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Control oriented model-based simulation and experimental studies on a compliant legged quadruped robot☆

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HIGHLIGHTS

- Paper presents three dimensional dynamic model of quadruped with compliant legs.
- Model is verified with simulation, animation and experiment results.
- Turning motion is demonstrated by providing differential leg tip velocity.
- Influence of leg compliance on quadruped locomotion is studied.
- Energy efficient structure, gait and foot trajectory have been carried out.

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ABSTRACT

Quadruped robots offer better maneuverability over wheeled mobile robots. However, a quadruped robot contains many joint actuators which have to operate in a coordinated fashion to achieve the desired locomotion. Joint actuations cause various degrees of disturbance on the robot body and may even destabilize the system. Thus, prior dynamic analysis plays an important role for development of control laws for quadruped locomotion. Here, a three dimensional dynamic model of a quadruped has been developed using the bond graph technique which can be interfaced with various controller models. This model contains a detailed sub-model for telescopic compliant legs. Results from simulations, animations and experiments are discussed. Turning motion at various leg speeds is studied for dynamic stability of the robot. The effect of leg compliance on locomotion parameters is studied which helps in selecting a suitable compliance. Performance measure is carried out using energy efficiency as deciding criteria. Study on energy efficient quadruped structure, energy efficient locomotion gait and foot trajectory have been carried out for designing an efficient quadruped.

1. Introduction

Legged robot offers many advantages over wheeled robots including greater adaptability to terrain irregularities and superior off-road mobility [1,2]. Legged systems require only a series of discrete footholds along the pathway for off-road locomotion. This property enables legged robots to traverse surfaces inaccessible to wheeled mobile robots. Compliance in the leg improves locomotion of legged robot [3]. Variable compliance in the legs [4] overcomes the size, weight, fragility and efficiency problem. Basically, legged robots are discrete systems in which joints of each leg have to operate in particular fashion. So, dynamics plays an important role in the operation and control of a walking robot. Recently, there has been a noteworthy increase in the use of computational dynamics for design, analysis, simulation and control of various robotic systems. This is due to availability of various multi-body dynamic analysis tools and faster computational resources. To this end, various researchers used different dynamic analysis methods for multi-body systems, such as the methods based on Lagrangian

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equation [5], Newton–Euler equation [6,7], Kane's equation [8–10] and variational methods [11].

Bennani and Giri [12] presented a dynamic model approach of quadruped considering open and/or closed kinematic chain mechanisms. It is based on Newton–Euler approach and the explicit formulation of kinematic holonomic constraints for the closed loop mechanism. Mahapatra and Roy [13] developed a dynamic model of six legged in CATIA solid modeler, SimDesigner and ADAMS multi-body dynamic solver and kinematic and dynamic simulation is performed based on virtual prototyping technology. Krishnan et al. [14] presented a bond graph model of compliant legged quadruped robot in a sagittal plane. The sagittal plane dynamics have been tested through experimental set-up. Soyguder and Ali [15] solved the stance and flight phase dynamic structures in a sequential closed loop for quadruped and obtained the equation of motion for pronking gait. Shah et al. [16] presented a concept of kinematic modules for the development of the dynamic model of the four legged robots where each module is considered as a set of serially connected links. Module-level Decoupled Natural Orthogonal Complement (DeNOC) matrices were introduced which helps to analyze the large number of links as a system with a smaller number of modules. Recursive kinematic relationships were obtained between two adjoining modules. Ganesh and Pathak [17] developed a dynamic model of four legged in a sagittal plane by formulating kinetic and potential energy equation of body and leg. These were used to derive Lagrangian function and then equation of motion. A locomotion control strategy for a quadruped robot has been presented in [18]. Dynamic modeling and analysis of quadruped robot through bond graph technique has been presented in [19].

