Kinematic and Gait Analysis Implementation of an Experimental Radially Symmetric Six-Legged Walking Robot

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Abstract

As a robot could be stable statically standing on three or more legs, a six legged walking robot can be highly flexible in movements and perform different missions without dealing with serious kinematic and dynamic problems. An experimental six legged walking robot with 18 degrees of freedom is studied and built in this paper. The kinematic and gait analysis formulations are demonstrated by an experimental hexapod robot. The results show that the robot walks well as it was simulated.

Keywords: Hexapod, Gait Analysis, Kinematics, Robotics.

1. Introduction

A multi-legged robot possesses a tremendous potential for maneuverability over rough terrain, particularly in comparison to conventional wheeled or tracked mobile robot. It introduces more flexibility and terrain adaptability at the cost of low speed and increased control complexity [1]. Multi-Legged robot locomotion has been such a keen interest over the years to the researchers because of the advantages of the superior mobility in irregular terrain and the less hazardous influences on environment comparing with the wheeled robots [2]–[4].

The kinematic properties of a six-legged robot can significantly influence locomotion procedure. A hexapod motion analysis is a complex combination of kinematic chains. Open chains when legs are in swing phase and closed chains when instance phase with the trunk body. Lilly and Orin [5] treats a walking robot as a multiple manipulators (i.e. legs) contacting an object, which is the trunk body. Wang and Din [6] analyzed a radial symmetric hexapod kinematic and gait analysis through a manipulation view by finding closed loops assuming the trunk is parallel to the ground and they did not consider the tilt of the trunk. Shah, Saha and Dutt [7] modeled legged robots as combination of floating-base three- type systems as kinematic modules where each is a set of serially connected links only. They used this idea for kinematic analysis of a biped and quadruped robots. This idea is used for solving inverse kinematic problem of a radial symmetric six- legged robot [8], [9]. In this kind of hexapod robot, each leg has a different coordinate frame orientation compared to the other legs unlike rectangular hexapods which two sets of legs are oriented as two parallel sets in sides of the rectangular trunk. So their gait analysis and legs behavior are different from each other in formulation.

The inverse kinematic problem of the designed six-legged robot is solved through the presented mobile view [7]. A hexapod prototype, ”SiWaReL” is built for demonstration of the simulation results. The kinematics formulation is used for gait study and the results of simulations have been verified by implementation on the experimental hexapod robot.

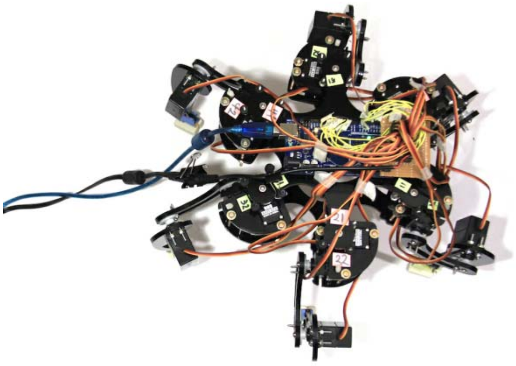

Fig. 1. SiWaReL hexapod prototype with real-time connection to PC.

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2. SiWaRel Hardware

A. Design of the Hexapod Robot Prototype "SiWaReL"

In order to perform real demonstration and verification of kinematic analysis, a real prototype of hexapod robot entitled as "SiWaReL" is built. The capability of real time connection with a computer is required for the prototype for online control. The hexapod body design is mainly based of Google's SKPR bot.

Each leg of the prototype has 3 degrees of freedom (DoF) which is biologically inspired by spider's leg, Coxa, femur, and tibia. For each revolute joint of the robot a servomotor is used.

The legs are alligned radially symmetric. The symmetry gives the robot the ability to walk any time in any direction regardless of alignment of the body.

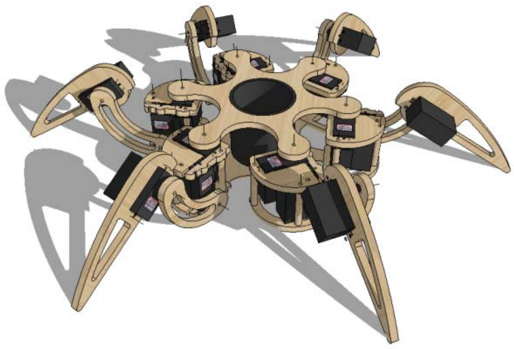


Fig. 2. 3D model of 18 DoF SKPRbot hexapod

B. Low Level control of the Robot

The aim is to establish a real-time connection between the robot and computer to implement the results for verification of formulation on an experimental model. One of the reasonable answers for connection challenge is to use a low level control architecture for tasks such as managing transmitting and receiving signals, sending the proper Pulse With Modulation (PWM) to all servomotors simultaneously. Then computer is used for a higher level control.

