2017 2nd -AL-Sadiq International Science Conference on Multidisciplinary in IT and Communication Science and Technologies -2nd- AIC – MITC – Baghdad – IRAQ

Quadruped Robot Creeping Gait Stability Analysis and Optimization Using PSO

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Abstract — The potential ability of the quadruped (four-legged) robot locomotion has been used for many different applications such as walking over soft and rough terrains. These applications are needed to grantee the mobility and flexibility. Generally, quadruped robots have three main periodic gaits: creeping gait, running gait and galloping gait. The stability criteria is the main problem of the quadruped robot during walking with a slow motion gait such as creeping gait. The static stability gait is completely depends on the stability margins during the walking which have been calculated in this paper. The quadruped robot kinematic model of the forward and inverse kinematics for each 3-DOF leg has been calculated which leading to find the minimum stability margins during walking on the vertical geometrical projection of the robot body. These margins are needed to be optimized for achieving the best stability margin during the robot walking.in this paper we using the PSO optimization algorithm to find the best value of the stability margin. Simulation and results verify the stability margin range values and the optimized results.

Keywords: Quadruped Robot Simulation, Stability Margins Analysis, Quadruped Robot Gait, PSO Optimization.

I. Introduction

In the last years, utilization of the leg-based walking systems has been turned out to be very familiar in robotics field. These systems have been adapted their ability to dealing with irregular territories particularly when it's compared with the wheeled systems [1]. This ability of the legged systems for dealing with uneven territories and the avoiding of obstacles are used with the quadruped robots in the planning of standard walking gaits [2, 3]. The quadruped robots are preferred among the other legged robots of having a less complex structure, this structure giving it to fulfill the requirements of the statically stable gait during walking. The quadruped robots locomotion has been frequently used in many research which is talking about the quadruped robot and how it similar in the investigation of natural biological animals and insects walking gaits. These studies have prompted to improvement of both statically stable walking gait and dynamic running gaits for legged robots [4]. The main goal of this paper is to design and implement of a robust quadruped robot which has the ability to be statically stable during its walking. These gaits of walking are repeated to achieve the main step sequence that is needed to make the quadruped robot stable over irregular places [5]. The quadruped robots has also the ability of arranging the step sequences and stability verification criteria on incline surfaces which needed to verify the omni-directional statically stable during this walking [6]. Stability criteria is depended on some elements such as CoG (Center of Gravity), Sm (Stability margin) and the support polygon that framed by the legs tip of the quadruped robot. These elements are very important especially when the quadruped robot walking using creeping gaits for walking as shown in [7, 8]. The generation of the leg sequence of lifting and placing during the quadruped walking is called gait [9]. In the general, the quadruped robot is trying to be statically stable when there are three legs at least fixed on the ground while the other leg is swing. In this paper, the PSO optimization algorithm is used to find the best stability margins during the robot walking gait. The creeping gait matches the nature of the biological stable gait of animals and insects. In the case of creeping gait the statically stable gait is necessary to guarantee a stable walking. During the quadruped is walking with the creeping gait, it will be stable if and only if the CoG vertical projection is inside the supporting polygon that is framed by the legs tips. The main problem when the quadruped robot walking is how to achieve and control of the legs sequences of putting and lifting all legs during the period of time. So, the main point to ensure the stable walking in the statically stable gait, the quadruped legs positions are playing an important role during the walking of the stability calculations. The legs tips positions should be found by driving the forward kinematics and inverse kinematics for the quadruped robot.

II. Creeping Gait Analysis and Sequence Description

The quadruped robots have three main gaits. This gaits are classified according to its duty factor (β_i) of each leg, where i=1,..4 which is defined as the ratio of the time periods between the leg periods of swinging to the period that the same leg is contact with the ground. These gaits are: creeping, running and galloping. The quadruped robot locomotion has

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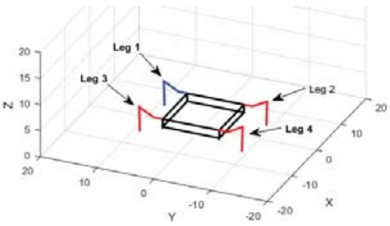
any type from these gaits according to its duty factor (β_i) When the quadruped robot walks using creeping gait, the value of the duty factor equals to 0.75 [10]. Hence, these gaits have been used by mammals. For example, cats are using the creeping gait for a very slow walking. Creeping gait has some advantages, this gait is ensure the statically stable movement which is used with the range of low-speed walking. The sequence condition of the creeping gait is need a three legs at least are contact with the ground. This sequence condition is needed to ensure the statically stable gait.