Many of the quadruped robots developed worldwide are biologically inspired. Process of natural selection governing evolution of species forces animals adapt to their specific physical features and environment by optimizing their locomotion. Some animals are better at doing certain things in comparison to others. Thus, keeping the required task or operation features in the view, more and more specialized biologically inspired quadrupeds are being developed now-a-days. Some of them are Baby Elephant [20], BigDog [21], Cheetah-cub [22], HyQ [23], LittelDog [24,25] and Tekken [26,27]. Hydraulically actuated Baby Elephant [20] was designed to work as mechanical carrier. It has 12 DOFs and compliant legs. Multi-body dynamic simulation was used in [20] for its design and the results were experimentally validated. BigDog [21] was developed with the goal to move in rough terrain without human assistance. It has twenty DOFs and about fifty sensors. Four joints of each leg are operated by hydraulic actuator. It uses a two-stroke internal combustion engine that delivers up to 15 hp power. Electrically actuated Cheetah-cub [22] was designed for high-speed locomotion. Cheetah-cub's legs are spring loaded and pantograph mechanism with multiple segments is used for shock absorption during running. This robot's self-stabilizing properties were demonstrated in hardware model and in simulation carried out in Webots software. HyQ [23] developed at IIT Genova was designed to perform highly dynamic tasks like jumping and running. It has 12 DOFs and both hydraulic and electrical actuation systems. During running and jumping, generated impact forces were absorbed by hydraulic actuation mounted on hip and knee joints in the flexion/extension plane of the leg. The hip abduction/adduction joint was actuated by brushless electric motor which provides constant output torque. LittleDog [24,25] has 12 DOFs and each joint is operated by a high-gain servo motor. Sensors mounted on the robot measure body orientation, joint angles and ground-foot contact. Sensing, communication and actuators are controlled by onboard PC-level computer. Tekken [26,27] is a light weight (4.3 kg) manually operated power autonomous compliant legged quadruped robot. It has 16 DOFs, 3 joints around pitch axis (ankle, knee and hip) and 1 hip joint around yaw axis at each leg. At ETH Zurich, two quadrupeds have been developed having similar structure, size, and morphology, but different concept of actuation [28]. The first, ALoF, is a classically stiff actuated robot that is controlled kinematically; whereas the second, StarlETH, uses a soft actuation scheme based on highly compliant series elastic actuators.

In this paper, three dimensional dynamic model of compliant legged quadruped robot using bond graph has been developed. Bond graph technique is a graphical tool presenting the energy exchange between elements representing the model properties. It is a common language to model any systems involving different energetic domains. It clearly shows the cause and effect relations in the model. Structural properties of the system can be also analyzed using bond graph. Controller model can be integrated with bond graph model and physical model-based control laws can be designed with it. These are the few reasons to choose bond graph as modeling tool. A quadruped robot configuration used for analysis is two links legged robot in which upper link is rigid and a lower link is compliant. Lower link is considered similar to a prismatic link in which, piston and piston rod is sliding inside the cylinder and movement is restricted by the spring which generates compliance in the leg. To validate the developed model, simulation and animation of the trot gait performed by the quadruped is carried out which is further verified by experiment results. Since trot gait is dynamically stable gait thus successful validation of model in trot gait ensures the model validity in other gaits also. To prove the versatility of the three dimensional model generated a turning motion of the robot is demonstrated by varying the leg speed in amble gait. Influence of compliance on quadruped locomotion and posture disturbance is studied. Performance analysis is carried out considering energy efficiency as deciding criteria. Performance analysis on rigid and compliant legged robots, static and dynamic gaits, and foot trajectory are carried out. A part of this work is published in [19].

This paper is organized in the following sequence. In Section 2, three dimensional dynamic model of quadruped robot is developed using bond graph. Dynamics of body and leg is discussed in detail. In Section 3, simulation, animation and experiment results of trot gait are discussed. In this section, turning motion of the quadruped robot, influence of compliance on locomotion and performance measure of various quadruped aspects by energy efficiency is also discussed. Section 4 concludes this paper.

2. Modeling of a quadruped robot

Modeling of a quadruped robot consists of modeling of angular and translational dynamics of robot body and legs. Fig. 1(a) shows physical model of quadruped robot, while Fig. 1(b) shows the schematic diagram of a quadruped robot model in which $\{A\}$ is an inertial frame and $\{B\}$ is the body frame attached to body center of gravity (CG). Frame $\{0\}$ is fixed at the hip joint of each leg which is fixed on the robot body. Each leg of the quadruped robot has two degree of freedom (DOF) with two revolute joints per leg. The joint between links i and $i+1$ is numbered as $i+1$. A coordinate frame $\{i+1\}$ is attached to $(i+1)$ joint. Frame $\{1\}$ is attached to joint 1 of each leg. Frame $\{0\}$ is coinciding with frame $\{1\}$. Frame $\{2\}$ is attached to joint $\{2\}$, while frame $\{3\}$ is attached to leg tip. The rotational inertias are defined about frames fixed at the CG of the link. The CG frame is fixed along the principal directions in the link or body. The surface on which the robot is walking is assumed as a hard surface.

2.1. Dynamics of a robot body

For a given instant, any rigid body has absolute translational velocity $\vec{v}$ and absolute angular velocity $\vec{\omega}$. The translational velocity and angular velocity vectors have been resolved into three