A novel biologically inspired tripod walking robot

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3 authors:

Conghui Liang
ZOOMLION Central R&D

Marco Ceccarelli
Università degli studi di Roma Tor Vergata

Giuseppe Carbone
Università della Calabria

A Novel Biologically Inspired Tripod Walking Robot

CONGHUI LIANG, MARCO CECCARELLI, GIUSEPPE CARBONE
LARM: Laboratory of Robotics and Mechatronics
University of Cassino
Via Di Biasio 43, 03043 Cassino (Fr)
ITALY
{liang.conghui, ceccarelli, carbone }@unicas.it   http://webuser.unicas.it/weblarm/larmindex.htm

Abstract: - This paper describes a novel biologically tripod walking robot that is inspired by the tripod gaits existing in nature. The mechanical design problem is investigated by considering the peculiar requirements of leg mechanism to have a proper tripod walking gait. The proposed tripod walking robot is composed of three leg mechanisms with linkage architecture. The proposed leg mechanism is modeled for kinematic analysis and equations are formulated for simulation. A program is developed in Matlab environment to study the operation performance of the leg mechanism and to evaluate the feasibility of the tripod walking gaits. Simulation results show the operation characteristics of the leg mechanism and the feasible walking ability of the proposed tripod walking robot.

Key-Words: - Robotics, Walking robots, Leg mechanisms, Gait analysis, Mechanical design

1 Introduction

Legged walking robots such as biped robots, quadrupeds, hexapods and eight-legged robots have attracted great interests in the past decades. Legged locomotion has a lot of advantages as compared with wheeled locomotion. It is versatile and flexible when it operates in rough terrain or in unstructured environments [1][2].

Among legged walking robots, biped walking robots are the human-like solutions but sophisticated control algorithms are needed to keep balance during operation [3]. Multi legged robots have a good stable walking performance and can operate with several walking gaits. However, the number of motors increases together with legs. How to coordinate control the motors and gaits synthesis are still difficult problems [2].

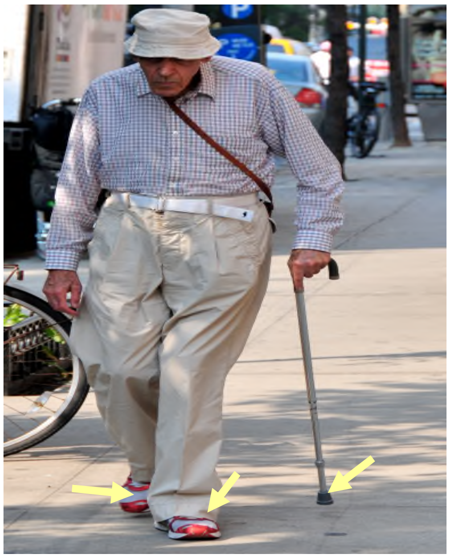
Leg mechanisms with a limited number of degrees of freedom (DOF) are widely used in legged walking robots for the purpose of reducing the number of motors and simplifying the control algorithms [4]. At LARM: Laboratory of Robotics and Mechatronics in Cassino, reduced DOF leg mechanisms have been implemented in several prototypes like one-DOF biped robot [5][6], and a rickshaw walking robot [7]. A one-DOF biped robot has been able to perform a biped walking gait in a lab test [8]. Additionally, research interests are focused on a biologically inspired tripod walking robot. With the aim to build a tripod walking robot with reduced DOF leg mechanisms and simplified control algorithms, so that it can walks on the ground stably by mimicking the tripod walking gaits existing in nature.

This paper deals with a design problem for a new walking robot by looking at solutions in elder people walking. Thus, a mechanism design is proposed as to be implemented for a novel tripod human-like walking robot.

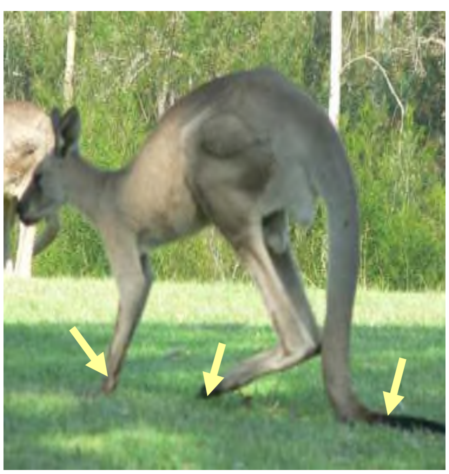
2 Biology Inspirations

Legged locomotion in walking robots is mainly inspired by nature. For example, biped robots mimic the human walking; quadruped robots perform leg motion like dogs or horses and eight legged robots are inspired to spider-like motion. Most of animals have an even number of legs with symmetry character. With this important character animals can move easily, quickly and stably. It seems that there are no animals with three legs exsisting in nature. How does a tripod walking robot look and how to implement a tripod walking gait?