(a)

Fig.1.Quadruped Robot with four legs labeling.

In this paper, quadruped robot leg sequence is (RR, RF, LR, and LF) where (R: right, L: left, R: rear, F: front). From the labeling Figure (1) it can be seen that RR is leg4, RF is leg2, LR is leg3, and LF is leg1. The advantage of choosing this leg sequence arrangement to have a safety walking which is ensure that the robot is body moving forward at the instance time[11]. So, the leg coordinates are very important in the analyzing and ensuring that vertical projection of CoG have been located inside the supporting polygon [12].

III. Kinematics Modeling of a Quadruped Robot

A. *Forward kinematics*

The quadruped robot is depending on the configuration of each leg. Because each leg represents as the physical constraints of the robot walking. In this paper, the robot leg has three-revolute joints which are labeled in the kinematical chain as (θ_1,θ_2 and θ_3). Modeling of the leg structure is to mimic the biological structures for animals and insects. To drive the geometrical model to each leg which is related to the robot center body, thus forward kinematics must be applied to find the position and orientation for each leg tip which is here named as (xi, yi, zi), i=1,2,3,and 4. The kinematical chains for any leg is showing in the Figure (2)

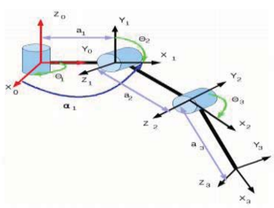


Fig.2. Coordinate frames for one leg of Quadruped Robot

Forward kinematics is depending on the D-H (Denavit-Hartenberg) parameters of the leg structure design; these parameters are showing in Table (I).

Table 1. The Denavit-Hartenberg parameters table for one leg in our quadruped robot

Link No.	Link name	$\boldsymbol{\alpha_i}$ (deg)	$\boldsymbol{a_i}$ (cm)	$\boldsymbol{d_i}$ (cm)	$\boldsymbol{\theta_i}$ (deg)
1	Coxa	90	a_1	0	θ_1
2	Femur	0	a_2	0	θ_2
3	Tibia	0	a_3	0	θ_3

Where the links parameter: a_1=2.5 cm a_2= 5 cm, and a_3= 9 cm. a_i are the lengths of the leg links. The transformation matrix used to translate from one link named i to another link named i-1 by using the D-H parameters table. The general matrix is given in equation (2)

$$T_i^{i-1} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

By multiplying each joint transformation matrix, the overall transformation matrix can be obtained as the following equation (2):

$$T_{coxa}^{base} = T_{coxa}^{femur} * T_{femur}^{tibia} \quad (2)$$

The transformation matrix for each joint in the quadruped robot leg is given by the following equations:

$$T_1^0 = \begin{bmatrix} c_1 & 0 & s_1 & a_1c_1 \\ s_1 & 0 & -c_1 & a_1s_1 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$T_2^1 = \begin{bmatrix} c_2 & -s_2 & 0 & a_2c_2 \\ s_2 & c_2 & 0 & a_2s_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$T_3^2 = \begin{bmatrix} c_3 & -s_3 & 0 & a_3c_3 \\ s_3 & c_3 & 0 & a_3s_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

Multiplications of these matrixes produce the final matrix that it used to describe the leg-tip position and orientation. The final position of the leg tip can be obtained as:

$$x_i = a_1c_1 + a_2c_1c_2 + a_3c_1c_{2+3} \quad (6)$$
$$y_i = a_1s_1 + a_2s_1c_2 + a_3s_1c_{2+3} \quad (7)$$
$$z_i = a_2s_2 + a_3\, s_{2-3} \quad (8)$$

Where: (x_i,y_i,z_i) is the leg-tip coordinates, i=1…4.

