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ADAPTIVE WALKING GAIT FOR HEXAPOD PHANTOM_|| ROBOT TO FOLLOW A SMOOTHED PRE-DEFINED PATH

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Adaptive tripod gait; hexapod modeling, path generation, sim-mechanics robot model.

ABSTRACT

Animals' natural locomotion shows a high level of robustness and adaptability which enable them to transfer through rugged terrains. Although hexapod robots have such great superiority to adapt with rugged terrains, it still has some difficulties to follow an exact smooth path. Regular periodic gates could not be able to adapt with such challenges. In this work, an adaptive walking gait is developed to deal with the challenge of following an exact pre-defined path in the Cartesian space. The case study hexapod Phantom_ll robot model is simulated at Sim-mechanics toolbox under MATLAB® to gauge the introduced adaptive gate. Besides, the case study hexapod Phantom_ll robot kinematic model is evaluated which consists of two main tasks, robot forward kinematics and robot inverse kinematics. Forward kinematic is calculated using Denavit-Hartenberg method and inverse kinematic algorithms are obtained geometrically. Moreover, the robot stability margin and kinematic constrains are considered. The simulation results proved the adeptness of the presented adaptive gait.

Introduction

Recently, mobile robot researches receive an enormous interest due to its wide applications in our daily life. According to the construction; mobile robots could be classified as wheeled, legged, and tracked mobile robot [1]. However, wheeled and tracked mobile robots have merits of simple construction and model, the thought of robotics researchers, now a day, goes to focus on the complicated legged robot. Such robots implement mechanical limbs to move better on uneven and unstructured terrains than tracked and wheeled robots [2, 3]. There are many types of legged robots based on the no. of its legs, for instance: bipeds [4, 5], tripods, quadrupeds, hexapods, and octopods [6-9]. Hexapod legged robots have been considered one of the most challenging platforms among the researchers.

The major character of legged robot is to create a machine that simulates some characteristics of biological plants [10]. To realize these characteristics, many walking gaits were announced, like tripod, wave and rippled gait. All of it depends mainly on moving the legs of the robot periodically to produce a cyclic motion by the consequence of a fixed leg step. Researchers exert a lot of their effort comparing between walking gaits to find the fastest and the most stable one.

Pavan, state that tripod walking gait is faster than wave and rippled walking gaits [11]. While Porta, declare that tripod gait is considered less stable than wave walking gait [12]. All these periodic and fixed gaits prevent this marvelous kind of robot from the ability to move through uneven and unstructured terrains. Besides, these traditional gaits are drastically diminishing the robot capability to follow especial smooth paths which might be essential to avoid collision with obstacles without the necessity to stop and make sharp turns.

Consequently, researches in adaptive locomotion have attracted the curiosity of many robotics researchers. Faigl et, present an adaptive locomotion gait to move over an inclination of 30 degree using position feedback only [13]. In the same way he implements his method to climb a standard stair. Further late, Kottege, have introduced an energetic-informed hexapod gait to move across different unstructured terrains by applying gait pattern adaptation strategy [14]

These research efforts challenge the weakness of the traditional locomotion gaits in crossing uneven terrains. However, the immense added value of these researches, the shape of path across the large obstacles is still neglected. Studies like chalk and cheese have been expressed to map these large obstacles in the robot workspace to avoid collision [15-17]. Hence, it is reasonable now to plan a path a cross these obstacles.

This work offers an adaptive locomotion gait which enhance the robot capability to follow especial smooth paths which might be essential to avoid collision with obstacles without the necessity to stop and make sharp or fixed turns. This proposed adaptive gait will enable the robot to follow pre-defined shaped paths, containing curves or lines. By applying this locomotion strategy hexapod can move continuously over the shortest path across the obstacles to reduce the consumed power and time.

In this work a Phantom AX Hexapod Mark II is used as a case study [18]. Section two presents a detailed kinematic model of the case study. Then, the methodology used in this work is explained in section three. Visualized simulation is demonstrated in section four. Results and discussion take place in sections five and six.