Actually, there are some tripod walking experiences in nature, even around our daily life. A significant example of tripod walking can be recognized in old men walking with a cane as shown in Fig.1.a). Two human legs and a walking cane as a third leg can produce a special tripod walking gait. With this kind of tripod walking gait, old people with aged or illness nervous system can walk more stably since they always keep two legs in contact with the ground at the same time. Additionally, a standing phase is more stable since there are three legs on the ground and forms a rigid triangle configuration. There are also some tripod motions in animals. Normally, a kangaroo moves by jumping with its powerful back legs in a kind of dynamic movement. However, as shown in Fig.1.b), a kangaroo can walk as with the front legs moving together as a first leg, the back legs moving together as a second leg and the tail as a third leg. With this peculiar walking gait smaller and dexterous stance motions can be obtained. In addition, even the brittle-stars can move very well with a weird locomotion with remaining three legs when it loses two legs.



a)



b)

Fig.1 Tripod walking gaits in nature; **a)** an old man walking with a cane; **b)** a kangaroo walks with legs and tail.

Therefore, from previous observations of old men walking gaits, biology inspirations can be obtained: three legs in contact with ground forms a triangle in horizontal plane with one leg ahead and other two legs back in the same line. In a standing phase, the gravity center of the tripod robot falls within the triangle, which is determined by three legs contact with the ground. In this condition, a very good static balance can be obtained and the tripod walking robot can implement some tasks with a manipulator installed on its body. In the motion phase, there will be always two legs in contact with the ground at the same time, by adjusting the gravity center of the robot between the two supporting legs, the static equilibrium can be achieved easily and adjusted with slight body motion. Additionally, in a full walking cycle, each leg should has 2/3 time on the ground and another 1/3 time swings in the air.

There are very few works dealing with the tripod walking robots. In the works [9][10] STriDER (The Self-excited Tripedal Dynamic Experimental Robot) is presented as developed at Virginia Tech University by using and controlling the passive dynamic behavior when one leg swings from back to forth. Another tripod walking robot has been developed at University of Yamagata, Japan, as actuated by several number of motors and its walking gait is analyzed in [11]. Thus, from the cases in nature and those preliminary robots design, it is possible to recognize a challenge for a tripod walking robot design as a promising solution for the easy-walking problem.

3 The Mechanism Design Problem

The mechanism design problem can be started by considering a concept of a tripod waking robot model as shown in Fig.2. The scheme of the mechanism in Fig.2 is a simplified structure with two degrees of motion and freedom which can perform a required back and forth, up and down movement in saggital plane. Actuation motors are fixed at the point C_1, C_2 and C_3. Two feet grasp the ground at point A_1 and point A_2 while the third leg swings from back to forth. The two legs in contact with the ground together with the robot body form a parallel mechanism.

It is intuitive to put two motors on each leg mechanism at the positions of hip and knee. However, this solution not only increase the number of motors but also greatly complicate the control algorithms. As it is well known, in a parallel mechanism coordinated control of the legs are needed to move the end effector to follow a prescribed trajectory. Therefore, how to plan the operation of each motor so that the two legs on the ground can propel the body forward stably without force confliction is a challenge problem. In addition, the dynamic balance of the robot has to be considered when it walks.

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In this paper, we propose to implement the reduce DOF leg mechanism in the leg design of a tripod walking robot. With only one DOF for each leg, the control algorithm can be simplified and even not needed, as well as the mechanism can be compactness and robust. In addition this introduces a low-cost easy-operation feature of the tripod robot as compared with traditional legged robot designs. In a previous paper [8], a investigation on the operation of an one-DOF leg mechanism is presented for an one-DOF biped robot. The one-DOF leg mechanism can produce an ovoid curve of a foot point in saggital plane. Thus three leg mechanisms with that design can be implemented in a tripod design. Since each leg produces a curve motion in saggital plane but with different actuation time, a force conflict exists between the two legs when they are in the supporting phase. Therefore, the leg mechanism can not be implemented in the tripod walking robot design directly but adjustments are needed, mainly in operation programming.

