Obstacle Crossing Gait Generation of a Two-Legged Robot using Differential Evolution Trained Neural Networks

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Abstract— This paper concentrates on the generation of dynamically balanced gaits of a two legged robot while crossing the obstacle after utilizing differential evolution trained neural networks (DE-NN). By virtue of the nature of the problem, there exists two cases while the robot trying to cross the obstacle, that is place the foot on the other side of the obstacle or landing the foot on the obstacle. It is important to note that the concept of inverse kinematics has been used to generate the gait related to lower limbs. Moreover, the trunk and swing foot gaits are generated by using NN-based gait planner. During this stage, the swing foot and hip-joint are assumed to follow cubic polynomial and straight line trajectories, respectively. As the performance of NN depends upon the structure of NN, DE is used to evolve optimal structure of NN. Further, the performance of the developed DE-NN gait planner has been tested using computer simulations and found to generate dynamically balanced obstacle crossing-gaits of a two-legged robot.

Index Terms—Biped robot, obstacle crossing, dynamically balanced biped robot, differential evolution.

I. Introduction

The humanoid robotics research is now taking rapid strides and several researchers had concentrated on the generation of dynamically balanced gaits of a biped robot for various situations. Numerous researches developed various biped robot mechanisms to achieve the successful motions for creating trajectories of the robot joints to follow. The objective of the research related to legged locomotion is not only to design a suitable gaits to negotiate on a particular terrain, but also see that the gaits generated are dynamically balanced or not. It is to be noted that the zero moment point (ZMP) proposed by Vukobratovic [1] is the important measure to find the dynamic balance of a legged robot. Few researchers worked on the dynamically balanced gait generation of a biped robot on various terrains, such as flat surface [2], staircase [3], sloping surface [4] and rugged terrain [5]. In [6], the rotary knee joint of the biped robot had been replaced with the help of a four-bar mechanism. Later on, Bououden and Abdessemed [7] developed walking control algorithm for a 7-DOF planar biped robot which was having 0-flat normal form. Sasirekha and Vundavilli [8] developed an analytical approach to solve the gait generation problem of a 7-DOF biped robot crossing the obstacle. Most of the works discussed above related to gait generation of biped robots on various terrains are purely mathematical in nature and does not involve any optimization. Therefore, the gait generated utilizing those methods was not optimal in any sense. Later on, few researchers used soft computing [9]-based methods for modeling and optimization of gait generation of biped robots on different terrains.

A neural network-based dynamically balanced gait generation of a biped robot had been attempted by Kun and Miller [10]. It was observed that the performance of the biped was improved with the help of NN-based training. Capi et al. [11] used GA for optimal trajectory generation of a biped robot that used prismatic joints at the knee. The developed algorithm was tested on a real biped robot. Later on, Rega and Pratihar [12] proposed multi-objective optimization of ascending and descending gait generation of a 7-DOF biped robot using GA and particle swarm optimization. Recently, few researchers used differential evolution (DE) [13] algorithm to optimize the structure of NN [14]. However, no work is reported in the literature on application of DE-NN system to solve the gait generation problem of the biped robot.

The present paper concentrates on the development of DE-NN gait planners for 7-DOF biped robot crossing the obstacle. The hip joint and swing foot are assumed to follow straight line and cubic polynomial trajectories, respectively. The lower limbs gait has been generated after utilizing the concept of inverse kinematics. Then the gaits related to the swing foot and trunk are obtained from the NN-based gait planners. Once the entire gait has been generated, its dynamic balance is verified by using the concept of zero moment point (ZMP). Further, the NN-based gait planner is compared with the analytical approach developed by the same authors [8].

II. Mathematical Formulation of the Problem

The present manuscript aims at generating dynamically balanced gaits of 7-DOF biped robot crossing the obstacle. It is to mention that there exists two cases based on the height of the obstacle. Case (i): stepping on the obstacle (refer to Fig. 1) and Case (ii): crossing the obstacle (refer to Fig. 2).