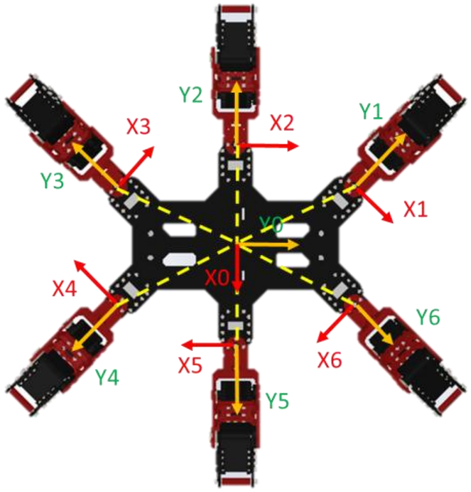


Fig. 1. Main body Frames of Phantom X | | Hexapod Robot

Mathematical Model

Hexapod robots like any other types of mobile robots have a mathematical kinematic model which defines the relationship between its local coordinate attached on it and the global world coordinate. Wheeled mobile robots have a quite straight forward relation depending mainly on wheels velocities and the steering angle. On contrary, the kinematic model of such hexapod walking robots is more complicated. This complicity has been evoked by replacing regular wheels with serial manipulators. So, each leg should be treated as an individual serial manipulator has its forward and inverse kinematic models. Moreover, the relationship between each leg base frame (Lbase) and the whole robot local frame (CG) should be established. Finally, the local robot frame (CG) needs to be defined with respect to the global world frame (g) and vice versa.

At the beginning forward and inverse kinematic representation of each leg is discussed.

A Forward kinematics

The Forward kinematics illustrated here using Denavit-Hartenberg method to obtain the leg tip Cartesian position and orientation [10, 11] Frames are assigned to the leg revolute Joints as shown in Fig. 2 and thus Denavit-Hartenberg parameter are obtained as shown in Table 1:

Table 1 DH parameters

Joint No./parameter	αi	ai	di	θi
1	90	52	0	θ1
2	0	66	0	θ2
3	0	137	0	θ3

Where,

θi The angle between the Xi-1 and Xi axes about the Zi-1 axes.

di …Distance from the origin of frame i-1 to the Xi axis along Zi-1 axis.

ai Distance between the Zi-1 to the Zi axis along Xi axis.

αi…The angle between the Zi-1and Zi axes about the Xi axes.

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

The transformation matrix is a series of transformations:

$$T_3^0 = T_1^0 * T_2^1 * T_3^2 \tag{2}$$

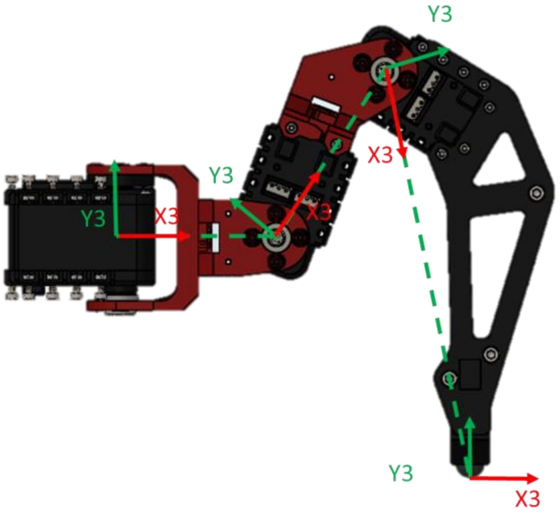


Fig. 2. Forward schematic model of leg

By substitution in Denavit-Hartenberg transformation matrices [19, 20]. The leg tip Cartesian position could be determined from the leg joints angles as following:

$$\begin{aligned} X &= \cos\theta 1 * (L1 + L2 * \cos\theta 2 + L3 * \cos(\theta 2 - \theta 3)) \\ Y &= \sin\theta 1 * (L1 + L2 * \cos\theta 2 + L3 * \cos(\theta 2 - \theta 3)) \\ Z &= L2 * \sin\theta 2 + L3 * \sin(\theta 2 - \theta 3) \end{aligned} \tag{3}$$