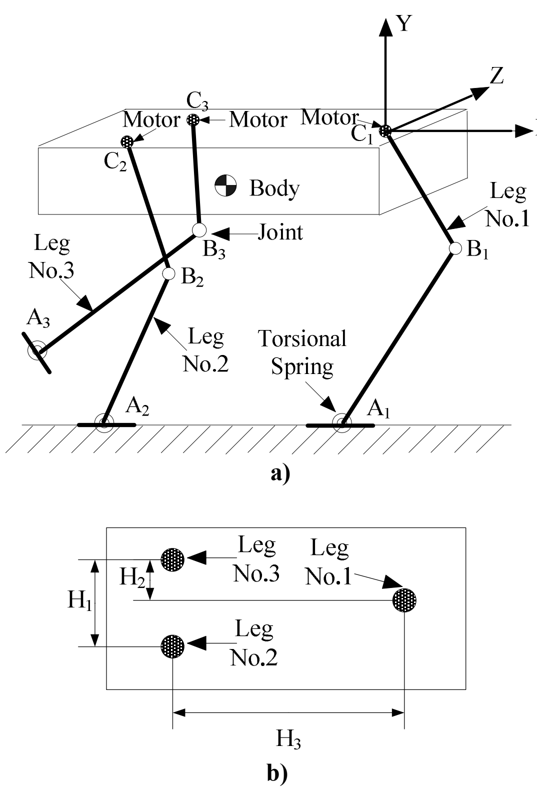


Fig.2 A simplified model of the conceptual design of a tripod walking robot; **a)** three legs configuration; **b)** contacts of three legs in horizontal plane.

In a tripod walking gait each leg must has 2/3 period of time in supporting phase and another 1/3 time in swinging phase. In order to avoid the problem of force conflict between legs, a solution is that the two legs on the ground can produce a straight line motion in horizontal plane with the same speed and without waving in vertical direction. Therefore, the operation of the three legs is the same with only 1/3 actuation phase difference. A careful analysis will help to define a propel operation of the leg mechanism. The problem is to propose an one-DOF leg mechanism which can produce a straight line motion in horizontal plane during 2/3 period of time of a cyclic motion. The tripod walking robot design problem can be solved with three of these leg mechanisms operating with different actuation phases.

4 The Proposed Mechanism

A scheme of the proposed mechanism for tripod walking robot is shown in Fig.3. The tripod walking robot is mainly composed of three one-DOF leg mechanisms. The three leg mechanisms are the same design which are installed on the robot body to have a triangle configuration in horizontal plane. All the three legs are fixed on the body and actuated by DC motors. The leg mechanism is sketched with design parameters in Fig.3.

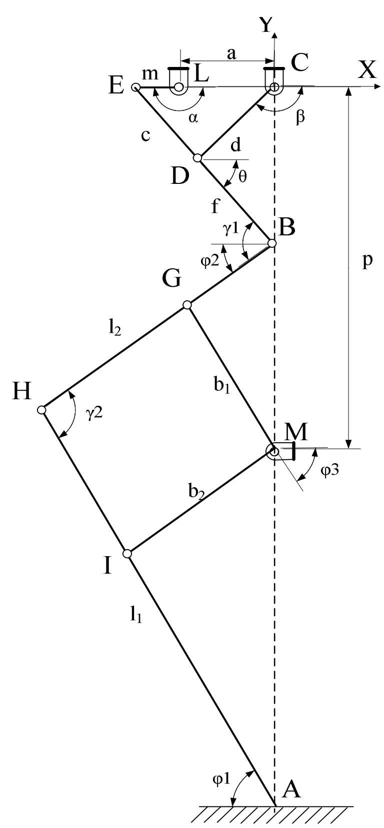


Fig.3 A scheme for the proposed leg mechanism with design parameters for a tripod walking robot.

The basic kinematics and operation characters of the proposed leg mechanism is investigated in the work [7]. This one-DOF leg mechanism is composed of a Chebyshev four-bar linkage CLEDB and a pantograph mechanism BGMHIA. Points L, C and M are fixed on the body. The Chebyshev mechanism and pantograph mechanism are jointed together at point B through which the actuation force is transmitted from the Chebyshev linkage to the pantograph leg. Linkage LE is the crank and α is the input crank angle. The transmission angles γ_1 and γ_2 of the leg mechanism are shown in the Fig.3.

When the crank LE rotates around point L, an ovoid curve with an approximate straight line segment and symmetry path as traced by foot point A as shown in Fig.4. Each straight line segment has a 180^o phase in the crank rotation input. The straight line segment represents the supporting phase and the curve segment represents the swinging phase. When the leg mechanism operates in a supporting phase it generates a horizontal motion to points L, C and M which are fixed at the body. Therefore, the body of the robot is propelled forward without force conflict between two legs contacting the ground.

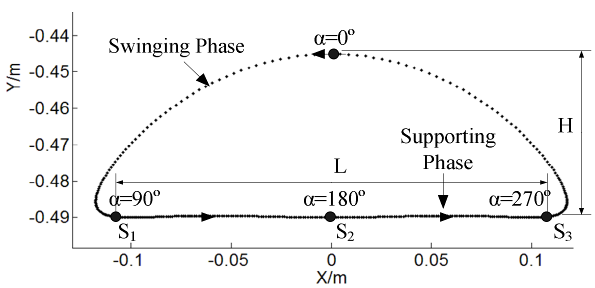


Fig.4 A scheme of the ovoid curve that is generated by point A of a leg mechanism in Fig.3.