B. Inverse kinematics

The inverse kinematics is used to formulate and achieve the joint angles from the leg tip position and orientation which has been calculated from the forward kinematics.[13]Here in this paper, the goal of inverse kinematics is to find joint angles of each leg, θ_1,θ_2 and θ_3, from the leg position. The leg configuration assumed to be similar with the natural biological insect as shown in Figure (3). To solve the inverse kinematics for every legs its need to use the geometrical methods to find (θ_1,θ_2 and θ_3) as shown in Figure (3,4)

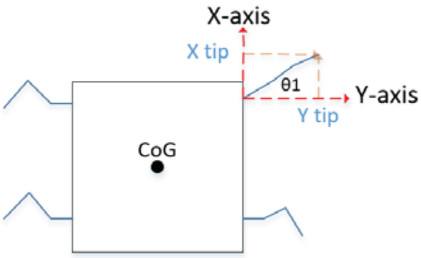


Fig.3. quadruped top view showing leg angle θ_1

θ_1, θ_2,and θ_3 can be calculated as:

$$\theta_1 = tan^{-1}(\frac{X\ tip}{Y\ tip}) \quad (9)$$

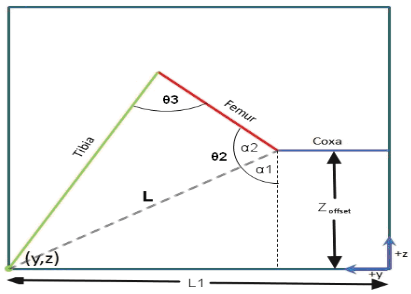


Fig.4: Quadruped robot leg and its links (Coxa, Femur, Tibia), θ_2 and θ_3 [13]

From Figure (4), θ_2 equals to:

$$\theta_2 = \alpha_1 + \alpha_2$$

$$\theta_2 = cos^{-1}\left(\frac{z_{offset}}{L}\right) + cos^{-1}\left(\frac{F^2+L^2-T^2}{2*F*L}\right) \quad (10)$$

By the same method, θ_3 is calculated as:

$$\theta_3 = cos^{-1}\left(\frac{F^2+T^2-L^2}{2*F*T}\right) \quad (11)$$

Where: F is the Femur link length and T is the Tibia Link length.

IV. Stability Analysis for quadruped creeping gait

The quadruped robot walks with a specific goal to have a statically stable movement. During the robot walking the vertical projection of CoG on the ground must be inside the supporting polygon. This is the main criterion which is conditioned for the statically stable walking. The quadruped robot is stable and will not turn down when it has been satisfied these conditions of the statically stable walking. The main advantage of the quadruped robot walking in periodically repeated locomotion is to produce a constant speed. This property is leading to the fact that the accelerations on the robot body are equal to zero, and the disturbances on the legs will be reduced. When the quadruped robot walking using creeping gait, the static stability walking is depending on the stability margins. These margins are defined as shortest distance between the vertical projection of CoG to the boundaries of the supporting pattern [11]. The next Figures are showing and explaining the quadruped robot model, and the stability margins mathematically analysis to find and calculate the stability margins as the following cases:

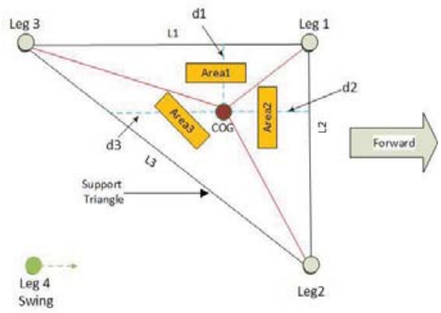


Fig.5: Quadruped robot (top-view) when leg4 is swinging and other legs are fixed on the ground

Case one: when the quadruped robot leg4 is swing and the other legs (1, 2, and 3) are fixed on the ground as showing in Figure (5). The supporting area will be divided into three areas called ($Area_1$, $Area_2$, and $Area_3$). The blue lines are the lines of the stability margins which are needed to be the minimum from the vertical projection of CoG to the supporting lines (L_1, L_2, and L_3). These blue lines are denoted as (d_1, d_2, and d_3). After this method is applied, the stability margins will be found as:

