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A new algorithm to maintain lateral stabilization during the running gait of a quadruped robot

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HIGHLIGHTS

- This is a new algorithm to keep the lateral stability of quadruped robots, which is a major problem in advanced walking robot in a running gait.
- The method can keep the locomotion parameters (stride frequency and stride amplitude) when a disturbance occurs during the running gait.
- It does not need an additional package to be included when a disturbance occurs, since the algorithm can manage these disturbances in a natural way.
- A fast approach is added that allows the algorithm to be executed at a frequency of 1 kHz (sample time = 1 ms).

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ABSTRACT

This paper presents a new uncoupled controller (based on a Kinetic Momentum Management Algorithm, KMMA) which allows a quadrupedal robot, whose operation is simple and fast, to run using a symmetrical gait patterns in a wide variety of scenarios. It consists of two tasks: calculating the lateral position and speed of the fore swinging leg when it next makes contact with the ground; and controlling the roll angle by mean of inertia forces using the stance legs.

The KMMA provides the benefits of modulation and the synchronization typically presented in CPG (Central Pattern Generation) models. Furthermore, it is able to maintain the locomotion parameters (such as stroke frequency of gait pattern) when the robot runs in a highly disturbed environment, thus resulting in a lower energy consumption. Additionally, the uncoupled scheme of the leg makes the operation computationally cheap, thus avoiding the use of a Virtual Actuator Control or a Hybrid Zero Dynamics.

The performance of the KMMA has been verified by means of co-simulation (using ADAMS and MATLAB) with a highly realistic model of a quadruped robot with uncoupled legs. The performance of the algorithm has been tested in different situations in which the following variables have been varied: frontal velocity, turning ratio, payload, external disturbances and terrain slope. Successful results in terms of stability, energy efficiency, and adaptability to a complex locomotion environment have been obtained.

1. Introduction

During the running gaits (e.g. amble, trot peace, gallop or bound) of a quadruped robot [1], two feet are in contact with the ground at the same time. This paper therefore deals with three concerns that define the dynamic performance of the robot: robot balance, postural management, and energy efficiency. These concerns are approached by exploiting the advantages of the uncoupled mechanism inherent dynamics.

With regard to the robot's balance, two main approaches are found in the literature: central pattern generation (CPG) and the zero moment point (ZMP) stability margin. CPG has become a popular model with which to control the locomotion of legged robots when a high velocity gait pattern is used [2]. CPGs are neural networks located in the spinal cords of vertebrates and are able to generate a control signal that can be used to manage certain periodic tasks (e.g. masticate, respiration, locomotion) [3–5]. Since Huygens discovered the synchronization properties of non-linear oscillators in 1656 [6], coupled non-linear oscillators has been

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largely used to design CPGs [7]. To date, models of CPGs for legged robots have proven successful, and are mainly used to generate joint trajectories [8]. These stability criteria properly perform in a environment with reduced disturbances. It is essential to add reflex feedbacks to compensate high disturbances [9]. When no disturbances affect the robot, joint trajectory patterns generated by CPG do not modify locomotion parameters (e.g. gait pattern, stride length, stride frequency, duty factor, etc.). However, when a minimum disturbance occurs, the system is desynchronized and the entrainment process implies a complete change in the locomotion parameters. This trajectory change in all the DOFs is very closely related to higher energy consumption.

Furthermore, the ZMP stability margin is an adaptation for the dynamic running of the ZMP [10], which is applied to statically stable walking [11]. The ZMP stability margin is used to calculate a virtual contact polygon in which the vertex employed is not only the stance legs but also the ground plane protection of the swing feet. Si Zhang et al. [12] utilized this stability criterion to generate a trot locomotion of up to 0.83 m/s.

With regard to the robot's balance, the proposed algorithm is based on the fact that, if each foot is considered as a point of contact (assuming non-sliding and non-holonomic contact), then the system is under-actuated. During the stance phase, the variation of kinetic momentum above the axis that joins two stance feet is given by the external force momentum. If no disturbances affect the system, the only external force is gravity. The means used to maintain the robot balance is that of managing this variation.

This paper presents a new algorithm for the stability control of a quadruped robot based on the kinematic momentum management, named as KMMA and described in Section 3.3 and following.