All the joints are assumed to be rotary in nature. Further, the mass of each limb is assumed to be concentrated at some convenient point on the limb. Moreover, the robot is allowed to move only in the sagittal plane. Therefore, the balance of the robot is checked only in the direction of motion. The swing foot of the robot is assumed to follow a cubic polynomial trajectory (refer to Eqn. (1)) to avoid collision with the obstacle.

$$Z = C_0 + C_1 X + C_2 X^2 + C_3 X^3 \qquad (1)$$

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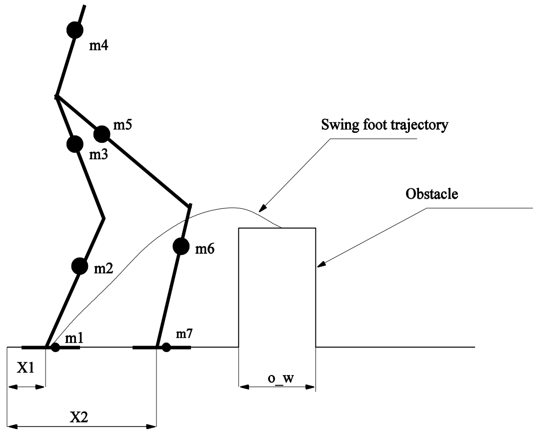

Fig. 1. Schematic view of a two-legged robot (7-DOF) stepping on the obstacle.

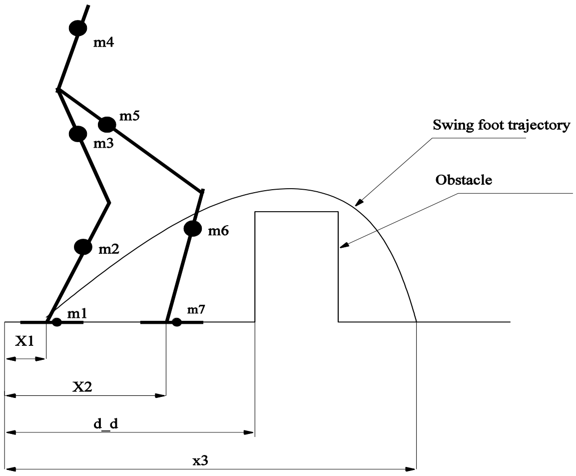

Fig. 2. Schematic view of a two-legged robot (7-DOF) crossing the obstacle.

where x is the distance from the reference point, Z indicates the height of the ankle joint and c0, c1, c2 and c3 are called the coefficients of the cubic polynomial, whose values are determined after applying the boundary conditions related to the terrain. The following are the boundary conditions used to solve the cubic polynomial trajectory for stepping on the obstacle case.

$$\begin{aligned} &\text{at } X=X_1; && Z=0 \\ &\text{at } X=O_d-X_2; && Z=O_h \\ &\text{at } X=O_d; && Z=O_h + fs/2 \\ &\text{at } X=O_d+O_w/2 - fs/2; && Z=O_h \end{aligned} \quad (2)$$

It is to be noted that the boundary conditions are different for crossing the obstacle (refer to Eqn. (3)).

$$\begin{aligned} &\text{at } X=X_1; && Z=0 \\ &\text{at } X=O_d - fs/2; && Z=O_h + fs/2 \\ &\text{at } X=O_d + Ow; && Z=O_h + fs/2 \\ &\text{at } X=X_3; && Z=0 \end{aligned} \quad (3)$$

where O_h and O_d are height of the obstacle and distance of the obstacle form the fixed reference frame, fs is the length of the foot and X_1, X_2, X_3 are the position of the foot placements. The lower limbs gait has been generated after considering the concept of inverse dynamics. Further, the swing foot and trunk motion are generating using DE-NN gait planner, which will be explained in the next section. Once the entire gait is generated, then the dynamic balance of the generated gait has been verified after calculating the ZMP as given in Eqn. (4).