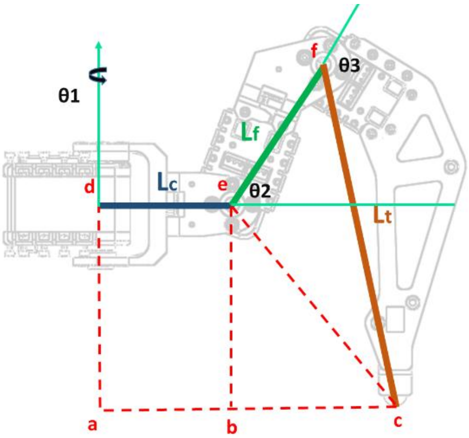


Fig. 3. Inverse schematic model of leg

B Inverse kinematics

Geometric approach is implemented to find each leg inverse kinematics representation. In Fig. 3. Leg joints angles ($\boldsymbol{\theta_1}, \boldsymbol{\theta_2}, \boldsymbol{\theta_3}$,) are determined from the corresponding leg tip position X, Y, and Z as following:

$$\theta 1 = \tan(Y / X) \tag{4}$$

$$ac = \sqrt{X^2 + Y^2} \tag{5}$$

$$bc = ac - Lc \tag{6}$$

$$ec = \sqrt{ad^2 + bc^2} \tag{7}$$

$$\theta 2 = \cos^{-1}((ec^2 + L_f^2 - L_t^2) / (2 * ec * L_f)) - (90 - \cos^{-1}(ad / ec)) \tag{8}$$

$$\theta 3 = 180 - \cos^{-1}((L_t^2 + L_f^2 - ec^2) / (2 * L_t * L_f)) \tag{9}$$

Now, in order to locate each leg base frame (Lbase) with respect to the CG frame, six coordinate frames should be assigned to each leg as shown in Fig1.

Each leg base frame (Lbase) has one translation and one rotation with respect to the CG frame. Eq. (10), Eq. (11) and Eq. (12) shows the transformation matrices required to finds each Leg base frame position and orientation with respect to the CG frame. To finds the position and orientation of the CG frame with respect to any leg base frame the inverse of the following matrices should be used.

$$\mathrm{L}_{Lbase_i}^{CG}(L_i, 0, 0) = \begin{bmatrix} 1 & 0 & 0 & L_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{10}$$

$$\mathrm{R}_{Lbase_i}^{CG}(\theta_{Lbase_i}) = \begin{bmatrix} \cos(\theta_{Lbase_i}) & -\sin(\theta_{Lbase_i}) & 0 & 0 \\ \sin(\theta_{Lbase_i}) & \cos(\theta_{Lbase_i}) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{11}$$

$$\mathrm{T}^{CG}_{Lbase_i}(L_i,\theta_{Lbase_i}) = \mathrm{L}^{CG}_{Lbase_i}(L_i) * \mathrm{R}^{CG}_{Lbase_i}(\theta_{Lbase_i}) \tag{12}$$

Finally, to finds the CG frame position and orientation with respect to the global frame (g). Eq. (13), Eq. (14) and Eq. (15) should be held. To finds the position and orientation of the global frame with respect to the CG frame the inverse of the following matrices should be used.

$$L^{g}_{\mathrm{CG}}(x, \mathrm{y}, z) = \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{13}$$

$$\mathrm{R}^{g}_{\mathrm{CG}}(\theta_{CG}) = \begin{bmatrix} \cos(\theta_{CG}) & -\sin(\theta_{CG}) & 0 & 0 \\ \sin(\theta_{CG}) & \cos(\theta_{CG}) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{14}$$

$$\mathrm{T}^{g}_{\mathrm{CG}}(x, \mathrm{y}, z, \theta_{CG}) = \mathrm{L}^{g}_{\mathrm{CG}}(x, \mathrm{y}, z) * \mathrm{R}^{g}_{\mathrm{CG}}(\theta_{CG}) \tag{15}$$

Methodology

This work aims to adjust hexapod robot traditional locomotion gaits to be more adaptive with the task of following a pre-defined shaped path. However, the traditional gaits could successfully move the robot forward and backward, it may have difficulties to keep it following an exact shaped path. To follow paths consist of various curves and lines, the robot legs paths ought to differ from each other's. So, the periodic fixed steps of the traditional walking gaits might not be suitable for that task and a kind of adaptive gaits should be used.