Unlike CPG, the aim of the proposed algorithm is to maintain most of the locomotion parameters constant, thus reducing the energy consumption related to entrainment. In addition, CPG frequently uses larger duty cycles to make the quadruped walk with long cyclic periods. This reduces the period in which the robot dynamics is similar to an inverted pendulum. The alternative is short cyclic periods and smaller duty cycle [13]. On the contrary, the proposed algorithm does not avoid the inverted pendulum configuration, and therefore, long cyclic period and small duty factor (0.5) are achieved, with the consequent benefits in terms of speed and efficiency. The proposed algorithm is also very different to the ZMP stability margin, since we establish a running pattern in which the set of footholds are arranged in a straight line. This strategy is used owing to the fact that the further the touch-down distance is from the sagittal plane, the higher the disturbances torques produced when the feet impact on the ground. We therefore paradoxically propose to set the stability margin near to zero [9].

In addition to the stabilization task, controlling a robot also involves postural management, which is a term designated to the DOF control that allows the trunk of the robot to gain a proper position according to the intended requirement of an specific behavior, such as operating while remaining standing, walking over rough terrain, and running uphill. The Virtual Actuator Control [14] was first developed by the MIT leg laboratory, and it decouples the effective actuation of coupled legs, working with them as though they have Cartesian behavior by simulating the performance of mechanical components in order to generate real forces or torques. Some years later, another approach with which to maintain the robot posture was developed in order to control the Rabbit biped robot [15]: the Hybrid Zero Dynamics, which is based on the imposition of virtual constraints on the system in order to simulate physical constraints [16]. Both require a dynamic inversion, which increases the execution time [17]. If uncoupled legs are used in the robot, as in the case of this work, there is no need to calculate the inverse dynamics, and the computational cost is therefore reduced.

When combined with stability and postural management, energy efficiency is a key factor in the success of a legged robot when used in real applications. Much research has been carried out in order to determine the biology and engineering factors that yield an efficient locomotion [18–21]. The Cheetah Robot researchers have recently lumped together design principles for highly efficient legged robots [22–24], of which the following can be highlighted: torque-density motor [25,26], variable joint stiffness [27,28], retraction speed to reduce impact losses [29] and the importance of a low leg inertia [30,31].

This paper is organized as follows: Section 2 presents the specifications of the DOGO II quadruped robot. The dynamical model is then obtained. Section 3 addresses the stability problem, while Section 4 shows the results of the simulation performed with the prototype and a discussion. Eventually, Section 5 shows our conclusions and the future of this project is also presented.

2. Problem statement

2.1. Leg mechanism

An almost completely uncoupled leg mechanism scheme has been developed with the purpose of simplifying control. A similar mechanism was previously presented in [31].

The leg mechanism is composed of three sequentially arranged four-bar mechanisms (see Fig. 1(a)). The three-DOF leg mechanism (i) allows the end of the leg (point P, paw) to describe an almost straight line and perpendicular trajectories in nominal locomotion, as shown in Fig. 2; and (ii) concentrates the mass near the chassis, thanks to the mechanism structure and the location of actuators [31], thus maintaining both the relative COM position to the chassis and the inertia tensor practically constant. These two properties make it possible to simplify the kinematic and dynamic models of the leg. A simplified leg mechanism model is proposed consisting of three perpendicular translational joints arranged in succession, while the bar masses are ignored (Fig. 1(b)). The mass properties (mass and inertia tensor) of each leg are integrated with the chassis. The common inertia tensor is designated as $\tilde{I}$.

2.2. Running specifications

The control approach presented in this work is designed for running gaits in which the left and right feet of each pair have equal duty factors and relative phases differing by 0.5. These were denominated by Alexander in [1] as symmetric gaits i.e., amble, trot and pace.

In the case of walking gaits (passive dynamics), a wide contact polygon ensures stability [32]. However in the case of running gaits (active dynamics), this study proposes that the contact polygon should tend toward a line (setting the dynamic stability margin close to 0 [12]) in order to achieve smoother running gaits. Observe that in cursorial quadrupeds the hooves of the same pair are kept laterally close in running gaits. The lateral distance between the hooves and the sagittal plane affect the self-disturbance. More specifically, the higher the lateral hoof distance is, the more the frontal DOF inertia forces affect the lateral stability and the higher the gravity disturbance torque is. In order to minimize this unwanted effect, the lateral DOFs of the hind legs are kept fixed as close to the sagittal plane as possible, the value of their DOF being the minimum required to avoid self-collision. The fore legs are consequently responsible for the lateral stability. To that end, a parameter exists that controls the fore leg lateral distance in order to minimize self-disturbance.