Modeling and Simulation of a Near Omni-Directional Hexapod Robot

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Abstract The present paper describes design and modelling aspects of a near omni-directional legged-wheel robot. While discussing the importance of twin frame legged robots with wheels in mobile robotic research, the basic geometrical configuration of the system was presented. The kinematic and dynamic analysis of the system facilitated improved overall design of the robot. Results of virtual simulation of the movement of this hybrid legged wheel system are also presented. An experimental lab-scale prototype has been developed and simulation results are compared with the test results to ascertain the technical feasibility of geometric model with respect to the mobility on different terrains.

1 Introduction

Mobile robots have become popular with myriad potential applications e.g. inspection, welding, painting, material/tool handling and transportation in manufacturing and hostile hazardous environment. In real factory world terrains and environment are not always smooth or structured. Wheeled locomotion has higher reliability, superior stability and higher energy efficiency when moving on flat terrain (Dutta et al. 2007). Legged locomotion has the highest adaptability to rough terrain because the contact points with the ground where the feet support can be chosen efficiently and safely. The added advantages introduce certain problems in terms of dead weight, energy efficiency, and speed of movement, etc. In order to acquire the benefits of both wheel and legged robots, researchers are trying to hybridize legged locomotion with wheeled locomotion depending on specific requirements to make it terrain adaptive which is the prime objective of this work.

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Over the last decade a number of legged mobile robot prototypes were developed, from biped to quadruped and hexapod robots (Sakagami 2002; Fielding and Reg Dunlop 2004; Ma et al. 2005; Fujii et al. 2006). Robots are independently driven by legs having degree of freedom (dof) 12 for quadruped, 18 for hexapod. More number of dof means low power to weight ratio with more control complexity leading to less efficient system. In order to rationalize these problems, total number of dof has to be abridged with minimum hindrance in the degree of mobility. Most of the practical walking robots are having hexapod configuration for stable motion. Researchers throughout the world have developed a number of mechanisms e.g. hexapod with 3 dof (Gurocak and Peabody 1998), 6 dof (Ota et al. 2001), 8 dof (Tsumaki 1993), 9 dof (Fukudaa et al. 1995; Koyachi et al. 1990), 11 dof (Krishna et al. 1997) and 18 dof.

Design of hexapod robot faces several challenges such as stability, turning, coordination of the legs, and path planning. It involves design of mechanism along with generation of complex control algorithm. Also for any legged vehicle, selection of proper gait and its sequence is essential depending on environmental and physical constraints. The environmental constraints are terrain condition, presence of obstructers and physical constraints are dof, speed, smoothness of body motion, stability of the body, ease of control, and power requirement. Large number of moving links makes the system more complicated necessitating further investigation and experimentations. In the present work, a simple twin frame near omni-directional hexapod system with wheels mounted at the tip of the feet is designed.

The paper is organized as follows. The proposed system is described in Sect. 2 including system configuration, characteristics, kinematics. Section 3 provides simulation and experimental results. Finally, Sect. 4 summarizes a few conclusions emanating from this work.

2 Configuration of the System

The robot consists of two parallel platforms having a relative rotational motion as shown in Fig. 1. Each platform holds three legs (Top platform holds Leg 1-3-5 and bottom platform holds Leg 2-4-6) in triangular fashion. Six legs formed a star like configuration providing a wide support area. 2D pantograph type leg is considered because of its decoupled kinematic characteristic for horizontal and vertical motion. Rigidity is high as the actuators are placed on the main body. This configuration with 13 dof enables the robot to move in any direction like an omni-directional robot. But here during change of direction of movement the robot is not rotating as a whole. One platform remains fixed allowing other platform to rotate for aligning in the direction of movement. Thus the proposed system is termed as near omni-directional system instead of omni-directional system. Walking motion can be accomplished as: (i) Legs 1-3-5 will go to the home position; (ii) First half cycle: Legs 2-4-6 will lift off and go to the home position and simultaneously bottom