$$X_{ZMP} = \frac{\sum_{i=1}^{7}(I_i \dot{\omega}_i + m_i x_i (\ddot{Z}_i - g) - m_i \ddot{x}_i Z_i)}{\sum_{i=1}^{7} m_i (\ddot{Z}_i - g)} \quad (4)$$

where $\dot{\omega}_i$ represents the angular velocity (rad/s2) of link i, Ii denotes moment of inertia (kg-m2) of i-th link, (xi, yi, zi) indicate the coordinate position of the lumped mass, mi represent the mass (kg) of the link, g denotes acceleration due to gravity (m/s2), $\ddot{X}_i$ and $\ddot{Z}_i$ is the acceleration (m/s2) of the link i in X- and Z- direction, respectively. Then the dynamic balance margin (DBM) of the legged mechanism is to be calculated using the equation given below.

$$X_{DBM} = (\frac{L_7}{2} - |X_{ZMP}|) \quad (5)$$

where L_7 and X_{ZMP} denote length of the supporting foot and distance of ZMP from the ankle joint of the supporting foot, respectively. The D-H parameter setting [15] for the 7-DOF biped robot is shown in Fig. 3.

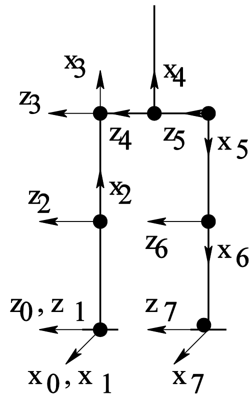

Fig. 3. D-H parameter setting of the 7-DOF biped robot.

III. Proposed Approach

In the present manuscript DE-NN (refer to Fig. 4) gait planner has been developed to solve the obstacle crossing gait generation of a biped robot.

Storn and Prince [13] introduced DE, which is also a population-based global search and optimization algorithm. Similar to GA-NN gait planner, in this case also two modules of NN are used to generate the gait of the biped robot crossing the obstacle. The only difference is that instead of GA, DE has been used to optimize the architecture of NN. As DE uses real variables to search in the solution space, the problem to be optimized consists of D-parameters that represent a D-dimensional vector. In this case, the value of D depends on number of neurons in the hidden layer. One such vector of DE is appearing as given below.

$$\underbrace{0.524}_{V^1_{1,1}}.....\underbrace{0.231}_{V^1_{2,M}}\underbrace{0.865}_{W^1_{1,1}}.....\underbrace{0.553}_{W^1_{2,N}}\underbrace{0.113}_{V^2_{1,1}}.....$$

$$\underbrace{0.976}_{V^2_{2,M}}\underbrace{0.444}_{W^2_{1,1}}.....\underbrace{0.774}_{W^2_{2,N}}\ \underbrace{0.00001}_{b_1}\ \underbrace{0.00011}_{b_2}$$

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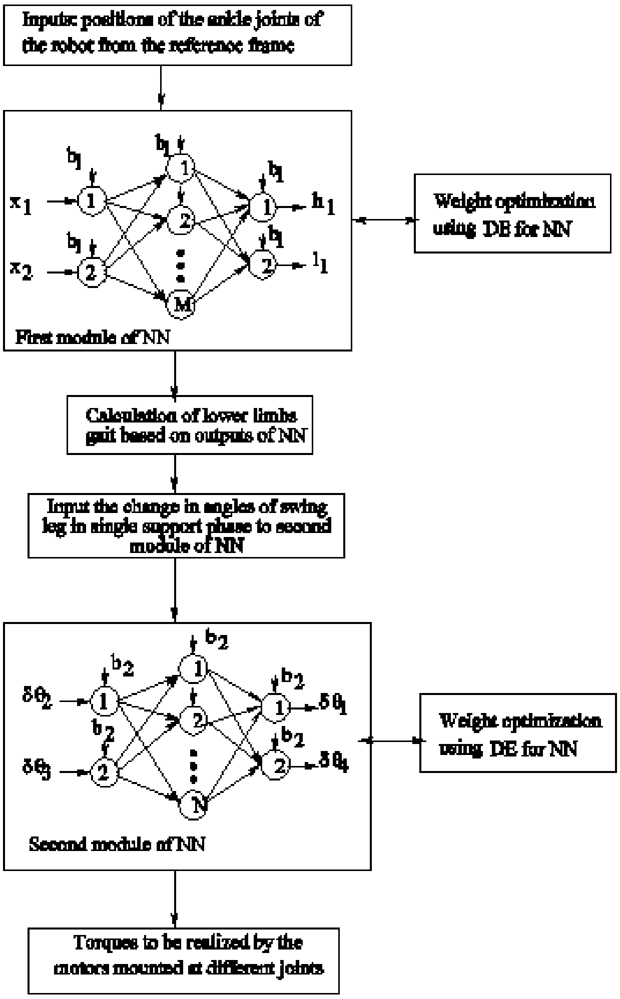