A board, which is an AVR microcontroller base board, is used for low level control. It controls servo motors directly and also is connected to a PC through a serial port. The micro controller on the board is programmed in a way to continuously reads the serial port, and ,based on the received data from computer, sends the specified PWMs to servo-motors.

The next step is to send proper joint angles arrays, with respect to time, to servo-motors through the designed and implemented interface board.

3. Kinematic Analysis of Siwarel

The Hexapod prototype we are working on has totally 18 DoF. Considering 6 DoF for the trunk the inverse kinematics can be solved using a modular view [8].

A. Inverse Kinematic of Hexagonal Hexapod Robot

The inverse kinematic of SiWaReL prototype is done using a modular view. Considering the body, ground and 6 kinematic chains, which are legs, the inverse kinematic formulation is done.

The process of inverse kinematic formulation is presented in details in [8] using a modular view [7]. In this approach legs' points are transformed to the main body coordinate frame and the kinematic chains are solved in main body's coordinate frame as it can be seen in figure 3a.

The inverse kinematic formulations is written as:

$$\begin{aligned} x_{lti} &= x_{tipi}\cos\theta_y\cos\theta_z \\ &+ y_{tipi}(\cos\theta_x\sin\theta_z + \cos\theta_z\sin\theta_y\sin\theta_x) \\ &+ z_{tipi}(\sin\theta_x\sin\theta_z - \cos\theta_x\cos\theta_z\sin\theta_y) \\ &- oo'_x + p_{ix} \end{aligned} \tag{1}$$

$$\begin{aligned} y_{lti} &= -x_{tipi}\cos\theta_y\cos\theta_z \\ &+ y_{tipi}(\cos\theta_x\cos\theta_z - \sin\theta_y\sin\theta_x\sin\theta_z) \\ &+ z_{tipi}(\cos\theta_z\sin\theta_x + \cos\theta_x\sin\theta_y\sin\theta_z) \\ &- oo'_y + p_{iy} \end{aligned} \tag{2}$$

$$\begin{aligned} z_{lti} &= x_{tipi}\sin\theta_y - y_{tipi}\cos\theta_y\sin\theta_x \\ &+ z_{tipi}\cos\theta_y\cos\theta_x - oo'_z - p_{iz} \end{aligned} \tag{3}$$

Where x_{lti}, y_{lti}, z_{lti}, x_{tipi}, y_{tipi}, and z_{tipi} are i's leg tip's coordinates in *i*'s leg coordinate frame and ground frame respectively. θ_x, θ_y, θ_z, p_x, p_y, p_z and $OO^{/}$ denote rotation around x, y, z, coordinates of the trunk, and the translational distance between the gournd frame and main body frame in the order given.

B. Inverse Kinematic Analysis of one leg

Robot's legs are seen as serial manipulators where their base are fixed on the robot's main body and their end point are on the ground or on swing path.

The position of the leg tip in main body coordinate frame can be found using homogeneous transformation matrix from base coordinate frame to endpoint coordinate frame.

Based on figure 3b Inverse kinematic formulations for *i*'s leg is written as [8]:

$$\theta_{1i} = \arctan2(y_{lti}, x_{lti}) \tag{4}$$

$$d_i = \sqrt{(x_{lti} - l_0 c_1)^2 + (y_{lti} - l_0 s_1)^2 + z_{lti}^2} \tag{5}$$