Another problem is how to prescribe the coordinated motion of three leg mechanisms. Since there must be 2/3 period of time on the ground for each leg so that a tripod walking gait can be obtained. However, as shown in Fig.4, the supporting phase and swinging phase of the leg mechanism are half time in a full cycle operation of a leg.

A feasible solution is that the actuation speed of the input crank is twice during swinging phase as compared with supporting phase. As shown in Fig.4, points A_i (i=1, 2, 3) are the end points of three leg mechanisms. They trace the same ovoid curve but with 90^o actuation phase differences in supporting phase. Therefore, there will be always two legs in contact with the ground and another leg swings in the air.

5 A Kinematic Analysis

A kinematic study of the proposed mechanism for the tripod walking robot is aimed to define the operation coordination of the legs. Since the mechanism architecture of the three legs are the same type with only 90^o actuation angle differences. Attention can be addressed to the operation among the legs. Therefore, operation performance of one leg mechanism only can be investigated.

A scheme of the leg mechanism with design parameters is shown in Fig.3. By fixing a reference frame XY at point C, the position of point B can be formulated as function of input crank actuation angle α as, [7]

$$X_B = -a + m\cos\alpha + (c+f)\cos\theta$$

$$Y_B = -m\sin\alpha - (c+f)\sin\theta \tag{1}$$

where

$$\theta = 2\tan^{-1}\left(\frac{-B + (B^2 - 4AC)^{1/2}}{2A}\right) \tag{2}$$

and

$$A = a^2 - d^2 + m^2 + c^2 + 2ac - 2m(c+a)\cos\alpha$$

$$B = 4mc\sin\alpha$$

$$C = a^2 - d^2 + m^2 + c^2 - 2ac + 2m(c-a)\cos\alpha \tag{3}$$

also

$$\beta = \cos^{-1}\left(\frac{-a + m\cos\alpha + c\cos\theta}{d}\right) \tag{4}$$

By considering the pantograph mechanism BGHMIA, the position of point A can be formulated as, [7].

$$X_A = X_B - l_2\cos\varphi_2 + l_3\cos\varphi_3$$

$$Y_A = Y_B - l_2\sin\varphi_2 + l_3\sin\varphi_3 \tag{5}$$

The close-loop equations for two transmission angles φ_2 and φ_3 can be solved to obtain as, [7]

$$\varphi_2 = 2\tan^{-1}\left(\frac{-E - (E^2 - 4DF)^{1/2}}{2D}\right)$$

$$\varphi_3 = \cos^{-1}\left(\frac{-X_B + (l_2 - b_2)\cos\varphi_2}{b_1}\right) \tag{6}$$

where

$$D = X_B^2 - b_1^2 + (l_2 - b_2)^2 + Y_B^2 + p^2 + 2(l_2 - b_2)X_B + 2Y_B p$$

$$E = -4(Y_B + p(l_2 - b_2)) \tag{7}$$

$$F = X_B^2 - b_1^2 + (l_2 - b_2)^2 + Y_B^2 + p^2 - 2(l_2 - b_2)X_B + 2Y_B p$$

By assuming that point A is fixed on the ground, according to the geometry relationship of the leg mechanism as shown in Fig. 3, the position of point L, C, and M can be formulated as function of the input crank angle α. The equations of velocity and acceleration of point A can be also obtained by derivating the equation (5). In this paper, equations (1) to (7) are used to perform a kinematic simulation in Matalb environment to characterize the operation performance of the proposed mechanism, even for operation programming purposes.

6 Simulation Results

Simulations have been computed in the Matlab environment with suitable codes of the proposed formulation. The design parameters of the mechanisms for simulation are listed in Tab.1. The rotation velocity of the input crank actuation angle is set at 270 deg/s. Each step lasts in 1/3 second for each leg, and numerical simulation has been computed for 2 seconds to evaluate a walking behavior in a stationary mode .

Table 1 Design parameters of the proposed leg mechanism for the tripod walking robot in Fig.3 and Fig.2.b).

Chebyshev Mechanism (mm)		Pantograph Mechanism (mm)		Leg Location (mm)
d=62.5	m=25	l_1=330	l_2=150	H_1=100
c=62.5	a=50	b_1=110	b_2=100	H_2=100
f=62.5	p=230	p=230	_	H_3=240

In Fig.5, the tripod walking robot is given at initial configuration with the input crank angles α_1=180°, α_2=90° and α_3=270°. At this initial time, the three legs are on the ground with two legs in supporting phase and the third leg is about to get into swinging phase.