Fig. 4. Flowchart of the proposed DE-NN gait planner

As each vector of DE represents one possible NN architecture, in this case also the whole training data set is passed through the vector and the average dynamic balance margin of all the training cases is assigned as fitness of each vector (refer to eqn. (6)). Then, this population is subjected to three important operators, namely mutation, crossover and selection to successfully improve the solution.

$$f = \frac{\sum_{i=1}^{S} DBM_i}{S} \quad (6)$$

IV. Results and Discussion

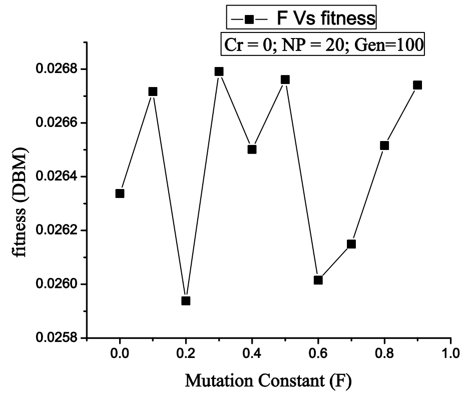
The developed gait planner has been tested for their ability to generate dynamically balanced gaits while crossing the obstacle with the following information related to the foot placements and width of the obstacle during computer simulations. $X_1 = 0.07$ M, $X_2 = 0.19$ M, $X_3 = 0.52$ M AND $O_w = 0.1$ M. Further, Table 1 shows the parameters related to different limbs of the two-legged robot.

The gait generation problem has been solved after utilizing two modules of NN. Initially, a study has been conducted to determine the number of neurons in the hidden layer of both the NNs. The number of neurons in the hidden layers of first and second modules of NN are seen to be equal to 6 and 3,

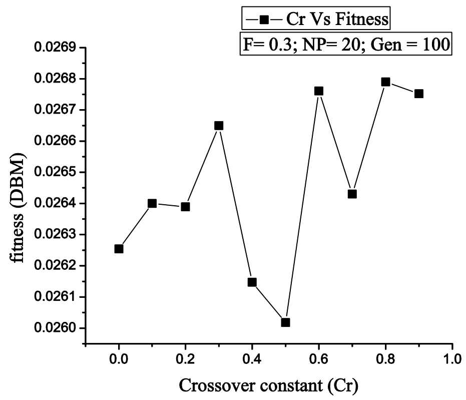
TABLE I: Parameters for Different Limbs of The Biped Robot

Limb	m (kg)	L (m)	r (m)	I (kg m^2)
1	0.5	0.06	0.02000	0.000600
2	2.0	0.34	0.20000	0.021067
3	5.0	0.30	0.24000	0.078000
4	30.0	0.60	0.48000	1.872000
5	5.0	0.30	0.24000	0.078000
6	2.0	0.34	0.20000	0.021067
7	0.5	0.06	0.02000	0.000600

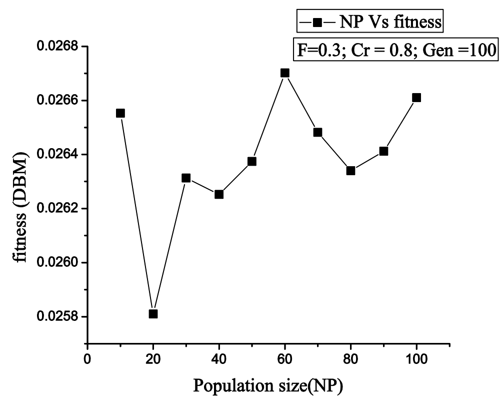
respectively. Based on this, the total number of variables are found to be equal to 39. Then a parametric study (refer to Fig. 5) has been conducted to determine the optimal parameters of DE that are responsible for better prediction capability of NN.



