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Stabilization of an autonomous rolling sphere navigating in a labyrinth arena: A geometric mechanics perspective

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ABSTRACT

Several concepts and results in geometric mechanics are used to analyze and control the locomotion system of an unconventional robot encapsulated in a sphere shell, assumed to roll without slipping on the floor and internally equipped with a set of inertia gyros as indirect driving devices. Lie group symmetries intrinsic to this problem, i.e., invariance of the system's Lagrangian and velocity distribution to some group of motions, allows the reduction of the equations of motion. This system whose motion ability is based on angular momentum conservation is established as a controllable nonholonomic system for which the attitude/position cannot be stabilized by smooth feedback laws. Pursuing the reduction process permits us to design a feedback law extensible to both kinematic and dynamic levels of actuation, enabling the robot to execute finite-time reorientation and repositioning maneuvers while confined to move in corridor-like domains. The derivation of the underlying nonlinearity contents via the geometric approach helps the analysis not to rely on a specific choice of coordinates and allows taking profit of the vector structure of the equations for further investigations.

1. Introduction

Traditionally, the research on nonholonomic rolling constraints was restricted at a kinematic level to domains such as manipulation by multi-fingered robotic hands or motion planning for wheeled vehicles. The field has recently been extended with a dynamic flavor to robotic systems in which the association of rolling constraints coupled with momentum principles permits unusual modes of locomotion [1–3]. In such systems, self-propelled movements are usually generated by creating imbalance or altering the system inertia. The present work emphasizes the motion control and guidance of a relatively new type of robot cast in a spherical shape, intended to maintain a rolling motion over quasi-flat surfaces. The sphere is conducted between configurations across confined corridors by inducing local body motion through an interior actuation system based on angular momentum conservation. The spherical construction offers omni-directional local mobility compared to wheeled mobile robots and more stability than legged robots in surpassing obstacles in cases where turning over or falling down may endanger the mission. Its economic mode of locomotion might only require an initial momentum for the motion to perpetuate rolling along straight paths, with only partial readjustments needed to engage slightly curved circuits; in contrast to wheeled or legged-robots that have to be motorized continuously. One alternative purpose for this system was to set up an original platform in order to implement diverse locomotion strategies issued from the geometric viewpoint of control.

1.1. Geometric mechanics and control

The modern treatment of mechanics is geometrical. Representing geometric objects in terms of coordinates can frequently lead to confusion and complexity, with corresponding derived equations relying on the specific choice of coordinates. Moreover when working with complex mechanical systems, an important step for dealing with the dynamics and control is to simplify the governing equations in the hope of gaining additional insights on their structure. This can be of significant help in designing controllers, identifying appropriate integral schemes and motion planning algorithms. Among existing control methodologies for nonlinear systems, few take account of the rich structure inherited by the broad class of "mechanical control systems". The mechanical systems framework also provides a natural setting for the introduction of symmetry-induced reductions and can be assimilated into geometric structures such as fiber bundles which help with the motion analysis [4–7].

1.2. Symmetry and reduction

Reduction is briefly defined as the act of factoring out the dependency to some variables from the equations of motion

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