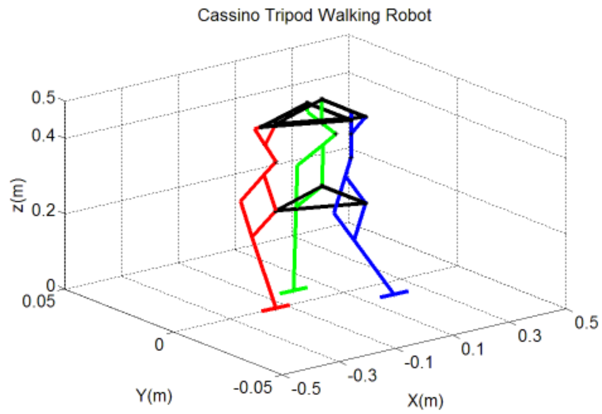


Fig.5 The tripod walking robot at initial configuration with α_1=180°, α_2=90° and α_3=270°

In Fig.6, a sequence of snapshots are shown for the tripod walking robot walks in three dimension space as computed in the numerical simulation. The trajectories of points A_i (i=1,2, 3) of the feet are depicted with small curves.
In Fig.7, the movements of the legs for tripod walking robot are shown in saggital plane. The positions of three feet are also shown in horizontal plane as referring to the computed snapshots in Fig.6. As shown in Fig.7, at each step, there are always two legs contacting the ground.
Actually, a balancing mechanism can be installed on the body of the robot to adjust the gravity center between the two legs, which grasp the ground at each step. A four-bar linkage with a proper mass at end is likely to be installed on the body of robot as a balancing mechanism. Therefore, with a very simple control algorithm and specially sized balancing mechanism the tripod walking robot can walk with a static equilibrium even while it is walking.
A typical walking cycle for the proposed tripod walking robot can be described as following by referring to Fig.6 and Fig.7. The leg No.3 leaves the ground and swings from back to forth in the so-called swinging phase; at the same time the leg No.1 and the leg No.2 are in the supporting phase, since they are in contact with the ground and they propel the body forward. The speed of the input crank in leg No.3 is twice than in leg No.2 and Leg No.1. When the swinging leg No.3 touches the ground, it starts the

propelling phase and the leg No.1 is ready to leave the ground. When Leg No.2 touches the ground, the tripod robot completes one cycle of walking.

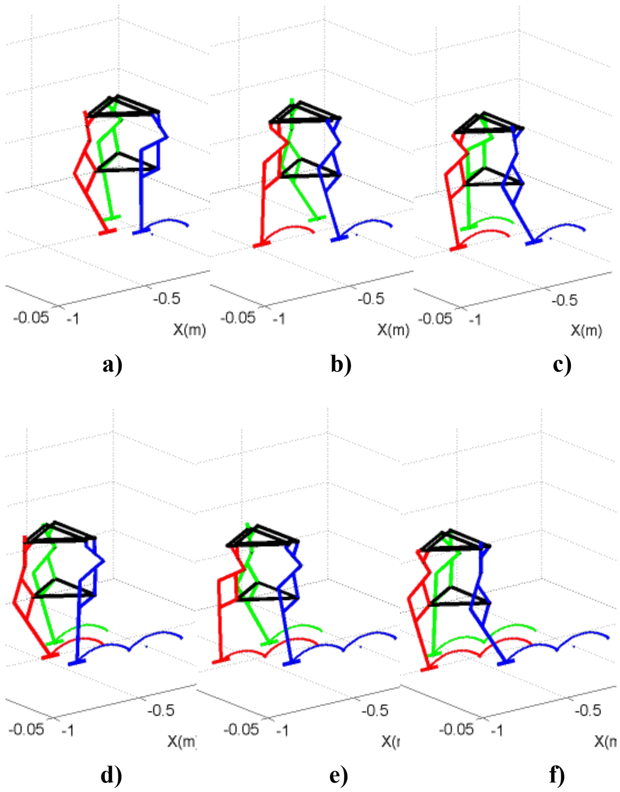


Fig.6 Walking snapshots of the tripod walking robot as function of the input for leg motion: **a)** α_1=270°; **b)** α_1=90°; **c)** α_1=180°; **d)** α_1=270°; **e)** α_1=90°; **f)** α_1=180°.

In order to investigate the operation characteristics and feasibility of the proposed mechanism, the plots of transmission angles γ_1, γ_2 and leg angles φ_1, φ_2 for three legs are shown as function of time in Fig.8 and Fig.9, respectively.

The plots are depicted for each leg. It can be found out that the transmission angle γ_1 varies between 60° and 170° and γ_2 varies between 70° and 120°. According to the kinematics rule of linkages, a feasible and effective transmission can be obtained for the proposed leg mechanism.

The plots of leg angles φ_1, φ_2 are shown in Fig.9. Angle φ_1 varies in a feasible region between 45° and 95°. It reaches the maximum value at the transition point from swinging phase to supporting phase and the minimum value vice versa. Angle φ_2 varies between 5° and 72°.Therefore, no conflict exists between pantograph mechanism and Chebyshev linkage in the proposed leg mechanism.