By expanding and simplify this matrix $Area_1$can be calculated as the following:

$$Area_1 = \frac{1}{2}\left\{\begin{matrix}(x_1 - x_{cog})(y_3 - y_{cog}) - \\ (x_3 - x_{cog})(y_1 - y_{cog})\end{matrix}\right\}$$

$$L_1 = \sqrt{(x_1 - x_3)^2 + (y_1 - y_3)^2}$$

$$d_1 = 2 * (\frac{Area_1}{L_1}) \quad (12)$$

By the same way, $Area_2$ and $Area_3$ will be found as:

$$Area_2 = \frac{1}{2}\left\{\begin{matrix}(x_1 - x_{cog})(y_2 - y_{cog}) - \\ (x_2 - x_{cog})(y_1 - y_{cog})\end{matrix}\right\}$$

$$L_2 = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

$$d_2 = 2 * (\frac{Area_2}{L_2}) \quad (13)$$

$$Area_3 = \frac{1}{2}\left\{\begin{matrix}(x_2 - x_{cog})(y_3 - y_{cog}) - \\ (x_3 - x_{cog})(y_2 - y_{cog})\end{matrix}\right\}$$

$$L_3 = \sqrt{(x_2 - x_3)^2 + (y_2 - y_3)^2}$$

$$d_3 = 2 * \left(\frac{Area_3}{L_3}\right) \qquad (14)$$

Finally, the first stability margin sm_1 is the minimum distance from these three margins:

$$sm_1 = min(d_1, d_2, d_3) \qquad (15)$$

The other stability margins have been calculated when the other legs are swinging respectively. As sm_1 analyzed, the other margins are equals to:

$$sm_2 = \min(d_4, d_5, d_6) \qquad (16)$$
$$sm_3 = \min(d_7, d_8, d_9) \qquad (17)$$
$$sm_4 = \min(d_{10}, d_{11}, d_{12}) \qquad (18)$$

V. Stability Margins Optimization using PSO

The stability margins is analyzed of each leg sequence when the quadruped robot walking with creeping gait. These margins are varying between ranges of values. It needs to achieve the optimal value of each stability margin. In this section an optimization method called Particle Swarm Optimization is used to optimize the stability margins to have the best stability margin during the quadruped robot walking with creeping gait locomotion.

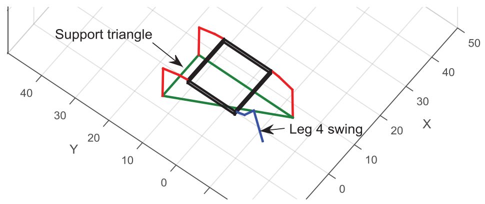
The PSO optimization algorithm is based on some features such as:

a) Cost function: this is the main function of the problem that it needs to be optimized. In this paper, the main parameters that will pass to the cost function are the robot body center in X-axis and Y-axis and the leg tips which are presented as the constraint of the cost function.
b) Minimum and Maximum values of variables: in this paper, the stability margin limiting values are presented as VARmin and VARmax
c) Number of iteration: the number of iteration is: 500 iteration
d) Number of population: the number of population equals to 5.
e) The initial weight : the initial weight $W_{initial} = 1$, and the damping weight $W_{damp} = 0.99$
f) The constant values $C_1$and C_2: C_1=3.999 and $C_2 = 0.001$.

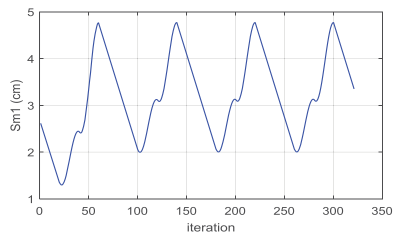
All these parameters are playing a very important role for enhancement the optimization method working. The PSO optimization results of the stability margins are showing in section VII.

VI. Simulation and Results

In this section, the quadruped robot walking according to the creeping gait sequence locomotion is shown. Each gait has its stability margin is varying between a range of values according to which leg is swing in the air. After finding the stability margin of each gait, applying the PSO optimization algorithm to achieve the best stability margin which gives the best stability that it used to balance the quadruped robot at the period when it walks with creeping gait locomotion. As shown in the following Figures.