The introduced algorithm in this work, deals with each leg individually to describe its unique path which could be accompanied with other legs paths to achieve the entire robot body path. At the start of that algorithm, the pre-defined required path CG frame with respect to the global frame (g) is given. Assume that each leg joints are fixed to the standing position values $(\boldsymbol{\theta_1}, \boldsymbol{\theta_2}, \boldsymbol{\theta_3})$ and the body path could be discretized to have (X, Y, Z) position, with respect to the global frame, at any instance along the path. Hence, by substituting in Eq. (1), Eq. (10) and Eq. (13) the locus of each leg path could be presented.

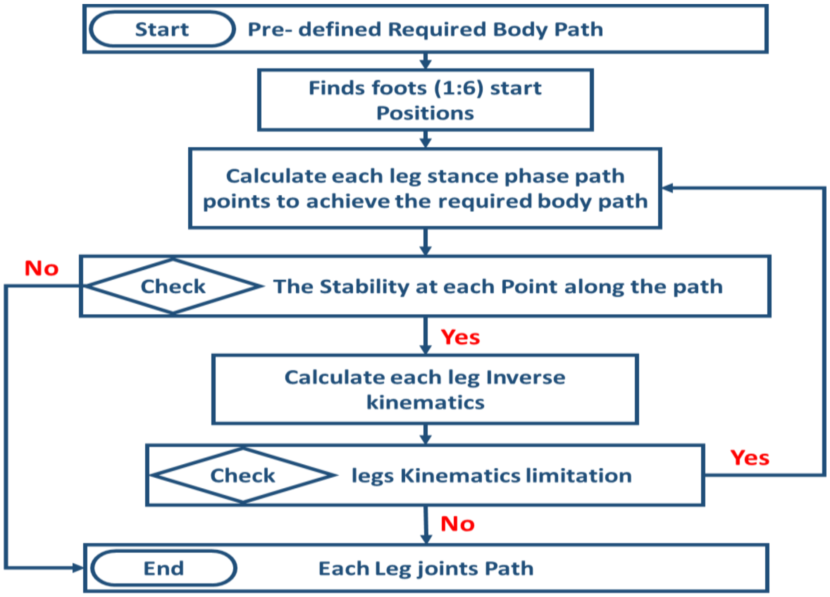


Fig. 4. Flow chart of path planning of Phantom X || Hexapod Robot

Now, the required overall path for each leg tip is defined. But the robot kinematic constrains and stability margin prevent it from taking such long paths in one shot. As shown in Fig.4 the path points for the three legs that should take the first step are checked for stability point by point before the inverse kinematic algorithm determines the relevant joint angles, BARYCENTRIC technique is used to check the robot static stability. If the stability margin is ok, inverse kinematic Eq. (1), Eq. (10) and Eq. (13) will take place for this point and the joint variable for each leg will be stored in arrays. If any time the stability margin is NOT ok or the joints variables for any leg exceed the kinematic constrains, the algorithm will end and start to repeat the process for the second step by the second legs set and so on.

The introduced algorithm elaborates the tripod gate from its cyclic and periodic fixed manner and makes it more adaptive. In another word by implementing that algorithm each leg could have its unique path which might defer from others.

Finally, each leg swing phase could be defined by the start and the end positions of each step. Cubic polynomial path is used to control joints velocity in swing phase in order to enhance the interaction between the leg tip and the ground.