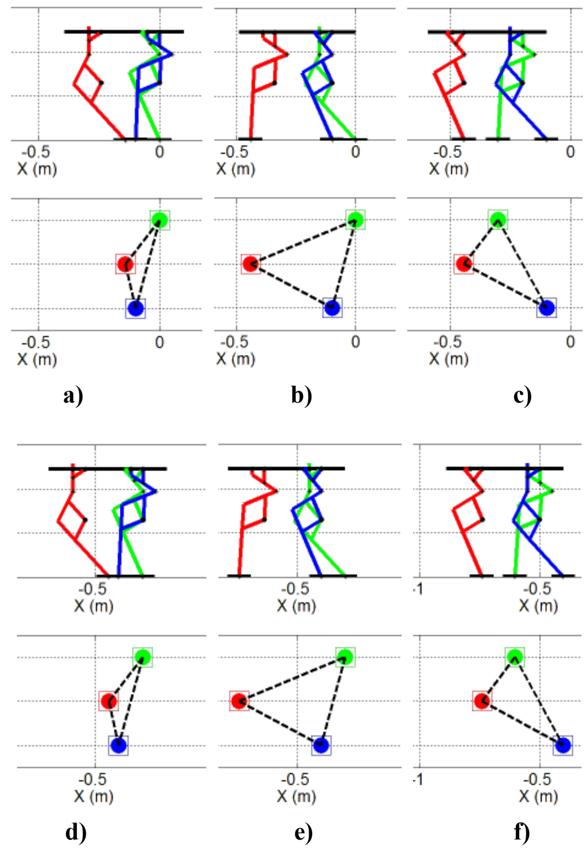
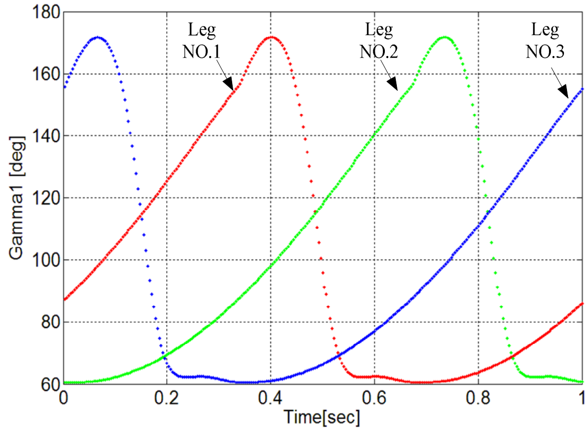


Fig.7 Walking sequences and trajectories of the feet in saggital plane and position of the three feet in horizontal plane as in Fig.6; **a)** α_1=270°; **b)** α_1=90°; **c)** α_1=180°; **d)** α_1=270°; **e)** α_1=90°; **f)** α_1=180°.

Fig.10.a) shows plots the motion trajectories in saggital plane for points A_i (i=1, 2, 3). Dimension of the length and height for each step are depicted as L and H, respectively. These two dimension parameters are useful to evaluate walking capability and obstacles avoidance ability for the tripod walking robot. They have been computed as L=300 mm and H=48 mm for each step.

A tripod walking gait is composed of three small steps. Fig.10.b) shows the positions of points of C_i (i=1, 2, 3) in saggital plane. It can be noted that the trajectories are approximate straight lines with very small waving. Therefore, the body of the tripod walking robot has a very small movement of less 5 mm in vertical direction and can be seem as an energy efficiency walking gait. It is computed that the body of robot is propelled forward 100 mm for each leg step. Therefore, the body is propelled forward 300 mm in a cycle of tripod walking gait. The walking speed can be computed as 0.3 m/s. However, there is a period of time that points C_2 and C_3 do not maintain the rigid body condition, but they move very slightly with respect to each other. Actually, this happens because the propelling speeds of two supporting legs are different. Therefore, a small difference of the motions between points C_2 and C_3 have been computed in the simulation of the walking gait.