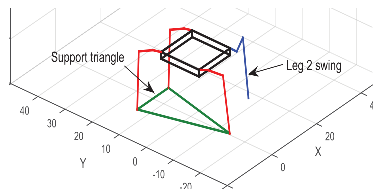


(a)

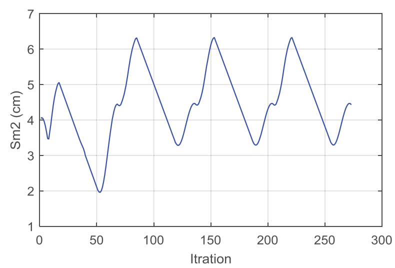


(b)

Fig.6 showing (a) Leg 4 in swinging phase (b) The stability margin Sm_1(cm) when leg4 is swing.

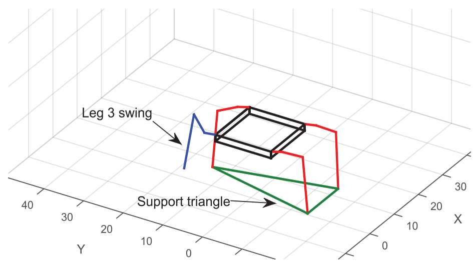


(a)

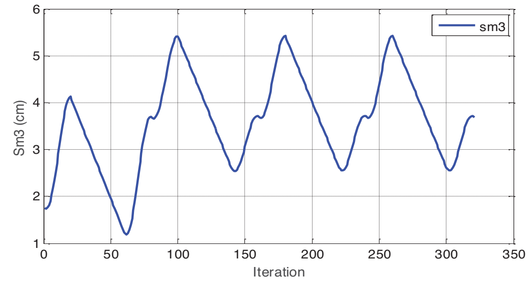


(b)

Fig.7 showing (a) Leg 2 in swinging phase. (b) The stability margin Sm_2(cm) when leg2 is swing.

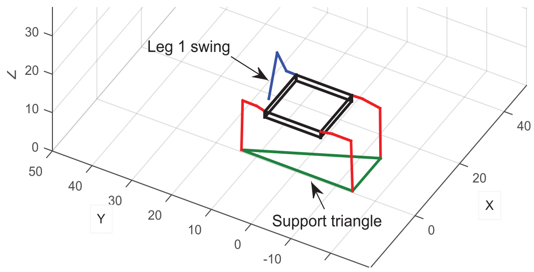


(a)

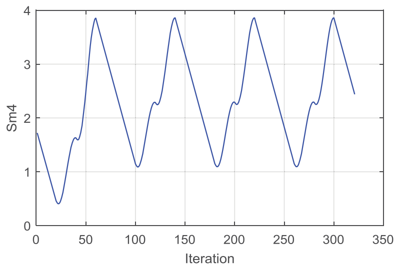


(b)

Fig.8 showing (a) Leg 3 in swinging phase. (b) The stability margin Sm_3(cm) when leg3 is swing.



(a)



(b)

Fig.9. showing (a) Leg 1 in swinging phase. (b) The stability margin Sm_4(cm) when leg1 is swing.