Simulation

There are a lot of software tools helps to design, simulate, and test the behavior of mechanical systems in different conditions [21]. These software programs make it easy to design the mechanical parts with a real-time view. Also, they make it possible to test the designed robot in three-dimensional space. Using these programs does not eliminate the need to design a working prototype of the mechanical systems, it decreases the error by making the required needed tests before building the prototype. Dynamic systems simulation uses software programs that can be used in many types of industries, with interest in robotics, due to the possibilities for modeling and simulation of many types of complex systems. Three-dimensional simulation of mechanical systems could be obtained by various software programs such as (i) Webot [22]; (ii) Simpack [23]; (iii) Adams Multibody Dynamic Simulation [24]; and (v) Matlab/SimMechanics [25].

Sim-Mechanics MATLAB toolbox is one of those software programs. One of the advantages of such integrated toolboxes is that they enable you to use other tools available in the simulation system to perform different tasks. For example, to design control system, to analyze simulation results, to visualize results, etc. Moreover, Sim-Mechanics enables importing CAD model from a CAD environment to the Simulink very easily.

The Simulation of the desired model is computed at SimMechanics MATLAB® toolbox because of its complicity as it has a higher degree of freedom in results of enormous number of links and joints. In order to recuperate modeling competences in SimMchanics, Math Works has created a tool called Simscape multi-body link. This tool allows the user to export CAD models and then import them into SimMechanics. From the CAD model, visual appearance, physical properties and coordinate frames are imported. The CAD model is built in SOLIDWORKS® which is used as a appropriate program for this purpose as shown in Fig. 5.

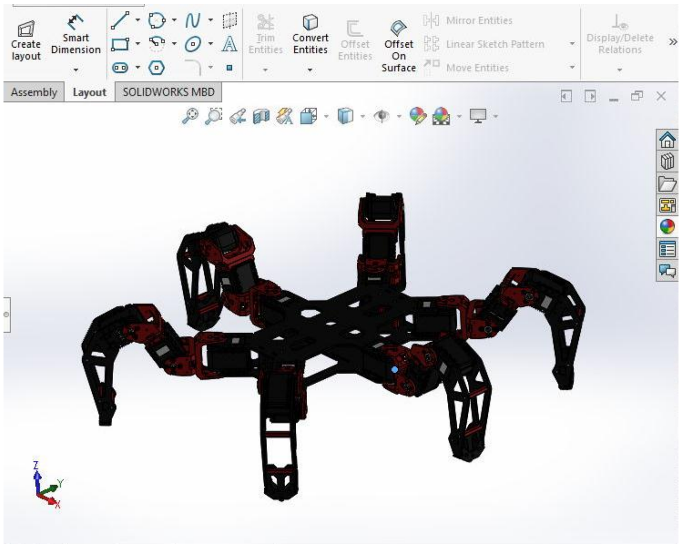


Fig. 5. Solid works modeling of Phantom X || Hexapod Robot

Then, the imported model which shown in Fig. 6 is consisted of main body block which connected to each leg by the aid of joints blocks and each leg consist of three body blocks (Coxa, Femur and Tibia) connected to each other by three joints.