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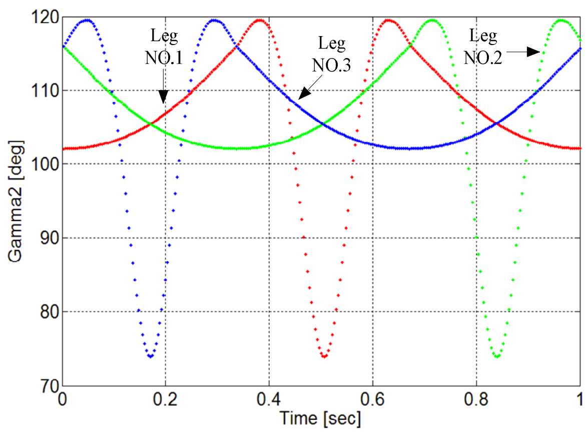
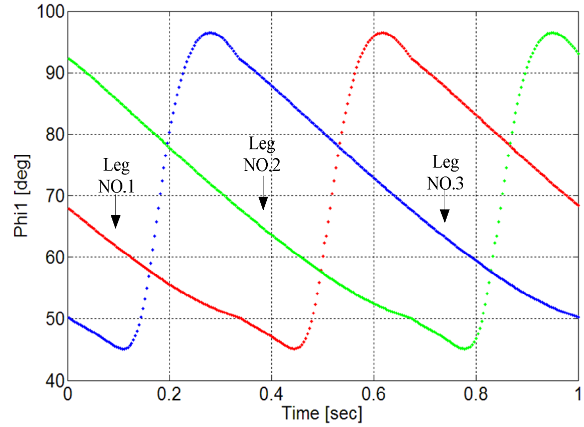


b)

Fig.8 The transmission angles of the three leg mechanisms during a simulated walking as function of time; **a)** transmission angle γ_1; **b)** transmission angle γ_2.

Fig.11 shows those differences between the positions of points C_i (i=1, 2, 3) as corresponding to Fig.10, during the tripod walking. Fig.11.a) shows the differences in X axis and Fig.11.b) in Y axis, respectively. The difference in X axis is less than ΔX_2=5 mm and difference in Y axis is less than ΔY_2=1.6 mm. The difference in Y axis can be used as compliance capability during the walking also to smooth the ground contacts. The difference in X axis can be compensated by installing a passive prismatic translation joint on the leg joints at the robot body.



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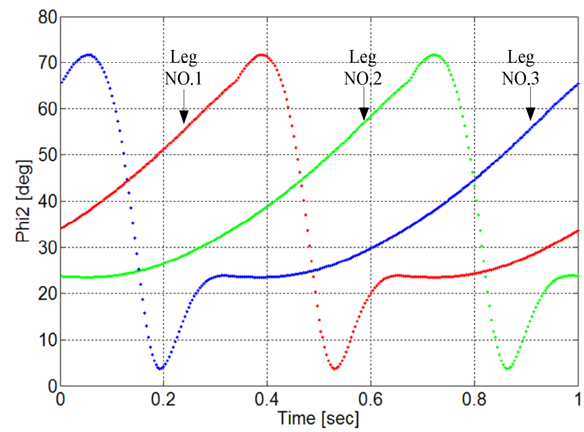

b)

Fig.9 The transmission angles of three leg mechanisms as function of time; **a)** transmission angle φ_1; **b)** transmission angle φ_2.

The plots of velocity at points A_i (i=1, 2, 3) in X and Y axis are shown in Fig.12.a) and .b), respectively. It can be noted that the velocity reaches the maximum value when the legs move to the highest point in a swinging phase in X axis. At the same point the velocity in Y axis is zero and the sign of velocity is changed. In the supporting phase because points A_i (i=1, 2, 3) are on the ground, the velocity is zero. Since the input crank speed is twice time in swinging phase than that in supporting phase, the plots are discontinuous at the transition point. Actually, this can be modeled as an impact between feet and ground, that can be smoothed by the above mentioned differences in the paths of C_i points.

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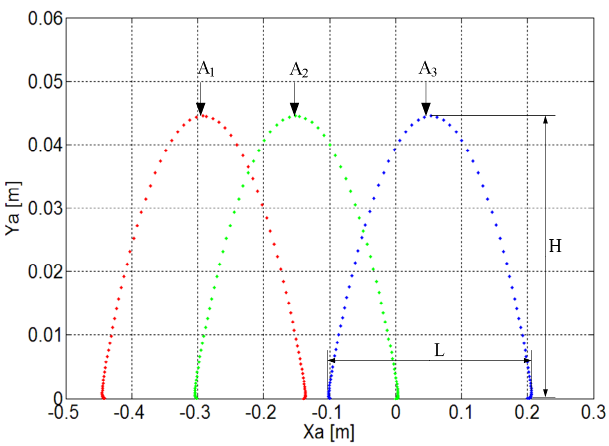

