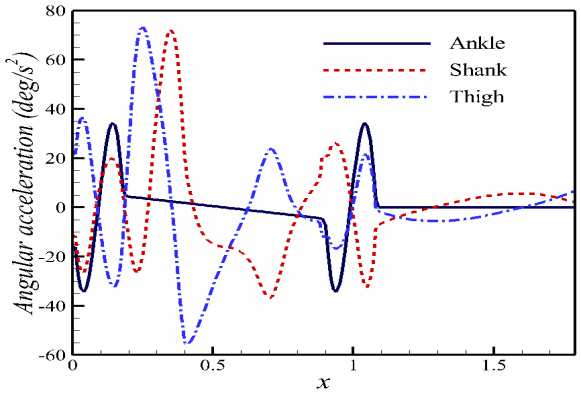


Fig. 10. Angular accelerations

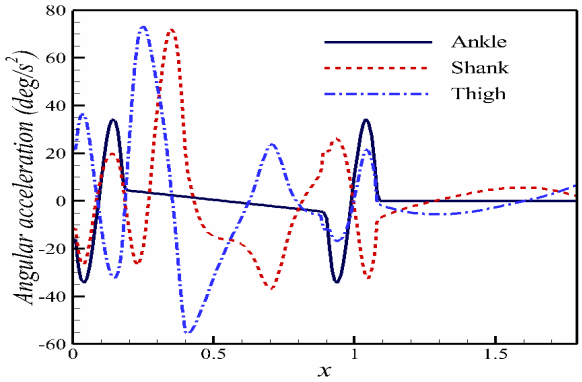


Fig. 10. Angular accelerations

Fig .9 represents angular velocities of ankle, shank and thigh. It shows that the angular velocities of the ankle, the shank and the thigh are smooth curves. In addition, during the double support phase, the supporting foot ankle has no rotation. So the angular velocity of supporting ankle is zero. Fig. 10 illustrates angular accelerations of the ankle, shank and thigh of the simulated robot. These curves are continuous and smooth. Fig .11. shows stick diagram of walking for the seven-linked biped robot. Fig .12. shows ZMP of the robot during walking. The dashed lines are acceptable margins.

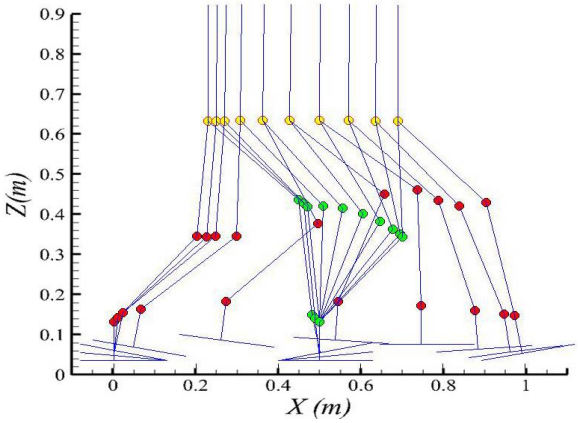


Fig .11. Stick diagram of walking for the seven-linked biped robot.

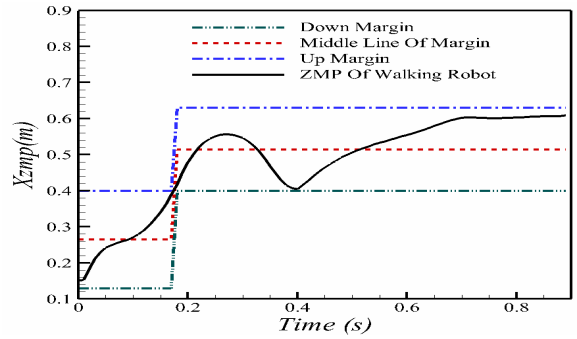


Fig. 12. ZMP of the robot

CONCLUSION

During the optimization process, it was found that the PSO algorithm is effective to achieve optimum values for humanoid robot, and it can generate stable ZMP for the robot. The pattern of walking robot is similar to human, and all these four parameters have important roles in stability. However, x_{ed} and x_{sd} had more important roles. Torso is attached to hip, and its weight is more than other links, so its position has significant effects on ZMP. By adjusting the torso angle during the walk the stability of the robot was improved significantly.

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