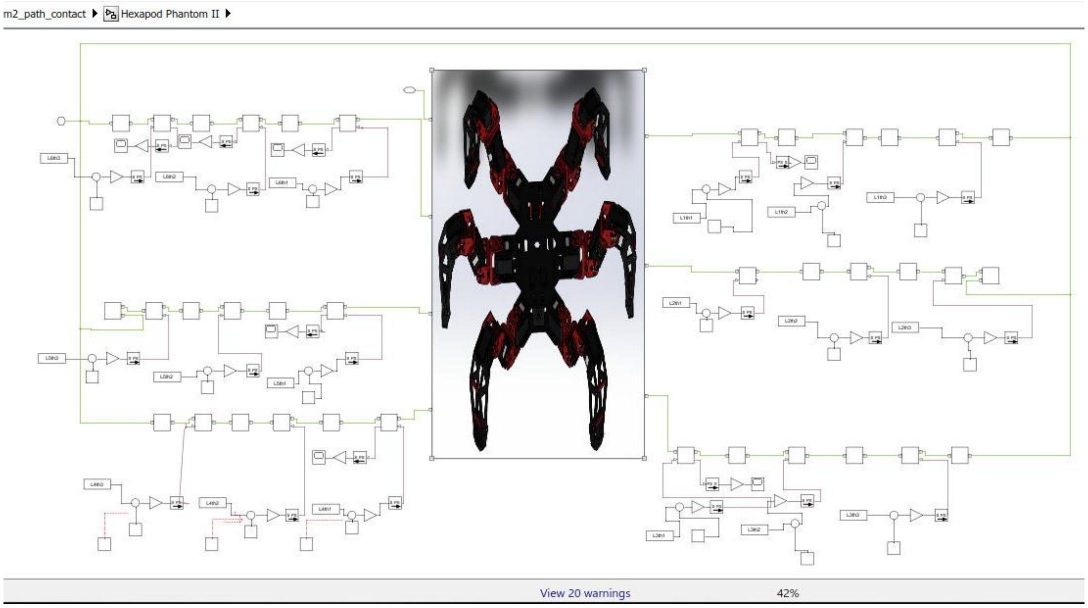
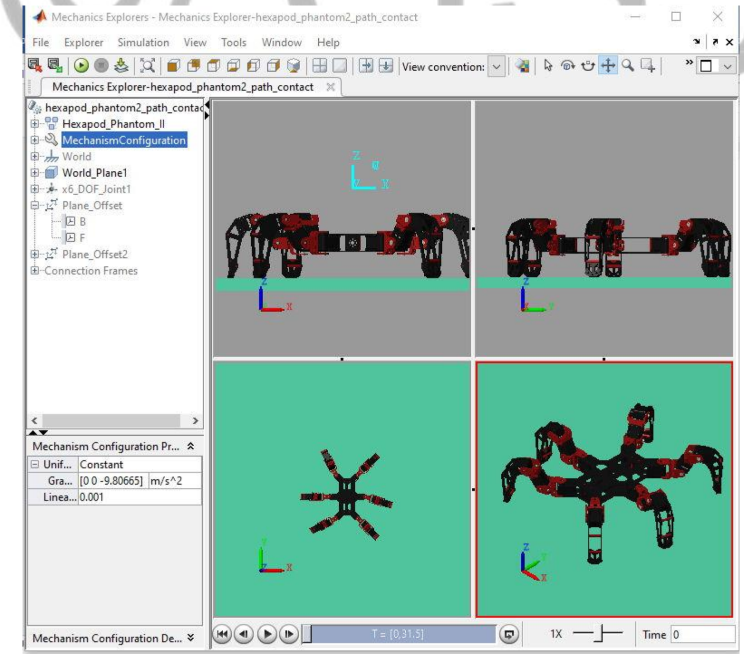


Fig.6. Sim-Mechanics model of 5 Phantom X || Hexapod Robot

Fig.7 shows the window of virtual simulation of Sim-Mechanics toolbox and the 3D animation of the Phantom X || Hexapod Robot that moves on floor base plan which has a friction coefficient with it and each leg has a contact force block with the floor.



Unif... Constant
Gra... [0 0 -9.80665] m/s^2
Linea... 0.001

Fig. 7. 3D Simulation of Phantom X || Hexapod Robot

Results

In this section, the results for applying Adaptive Walking Gait technique and the stability technique which allow the hexapod robot to be stable all over the pre-defined path are discussed. The tripod adaptive gait is proved as each leg has different step angles to adapt and follow the pre-defined path which mean that low energy consumption for actuators and more stability for the robot