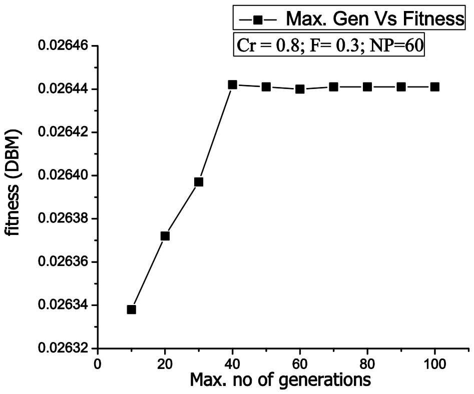
(a)



(b)



(c)



(d)

Fig. 5. Graphs showing the results of parametric study for DE-NN gait planner, (a) fitness vs. mutation constant, (b) fitness vs. crossover constant, (c) fitness vs. population size, (d) fitness vs. number of generations.

The optimal parameters of DE obtained from the parametric study are given below.
Mutation constant, F = 0.3
Crossover constant, Cr = 0.8
Population size, NP = 60
Number of generations = 40

Once the optimal DE-NN gait planner is obtained, its performance has been tested by passing a test case, through the network. The variation of ZMP and power consumption for the test case is shown in Figs. 6 and 7 for crossing and landing on the obstacle, respectively. Here, the ZMP values are found vary from negative to positive, which indicates that the ZMP point is moving in the direction of motion. Further, DE-NN gait planner has generated stable gaits at all intervals.

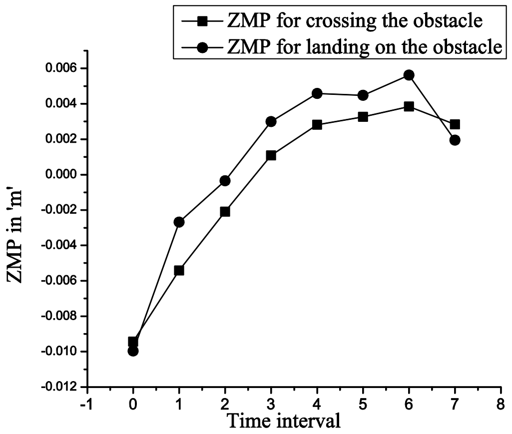


Fig. 6. Variation of ZMP of the biped robot while crossing and landing on the obstacle.

It is also interesting to note that the torque required at knee joint (that is, joint 6) obtained using DE-NN gait planner is coming out to be more when compared with all other joints. It may be due to the reason that the knee joint is supporting the whole structure while moving from one location to the next. This is also true in the case of analytical approach developed by the same authors [8].

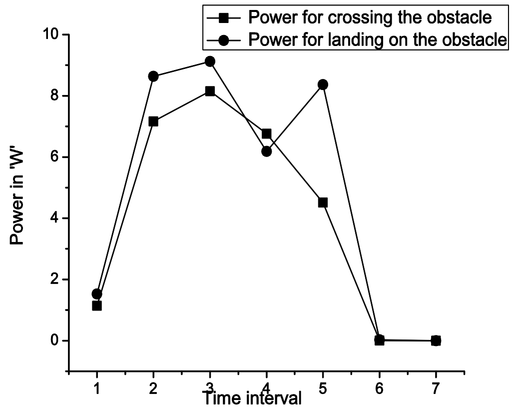


Fig. 7. Variation of power requirement of the biped robot while crossing and landing on the obstacle.

From the data, it can be observed that the obstacle crossing gait generated by the DE-NN gait planner is found to be dynamically balanced. Later on, the comparison of average DBM and power consumption values for the biped robot while crossing the obstacle and landing on the obstacle using DE-NN and analytical approach [8] are shown in Figs. 8 and 9, respectively. It is interesting to note that the average DBM values for DE-NN and analytical gait planners are seen to be equal to {0.02630, 0.01904} and {0.02599, 0.01907} for crossing the obstacle and landing on the obstacle, respectively. Moreover, the average power consumption values for the above order of the gait planners are seen to be equal to {25.4408, 43.8942} and {27.9163, 81.0946} for crossing the obstacle and landing on the obstacle, respectively. Therefore, it can be observed that DE-NN gait planner is found to perform better than analytical approach in both the cases that is crossing the obstacle and landing on the obstacle.