$$B_i = a\cos(\frac{d_i^2 + l_1^2 - l_2^2}{2 l_1 d_i}) \tag{6}$$

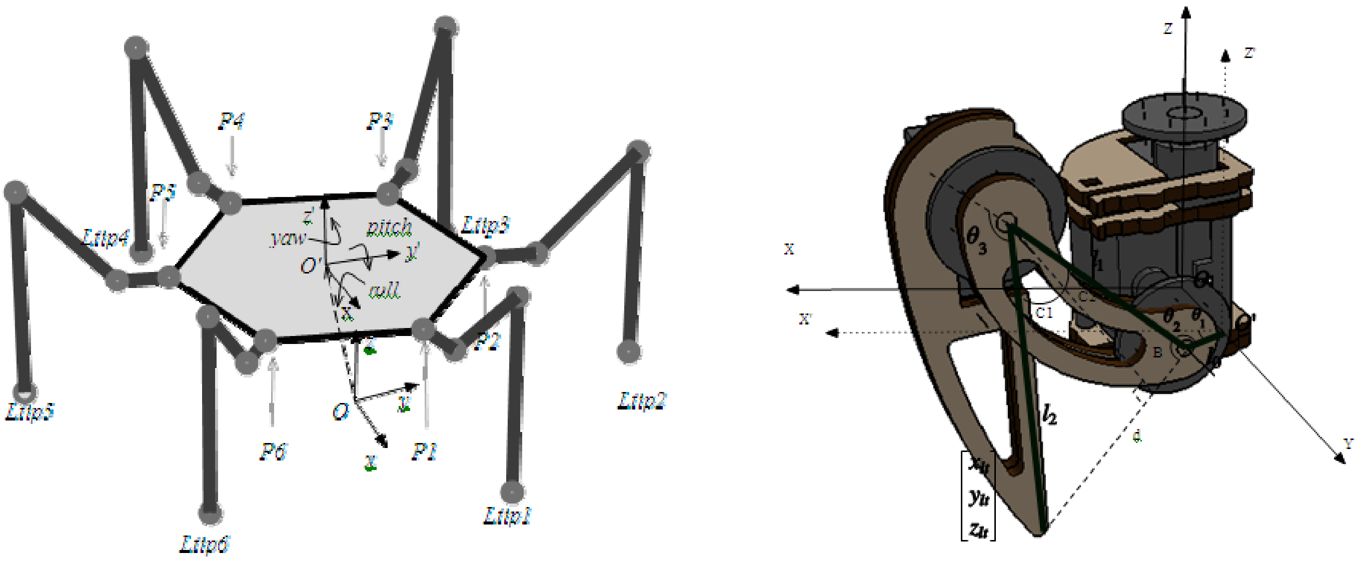
$$\theta_{2i} = a\sin(\frac{-z_{lti}}{d_i}) - B_i \tag{7}$$

$$C1_i = a\cos(\frac{l_1 \sin B_i}{l_2}) \tag{8}$$

$$C2_i = \frac{\pi}{2} - B_i \tag{9}$$

$$\theta_{3i} = \pi - C1_i - C2_i \tag{10}$$

Where θ_{1i}, θ_{2i}, θ_{3i}, L_0, L_1, L_2, s1, c1 are joint variables of *i*th leg, coxa, femur and tibia lengths (shown in figure 3b), $\sin(\theta_{1i})$ and $\cos(\theta_{1i})$ respectively.



(a) Hexagonal hexapod coordinate frame assignment, ground frame O and trunk frame O$^{/}$

(b) A 3 DoF hexapod leg design link assignment and parameters for inverse kinematic analysis of one leg

Fig. 3. Coordinate frame assignment for inverse kinematics analysis of hexapod

4. Gait Analysis of Siwarel

Gait analysis is the study of time sequence of legs in stance and swing phase. Walking gaits are simplified to some similar rules for taking steps. By applying these time sequences to each leg walking can be achieved. In gait analysis leg movement can be divided in two phases, stance and swing phase [11].

When the robot is moving on desired trajectory some legs on the ground are pushing the body to move the trunk in desired direction, in the meanwhile, the other legs are getting into new foothold position.

While legs are in swing phase, It is important for legs to not to impact the ground as they go to new footholds; The velocity at the start and end of swing phase should be zero. A typical swing cosine function [12], [13] is used for also having smooth actuation signals.

A. Testing Gaits

Two walking gaits, wave and tripod gait has been studied and simulated. In tripod gait for example two equilateral triangles are defined, one for standing legs and one for another swinging legs. The standing legs are on the ground and form a triangle. When the robot is going forward on standing legs the other triangle (the other three legs tip forms) is moving forward above the ground to get into new position, i.e. swing phase. In wave gait robot moves its legs one by one to get the highest stability margin but so slower. Figure 4 show time sequence of these two gaits.

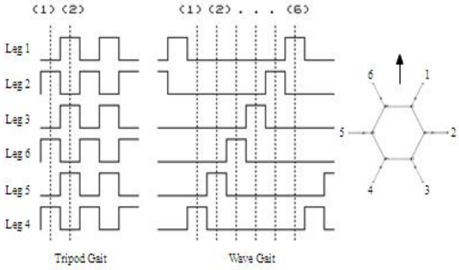


Fig. 4. Tripod Gait and Wave Gait signals sequences.