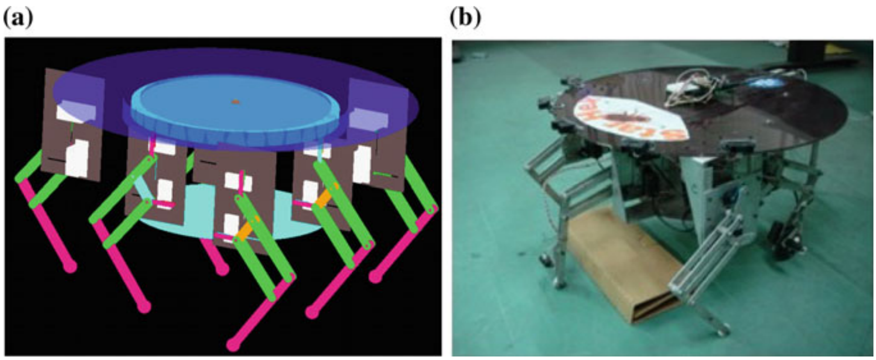

Fig. 1 **a** 3D model of the proposed hybrid system. **b** Prototype model

platform will rotate to the desired heading angle. At the same time Legs 1-3-5 which is on the ground will push the body in the forward direction until the full stroke; (iii) Second half cycle: Legs 1-3-5 wil lift off and go to the home position and simultaneously top platform will rotate in the opposite direction depending on the desired heading angle. Besides that, two motorised wheels are mounted at the tip of Leg 1 and 3 for rolling motion on flat terrain where Leg 5 gives the support with the help of a roller.

The proposed hybrid system have the following performance characteristics:

(a) It can navigate on flat terrain with high speed using wheels. If required it can also walk over rough terrain.
(b) During walking, translational and rotational movements are decoupled in nature. Translation will be accomplished by the actuation of six legs, whereas rotational movement is carried out only by the central actuator within top and bottom plate.
(c) The system does not have to change the gait pattern to move any direction. Only single gait pattern is sufficient for entire movement.
(d) Because of pantograph configuration of the leg, length of the stride and lift has the flexibility to overcome the obstacles within its limit.
(e) For the smooth relative rotational movement between top and bottom frames, top frame is sufficiently large enough compared to bottom.

The sizes of top and bottom platforms are largely dependent on the workspace of the each leg to avoid any obstruction for the continuous movement. System rigidity would decrease with increase of the top plate size. In transfer phase, the three legs which are mounted on the top plate are hanging away from the center support by the bottom plate. In the proposed system, smooth relative motion between two platforms is accomplished by means of thrust bearing. Based on design considerations the diameter of the top and bottom plates are found as 500 and 250 mm respectively.

Array of IR sensors is mounted at different levels to detect the obstacles. Five sensors are mounted on the top plate as shown in the Fig. 1b. One sensor is fitted just above the foot of the Leg 2 and another two sensors are mounted on wheels. These three sensors will guide the change of locomotion mode from wheeled to legged whereas array of five sensors is utilized for detection and avoidance of the obstacle. Thirteen Hitec motors (weighing 65 g each) are used as actuators. The controller resides on one PIC based microcontroller with capability of sensor interfacing and motor actuation according to locomotion requirement.

2.1 Kinematics of Legs

As shown in Fig. 2a, B_0 is the body frame about which top and bottom platform can rotate. Two frames for top and bottom platforms are B_t and B_b respectively. On each platform three more frames are attached at the hips of three legs. E is the earth-fixed frame. In order to increase the system stability, legs in front and rear direction are mounted on the platform in opposite direction as shown in Fig. 1. Each pantograph legs (as shown in Fig. 2b) have five moving links and translational motions in vertical and horizontal direction are imparted through slider-crank mechanism. In order to increase the area of support polygon, horizontal slots are placed away from the center line. The constant R is the magnification factor of pantograph legs, and is defined as