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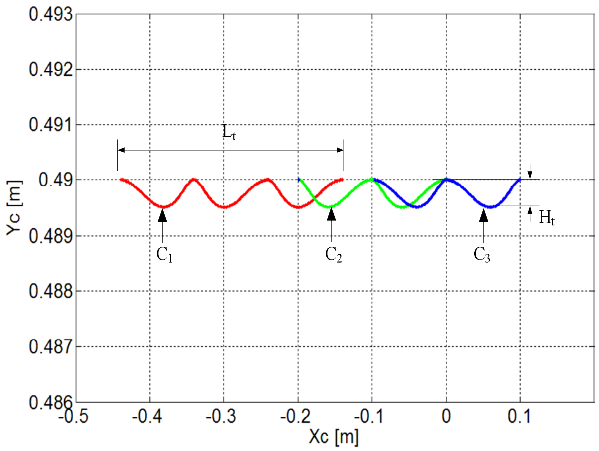
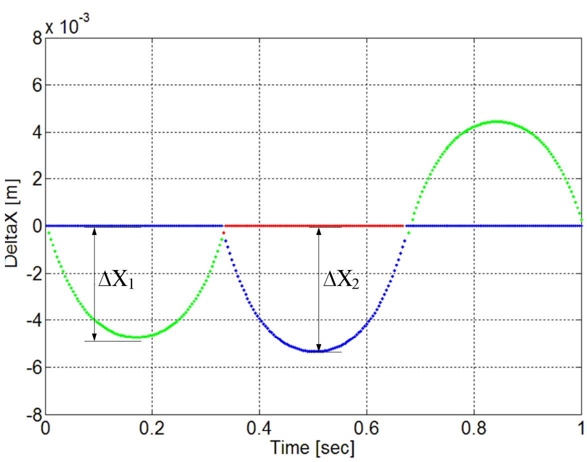


b)

Fig.10 The position of point A and point C in Saggital XY plane for three legs; **a)** positions of points A_i (i=1, 2, 3); **b)** positions of points C_i (i=1, 2, 3).



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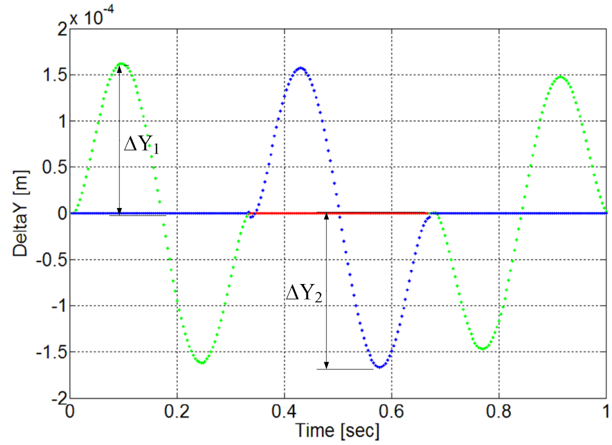
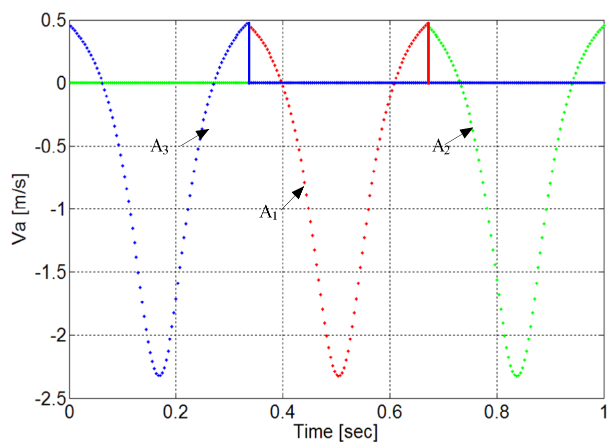


b)

Fig.11 The errors between points C_i (i=1, 2, 3) in Fig.10 as function of time; **a)** errors in X axis; **b)** errors in Y axis.



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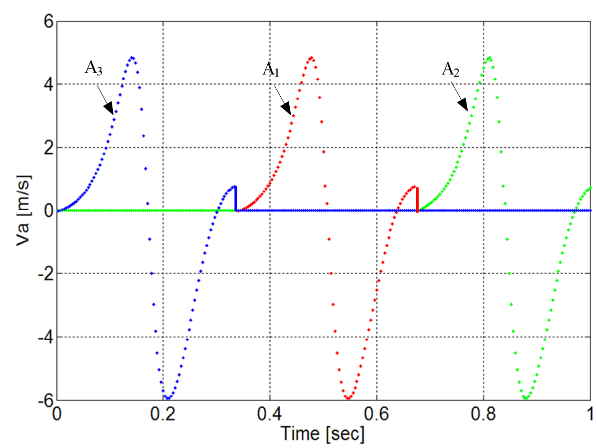

b)

Fig.12 The velocity of points A_i (i=1, 2, 3) as function of time; **a)** velocity in X axis; **b)** velocity in Y axis.

7 Conclusion

In this paper, a novel biologically inspired tripod walking robot is proposed by defining suitable design and operation solution for leg mechanism. The proposed mechanism of the tripod walking robot is aimed to reduce the number of motors and to improve walking behavior in a static equilibrium mode. The kinematic characteristics of the leg mechanism are analyzed and equations are formulated to size the mechanism and to define operation input. Simulation results show the operation performance of the leg mechanisms and feasible walking ability of the proposed tripod walking robot.

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