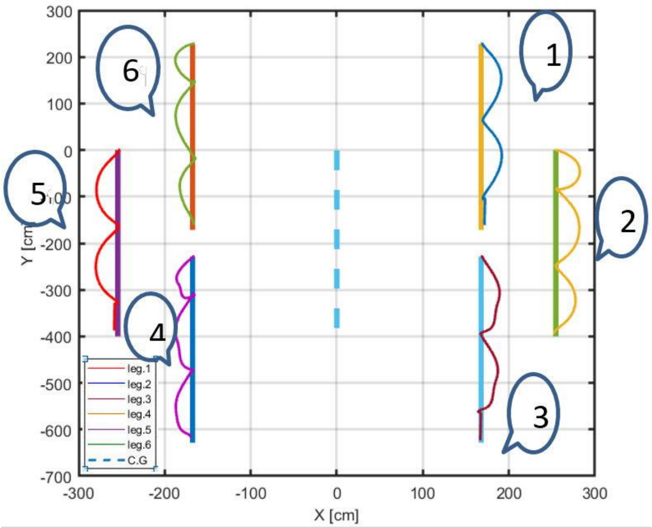


Fig. 8. Straight Path behavior of hexapod robot

In Fig. 8 shows the behavior of the hexapod robot to walk pre-defined straight-line path for the 1st set legs (1, 3 and5) and the 2nd set legs (6, 4 and 2) with inequivalent steps to adapt the path length.

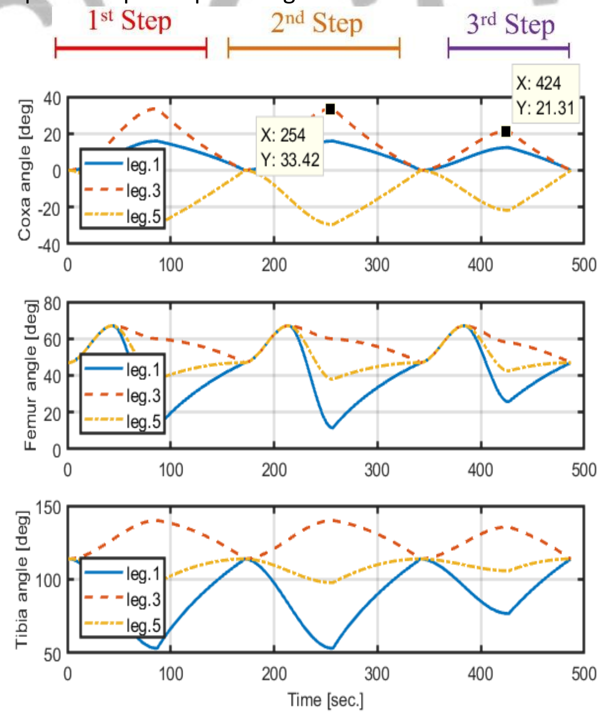


Fig. 9. Angles of 1st set of legs (1,3,5) moving a line

Fig 9 and Fig 10 show the angles of each leg' links for 1st and 2nd set legs, respectively. It's clear that the straight-line path consists of three steps; the 1st and 2nd steps are almost equivalent but the 3rd step is different as it smaller than the others and the link angles are different for the same set legs which validate the purpose of the desired adaptive walking gait technique.

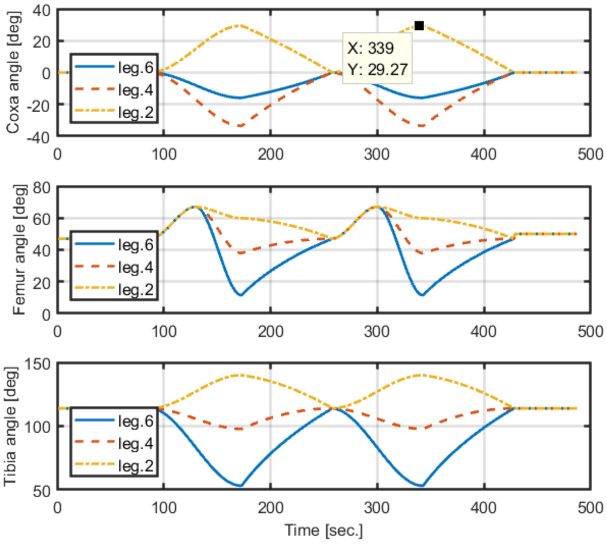


Fig. 10. Angles of 2nd set of legs (6,4,2) moving on a line path

Fig. 11 shows the behavior of the hexapod robot to walk pre-defined circular path for the first set legs (1, 3 and5) and the second set legs (6, 4 and 2) which seems that steps of the outer side of the robot is larger than the inner side to adapt the path length and radius of rotation.