$$R = \frac{BC}{BA} \tag{1}$$

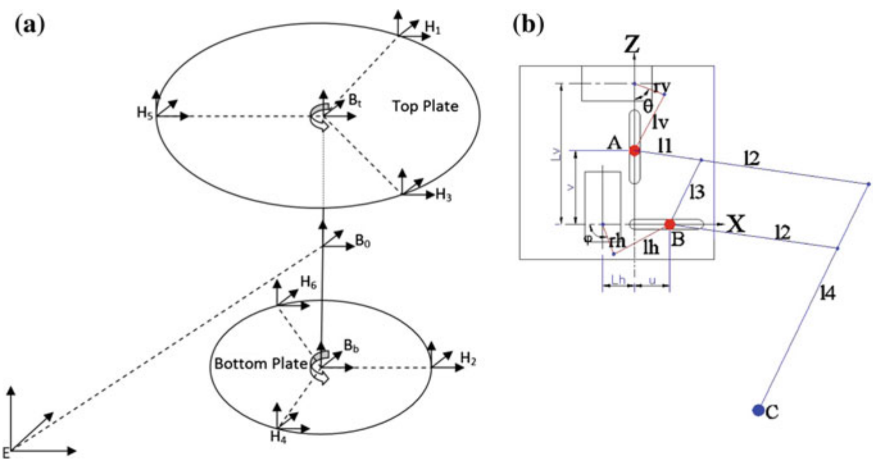

Fig. 2 **a** Schematic diagram of all the co-ordinate frames. **b** 2D Pantograph leg mechanism

The forward kinematics equation which relates the foot position $\left[X_{fj}^h \quad Y_{fj}^h \quad Z_{fj}^h \right]$ attach to the hip of Leg j with the displacements of the two actuators (θ_j, ϕ_j) can be defined as

$$P_{fj}^h = \left[X_{fj}^h \quad Y_{fj}^h \quad Z_{fj}^h \right] = \begin{bmatrix} (1+R)u_j \\ 0 \\ Rv_j \end{bmatrix} \tag{2}$$

where,

$$u_j = Lh - rh\cos\phi_j^h + lh\sqrt{1 - (\frac{rh}{lh})^2 \sin^2\phi_j^h},$$
$$v_j = Lv - rv\cos\theta_j^h - lv\sqrt{1 - (\frac{rv}{lv})^2 \sin^2\theta_j^h}.$$

And the inverse kinematics can be determined as

$$IP_{fj}^h = \left[\theta_{fj}^h \quad \phi_{fj}^h \right] = \begin{bmatrix} 2\tan^{-1}\sqrt{\frac{1-M}{1+M}} \\ 2\tan^{-1}\sqrt{\frac{1-N}{1+N}} \end{bmatrix} \tag{3}$$

where,

$$M = \frac{\left(Lv - \frac{Z_{fj}^h}{R}\right)^2 + rv^2 - lv^2}{2\left(Lv - \frac{Z_{fj}^h}{R}\right)rv}, N = \frac{\left(Lh - \frac{X_{fj}^h}{R}\right)^2 + rh^2 - lh^2}{2\left(Lh - \frac{X_{fj}^h}{R}\right)rh}.$$

The geometrical parameters of each leg of the developed lab scale prototype with magnification factor is 2.516 are provided in Table 1.

2.2 Gait

The developed omni-directional robot can move in any direction but it first needs to align towards the direction by means of the central actuator for relative motion

Table 1 Geometrical dimensions of each leg

Links	Dimensions (mm)	Weight (g)	Links	Dimensions (mm)	Weight (g)
rv	18	6	lv	36	10
Lv	80	–	l1	38.2	10
l2	134	68	l3	41	14
l4	143	71	rh	18	6
lh	36	10	Lh	18	–

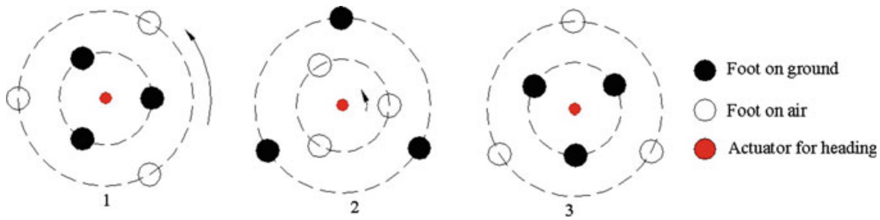

Fig. 3 Representation of wave gait with central rotation

between two plates and then moves in a straight path. The system can take spot rotation though it cannot execute curvilinear motion with high accuracy. It can follow any curve piecewise by adopting the most popular and simple wave gait with the central rotation. When three legs are on the ground, other three are reconfigured for the next turn. Simultaneously, it would change the heading as shown in Fig. 3.