5. Implementation Gait Analysis and Inverse Kinematic Formulations on Siwarel Prototype

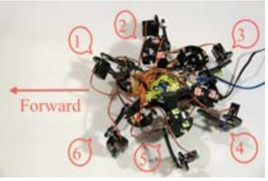
SiWaReL prototype is used to verify the formulation. In previous sections, the inverse kinematic formulation is analyzed with two typical gaits, tripod and wave gait. In both gaits, the related joint-time arrays are generated. Using these specific values and sending them to SiWaReL hexapod prototype, the results of walking can be seen with feed forward control.

Therefore, by sending the gait analysis results, i.e., joint values to the prototype, it can be seen how it walks. The connection between the robot and computer is established and the sampling of joint values is done every 10 miliseconds which results in smooth walking of the robot.

As it is shown in figures 5 and 6, the robot walks without any problem as it was predicted in the simulations [8]. The robot walks simultaneously as computer sends joint values. The micontroller which manages the connection between the computer and the robot is programmed considering the stability in cases that computer is busy or in cases there’s delay in sending signal. This feature provides robust connection for the real time control.

6. Conclusion

In this paper inverse kinematic formulation of a radial symmetric (hexagonal) hexapod has been verified and demonstrated by an experimental hexapod robot. SiWaReL hexapod robot prototype and its design is discussed and the implementation process is studied. It is shown that a modular view for solving inverse kinematic problem and gait analysis for this kind of robot works well.



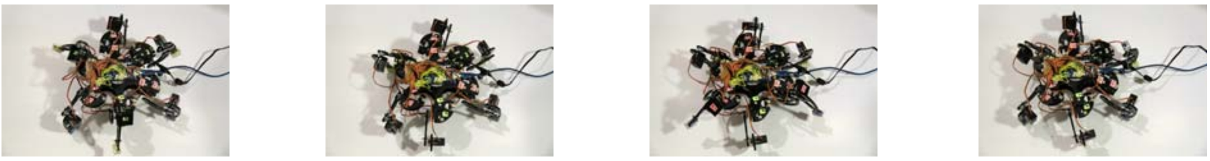
(a) Robot at rest

(b) Legs 1,3 and 5 are moving into new position.

(c) Legs 1,3 and 5 are in new position.

(d) Legs 2,4 and 6 are moving into new position.

(e) Legs 2,4 and 6 are in new position.



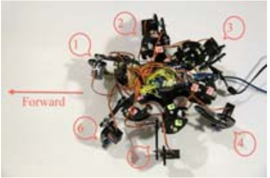
(f) Legs 1,3 and 5 are moving into new position.

(g) Legs 1,3 and 5 are in new position.

(h) Legs 2,4 and 6 are moving into new position.

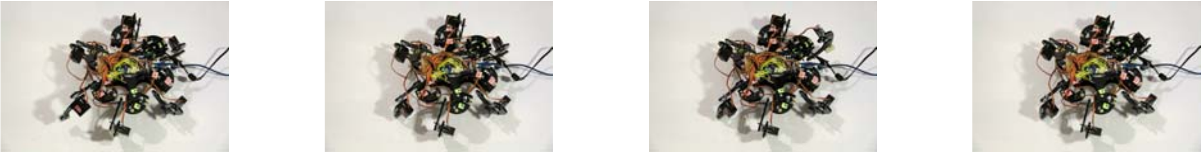
(i) Robot is standing.

Fig. 5. Tripod gait implementation on SiWaReL prototype in 2 steps

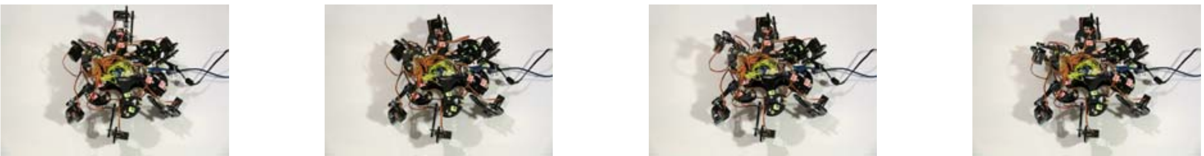


(a) Robot in Rest.

(b) Leg 4 is moving. (c) Leg 4 is in new position. (d) Legs 5 is moving. (e) Legs 5 is in new position.



(f) Leg 6 is moving. (g) Leg 6 is in new position. (h) Leg 3 is moving. (i) Leg 3 is in new position.



(j) Leg 2 is moving. (k) Leg 2 is in new position. (l) Leg 1 is moving. (m) Leg 1 is in new position.

Fig. 6. Wave gait implementation on SiWaReL prototype in one step

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