Mechanism and Machine Theory 121 (2018) 228–244

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmachtheory

Research paper

Fault accommodation in compliant quadruped robot through a moving appendage mechanism

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ARTICLE INFO

Article history:
Received 2 April 2017
Revised 3 August 2017
Accepted 14 October 2017

Keywords:
Quadruped robot
Moving appendages mechanism
Fault accommodation
Bond graph model

ABSTRACT

Quadruped robots provide better stability and speed in comparison to other legged robots. However, its joint actuator or sensor failure severely affects locomotion. Strategies for actuator and sensor fault accommodation in a compliant legged quadruped are presented here. A pair of orthogonally mounted moving appendages mechanism is proposed here to accommodate locked joint failure. These appendages as rack mounted inertias perform controlled motion during actuator failure. A strategy for sensor fault accommodation is also presented. A three-dimensional multi-body dynamics model of quadruped robot and its fault accommodation strategies are developed using bond graph modeling approach. The control performance is validated both through simulations and experiments.

1. Introduction

Mobile robots mostly follow three kinds of designs. The first kind is supported on wheels which allow high-speed motion on flat terrains but it is difficult to operate such a robot on uneven surfaces and to carry out specific tasks like step climbing. The second kind is based on anthropomorphic legs which offer better locomotion on uneven terrain, obstacle avoidance, etc. at the cost of speed. The third kind is a hybrid design which combines wheels at the leg tips to give a compromise design. The Cassino hexapod [1] is a hybrid mobile robot where rolling is possible on a flat ground and walking on irregular terrains. In case of multi-legged robots, three appropriately placed legs are required to maintain static stability. Since at least one of the legs needs to be lifted-off the terrain for locomotion, the minimum number of legs required is four. As the number of legs increases, the stability during locomotion increases and the robot can remain operational in the presence of failure of a few legs [1]. Also, the redundant legs can be deployed as hands for manipulation purposes. This has motivated development of varieties of hexapod robots [2] and robots with still higher number of legs. However, the locomotion speed and agility of hexapod robots is less than quadruped robots. In the case of typical tasks like obstacle avoidance, step climbing, etc., more legs means more complex gait patterns. One can think of an imagined horse-sized six legged animal trying to clear an equestrian huddle to understand the problems associated with too many limbs. The motion of legs should not interfere with each other and hence with more number of legs, the step size reduces and the length of the robot increases (such as in ants, centipedes and millipedes). In that respect, four-legged robots offer a good compromise between locomotion stability versus locomotion agility and speed. However, unlike a hexapod which can tolerate failure of up to two legs (excluding

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https://doi.org/10.1016/j.mechmachtheory.2017.10.011
0094-114X/

some specific cases), a quadruped as such cannot operate efficiently when a leg fails. This article precisely deals with such failure in a leg of a quadruped and suggests the deployment of redundant hardware in the form of moving appendages to overcome this handicap.

Safety and reliability are the critical issues in any automotive system design. Quadruped robots are meant to work in hazardous environment. Sensor and actuator faults are more likely to occur when the robot is put to work in such an environment. Thus, fault tolerant control (FTC) and reconfiguration is an emerging field of research for quadruped robots. In literature, one cannot find sensor fault accommodation of a quadruped robot. However, few researchers have worked on sensor fault detection and isolation for electrical systems [3,4] and pneumatic systems [5,6]. Position sensor fault can be detected and isolated through analytical redundancy, hardware redundancy or both of them. Hardware redundancy is a reliable solution but its use is limited due to cost and space constraints. Analytical redundancy based solution requires a well-developed and validated mathematical model which is used to generate residuals, i.e., the differences between predicted fault free measurements and actual sensor readings [5]. These residuals can be used to detect and isolate varieties of faults in the robotic system.

Locked joint failure in case of actuator is a kinematic failure under which a joint cannot move and is locked in place. However, body supporting ability is preserved. Due to this characteristic, the failed leg may yet contribute partially towards the robot locomotion if it is appropriately deployed. The locked joint failure is more common due to more frequent causes like friction in bearings, slipping of clutches, broken gear teeth jamming the motor, and misalignment/bending in the rotor shaft. In this situation, locomotion can be carried out by either implementing fault tolerant gait pattern or applying control laws to the redundant hardware. Different fault tolerant gaits have been suggested in [7–10] for locked joint failures. Fault accommodation through reconfiguration [11,12] is accomplished by on-the-fly deployment/activation of alternate standby devices, called hardware redundancies, in the place of faulty actuators and adapting control laws to the modified system's architecture.

This paper presents sensor and actuator fault accommodation strategies. In the faulty state, sensor/actuator may react differently. Here, it is assumed that those are not responding at all in the faulty state. Redundant sensor is used to accommodate sensor fault. Actuator fault is assumed to be of locked joint type failure. To accommodate this fault, two moving appendages (MA) which are realized in the form of rack pinion arrangements are proposed. The appendage device serves as a redundant hardware which is to be activated only when the base quadruped robot experiences a locked joint failure. The present work shows that the fault (locked joint failure) accommodation is effectively performed through this arrangement. To demonstrate the proposed control strategies, a three-dimensional dynamic model of a walking robot is developed using bond graph approach [13–16]. Bond graph is an efficient tool for system modeling from the physical paradigm itself and various control strategies can be developed by modifying the physical paradigm [17–19].

This paper is organized as follows. Section 2 presents the proposed moving appendages device. Sensor and actuator fault (locked joint) remedies are presented in Section 3. Dynamic simulation model and physical model used in experiments are presented in Sections 4 and 5, respectively. In Section 6, results are presented to validate the proposed strategies. Finally, Section 6 concludes this article.

2. Moving appendage device

Schematic diagram of a compliant legged quadruped robot with two moving appendage devices is shown in Fig. 1. Each leg of quadruped robot comprises two links. Link 1 is connected with the robot body through revolute joint (hip joint) whereas link 2 is assembled with link 1 through a revolute joint (knee joint). For modeling of quadruped robot, frame {A} is considered as the inertial frame and the body fixed frame {B} is attached at the center of gravity of the robot body. At each leg, frame {0} is fixed at hip joint while {1} is fixed at joint 1. Here, frame {0} and {1} coincide with each other. Also, frame {2} is fixed at joint 2 or knee joint and frame {3} is fixed at the leg tip.

The moving appendage device is mounted on the top of the body. This device is also called posture control (PC) device as it is used to control posture of the quadruped robot [20]. However, control strategy in posture control is different than fault accommodation. First, the use of PC device is introduced in [21] for locked joint fault accommodation through reconfiguration of planar sagittal plane model of quadruped robot. In this paper, attempt is made to accommodate locked joint failure through reconfiguration on three-dimensional model and validate the same through experiments.

The moving appendage consists of a rack and pinion where the pinion is operated by a motor. The rack can perform only linear motion along the path/guide-way provided on the body. The rack movement causes the change in position of the center of gravity (CG). Thus, by controlling rotational motion of the pinion, orientation of the body can be controlled. The body orientation about X and Y, i.e., ψ and θ can be controlled using two moving appendage devices.

For conceptualization, schematic diagram of a moving appendage controlling only the pitch angle (ψ) is shown in Fig. 2. A linearly movable rack with a central mass acts as the moving appendage.

The moving appendage which controls orientation ψ, has rack motion along y direction. The position of the CG of the moving appendage onrack1 with respect to the inertial frame {A} is given as

$$Y_{r_1} = Y_{CG} - l\cos\psi \tag{1}$$

$$Z_{r_1} = Z_{CG} - l\sin\psi \tag{2}$$