3 Simulation and Results

Proposed model has been simulated over circular as well as a spline path as shown in Fig. 4. From the figures it is observed that the proposed system can move in any direction but piecewise.

The proposed system was also simulated using Adams software. Solid model was developed with specified leg parameters and diameters of top and bottom plates. Here stroke length and ground clearance is 120 and 90 mm respectively. Material of construction is considered as aluminium except the top and bottom plate and ball mounted twin plates which are made by acrylic plastic. Weight of each

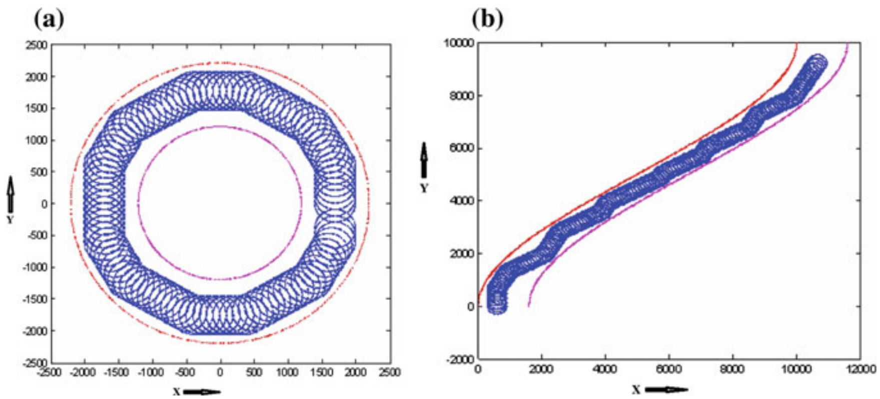

Fig. 4 Robot path over **a** circular path and **b** spline path

motor is 65 g. In the leg, two slots for sliding motion are layered with acrylic plastic to reduce friction force.

In order to select the motor, simulation has been carried out for a path as first go straight, then turned 30 and then go straight with full stride. Parameters for foots contact with ground are considered as follows: static co-efficient of friction = 0.3, dynamic co-efficient of friction = 0.1, damping co-efficient during landing = 10.0, allowable penetration depth = 5 mm. Figure 5 depicts the foot contact forces. Contact forces are dependent on the distribution of mass. It is clearly evident from the curve that due to the forward motion of body with respect to the support foot, contact forces for the supporting front legs are gradually increasing, whereas for rears legs, the effect is just opposite.

Simulation has also been carried out to find out the minimum frictional forces required for the turning action. It has been observed that system can turn efficiently if the friction co-efficient is below 0.11. Required motor torques has been computed from the simulation results and is shown in Fig. 6. Based on the average torque requirement of each joint, suitable actuator with maximum torque of 32 kg cm has been selected in our experimental prototype.