From the PSO optimization algorithm are showing in the following Figures

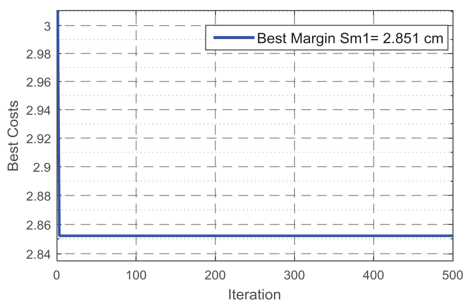


Fig.10 . Best cost for the stability margin Sm_1

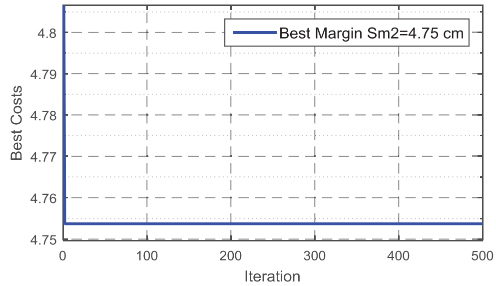


Fig.11 . Best cost for the stability margin Sm_2

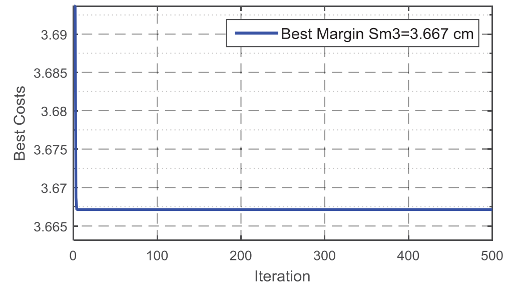


Fig.12 : Best cost for the stability margin Sm_3

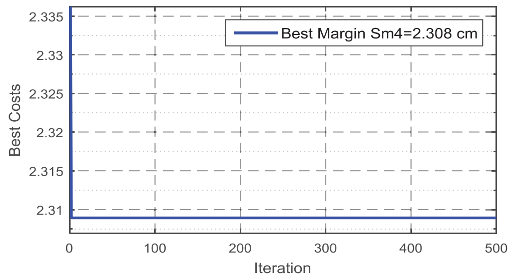


Fig.13 . Best cost for the stability margin Sm_4

The following Table (II) produces a comparison between the classical stability margins analysis and proposed optimization using PSO algorithm method.

Table II. Stability margins comparison between the classical analyses and the optimized method

Classical Analysis Method	**Proposed Optimization using PSO algorithm**
1.When Leg 4 is swing, the Sm_1 equals to 2.9 cm	1. When Leg 4 is swing, Sm_1 equals to 2.851 cm
2.When Leg 2 is swing, the Sm_2 equals to 4.1 cm	2. When Leg 2 is swing, the Sm_2 equals to 2.75 cm.
3. When Leg 3 is swing, the Sm_3 equals to 3.85 cm	3. When Leg 3 is swing, Sm_3 equals to: 3.667 cm.
4. When Leg 1 is swing, the Sm_4 equals to 2.5 cm	4. When Leg 1 is swing, the Sm_4 equals to: 2.308 cm.

During the optimized creeping gait sequence, the quadruped robot leg angles are changing. These angles are (θ_1,θ_2 andθ_3) of each leg when the robot is walking with the optimized stability margins. This changing is showing in Figure (13, 14, and 15).

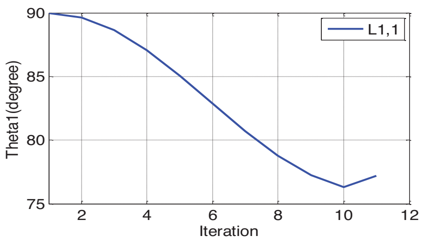


Fig.13: Changing of Coxa-angle in one step movement

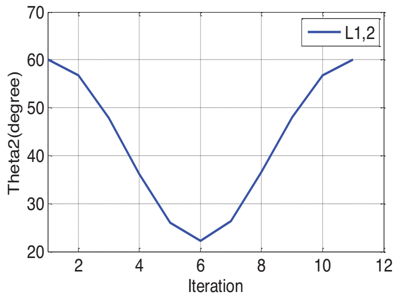


Fig.14. Changing of Femur-angle in one step movement

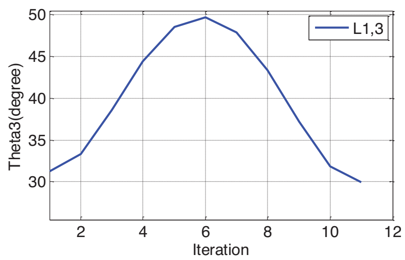


Fig.15. Changing of Tibia-angle in one step movement

VII. Conclusion

Illuminating main points of this paper is about the analyze the walking of quadruped robot creeping gait also the derivation, confirm and demonstrate that the robot is statically stable throughout walking. In order to access the goal of the work, first, the entire forward and inverse kinematics model derived and has been used for stability validation of walking steps. Thus the intersection between sequence of creeping gait for this robot and the modeling of geometric for robot legs-tip has been all derived to find all the static stability margins throughout walking. The results obviously demonstrate the best stability margins possess the minimum values by using PSO algorithm that guarantee the preservation of robot COG into the supporting triangle via the swing phase for one leg with the rest legs are on the ground. Moreover, an improvement for future work is necessary to enhance and analyze the quadruped robot walking on rough and hard terrain.

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