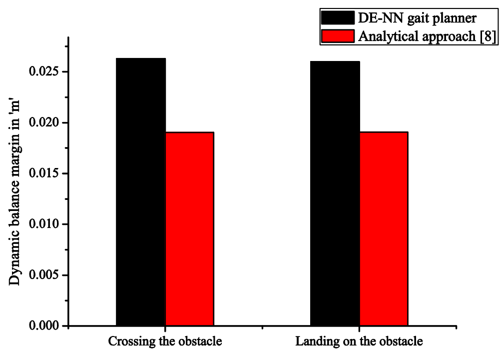


Fig. 8. Comparison of average DBM for obstacle crossing and lading gait generation of a biped robot.

Moreover, the gait generated during crossing the obstacle and landing on the obstacle using DE-NN (Fig. 10) gait planner is shown with the help of stick diagram.

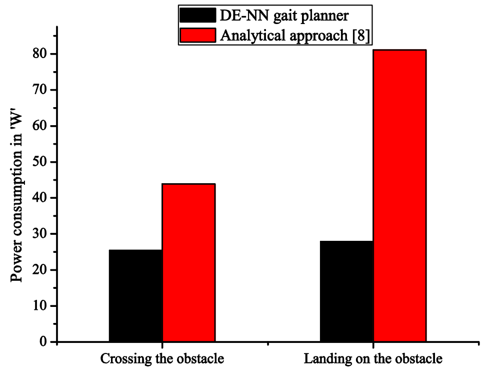
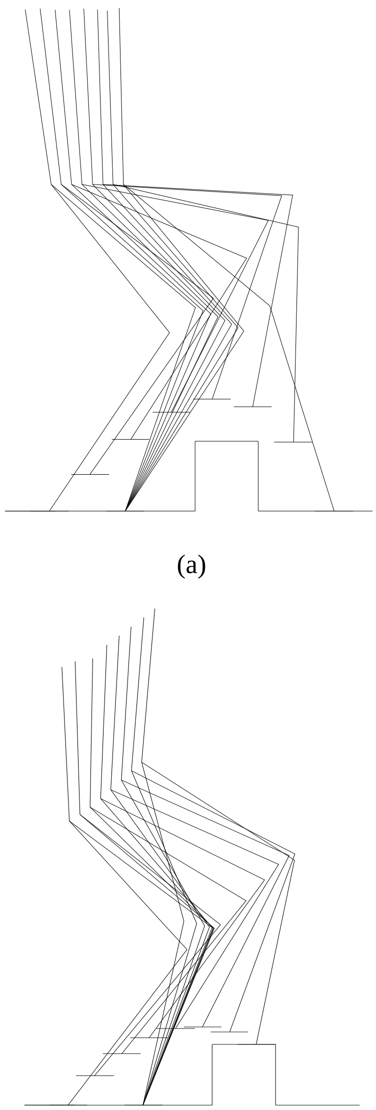


Fig. 9. Comparison of average power for obstacle crossing and lading gait generation of a biped robot.

From the stick diagram, it can be observed that in both the cases, that is, crossing the obstacle and landing on the obstacle, DE-NN gait planner have generated the gaits successfully after following the repeatability conditions.



(a)

(b)

Fig. 10. Stick diagram showing the gait generated using DE-NN gait planner (a) crossing the obstacle, (b) landing on the obstacle.

V. Conclusions

In the present study, DE-NN gait planner has been developed to generate the obstacle crossing gait generation of a biped robot. The results of simulation show that DE-NN gait planner has developed dynamically balanced obstacle crossing and landing on the obstacle gaits successfully. It has been observed that the gait generated during crossing the obstacle is more dynamically balanced when compared with the gaits generated during landing on the obstacle. On the other hand, the gait generated during crossing the obstacle consumes less power when compared with the gait generated during landing on the obstacle. Further, the knee torque is coming out to be more when compared with the torques required at other joints, which is exactly matching with the experience of human beings.

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