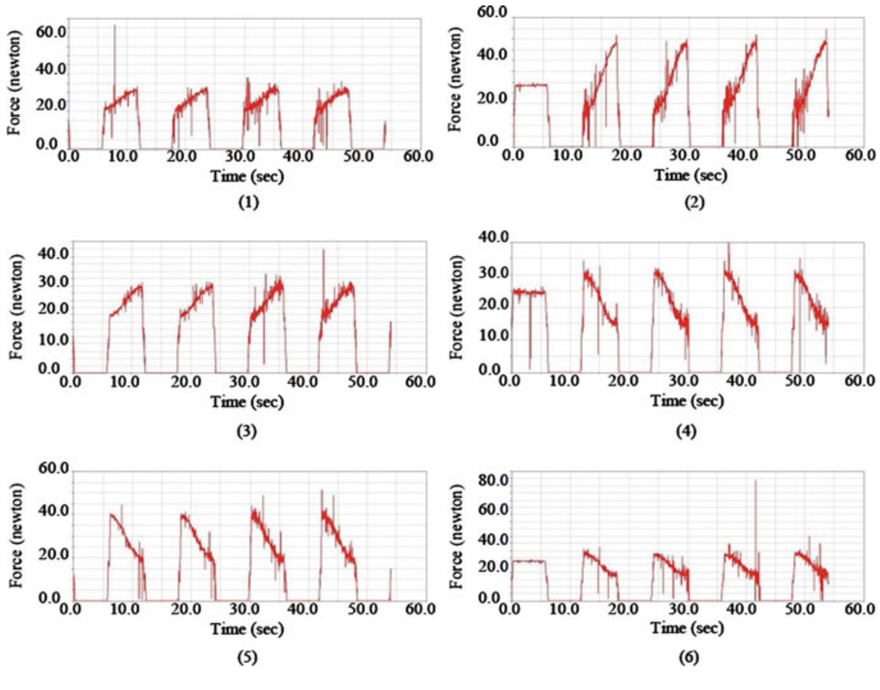

Fig. 5 Foot contact forces for legs 1–6 are shown in curve (1)–(6) respectively

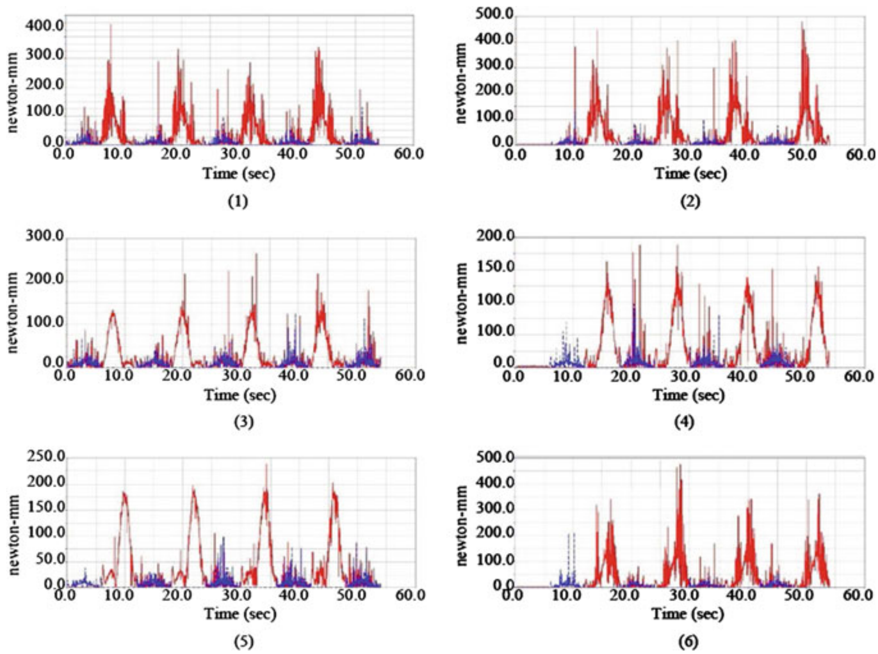

Fig. 6 Motor torques in legs 1–6 are shown in curve (1)–(6) respectively where *red lines* depict for horizontal and *blue* for vertical actuators

4 Conclusions and Future Work

An experimental prototype of a very simple hybrid legged-wheel system called near omni-directional hexapod has been developed. Legged system is a twin frame based hexapod where three wheels (two active, one castor) are fitted with three legs mounted on the bottom frame. The system can move near omni-directionally either by walking mode or wheel mode subject to terrain as well as environment condition. Wave gait pattern is adopted for translational motion during walking whereas turning motion is generated by a central motor attached within the two frames. Required work envelope has been evaluated for each leg which is the main parameters for fixing the dimensions of each frame. The developed prototype has been tested successfully in the laboratory. The system can be utilized for remote inspection of any hazardous environment.

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