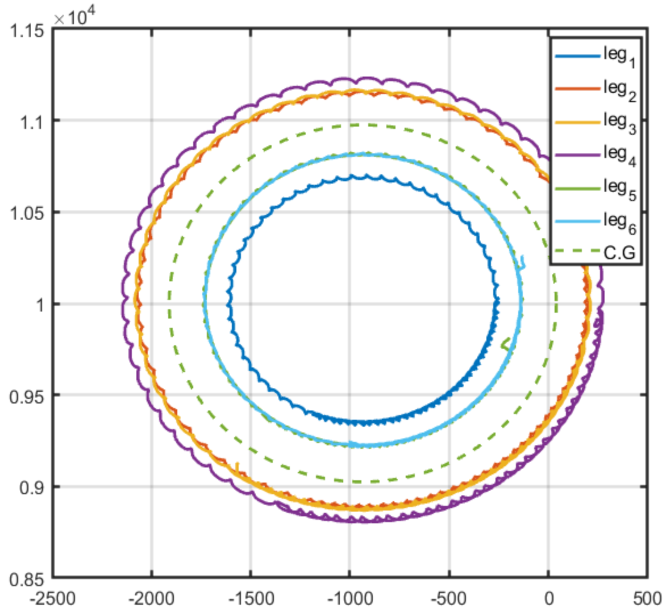


Fig. 11. Circular path behavior for hexapod

Fig.12 and Fig.13 show the angles of each leg's links for 1st and 2nd set legs, respectively. It's appeared that the steps of the 1st and 2nd set are inequivalent and the same link angles for the same set legs are different which validate the purpose of the desired adaptive walking gait technique.

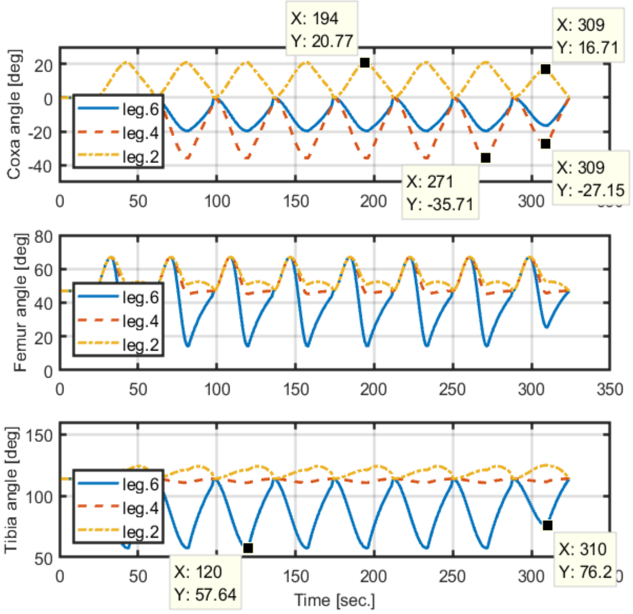


Fig. 12. Angles of 1st set of legs (1,3,5) moving a part of circular path

The scenario of the simulation is that the hexapod walks in straight path and circular path on a smooth level terrain. All the videos of the simulation achieved in this work are found in [26-28].

Conclusion

In this work, an adaptive walking gait is developed to deal with the challenge of following an exact pre-defined shaped path. Traditional periodic and cyclic gaits fail to satisfy the demand of following such paths accurately. Forward and inverse kinematics are clarified in this paper. Forward kinematic is calculated using Denavit-Hartenberg method and inverse kinematic algorithms are obtained geometrically. Moreover, the robot stability margin and kinematic constrains are considered. Results show the proficiency of the presented adaptive gait to follow a linear and circular path which can be combined to introduce any complex path. By applying this locomotion strategy hexapod can move continuously over the shortest path across the obstacles to reduce the consumed power and time. It is worth mentioning that, the slipping of the legs over the ground points out the importance of determining the interaction forces between the leg tip and the ground. In future work, model-based controller will be implemented to eliminate the leg tip slipping over ground. This work may be enlarging the application of such robots in our world, especially in hazardous environments

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