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研究課題名（英文）Dynamic model-based motion planning and control strategies for spherical rolling robots

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研究成果の概要（和文）：本研究では球型転がりロボットの運動計画を構築する。ロボットの動作生成のため、三つのステップからなる制御戦略を提案した。二種類のロボットを研究し、振り子を用いたロボットは、動力学モデルを導出し、動的可能性の条件を確立した。具体的には転がるスピンがない場合は、計画の問題が動力学的なレベルに切り離すことができる。この場合、運動計画は最適制御に基づく手法が提案された。内部ローターを用いたロボットは、デカップリングはできないが、動力学モデルは角運動量保存により減少が可能である。提案した計画アルゴリズムは幾何学的位相を用いた。更に、ニルポテント近次と反復性ステアリングを用いた軌道計画についても確認した。

研究成果の概要（英文）：The research deals with motion planning for rolling robots with minimal number of actuators. Two types of robots, actuated by a pendulum or internal rotors, were considered. A motion planning strategy, consisting of two trivial and one non-trivial maneuvers, has been proposed. For the first robot, a dynamic realizability condition was established. It was shown the planning problem can be decoupled to kinematic and dynamic levels if the robot rolls without spinning. In this case, the planning is reduced to a boundary value problem for a hoop-pendulum system rolling along a contact curve, and a technique based on the linearized optimal control solution was proposed. For the second robot, the decoupling is not possible but the dynamic model is reduced by the conservation of the angular momentum. A planning technique based on the geometric phases approach and the nilpotent approximation of the robot dynamics, has been proposed. Two spherical rolling robots were designed and prototyped.

研究分野：工学

キーワード：ロボティクス　モーションプランニング　非ホロノミックなシステム　転がりロボット　拘束運動　最適制御

１．研究開始当初の背景

Spherical robotics is an emergent research field. In recent years, there has been a growing interest to robotic systems where non-holonomic rolling constraints are used not only for manipulation but also for locomotion. In such systems, self-propelled movements are usually generated by creating imbalance and changing the system inertia. These vehicles can be useful when the usage of traditional machines is limited or undesirable. The main driving principles of these vehicles are based on a) changing the center of mass of the robot, and b) generating a reactive torque by internal rotors. While the motions of spherical rolling robots appear aesthetically beautiful, it is far from being clear how these motions can be planned in the full state space (including the orientation of the vehicle) if the dynamics of the actuators must be taken into account. Answering this question is very important for the construction of intelligent control systems for rolling robots.

２．研究の目的

The rolling robots, considered as single wheel vehicles, represent a new type of mechanical systems demonstrating rich and intriguing dynamics. However, the dynamics and control of such systems are not understood well due to the enigma of nonholonomic constrains, and too often oversimplified models, emasculating the nonholonomic nature of the systems, are used in the control synthesis. Therefore, the two main goals of this project were formulated as follows. First, develop the exact mathematical models which will take into account the dynamics of the driving mechanisms and nonholonomic constraints imposed on the motion of the rolling vehicle, and then develop on-line implementable dynamics-based motion planning strategies for reconfiguring the robotic system in the full state space from a given to a desired configuration.

３．研究の方法

The project combined both the theoretical and the experimental parts. In the theoretical part, we used methods of analytical mechanics, nonlinear dynamics, optimal control, and geometric control theory, in order to derive kinematic and dynamic models of the robots, and develop based motion planning strategies and control algorithms for steering spherical robotic systems with minimal number of control inputs subjected to nonholonomic rolling constraints. In the experimental part, we prototyped two spherical rolling robots, one actuated by a single pendulum and another one actuated by symmetrically placed internal rotors.

４．研究成果

First, we considered motion planning for a spherical rolling robot actuated by two dynamically symmetric internal rotors that are placed on two orthogonal axes. The full mathematical models, featuring 12 states and 2 control inputs, was first derived. It was reduced then to a 5 states-2 inputs by the conservation of the angular momentum. It was found that conventional decoupling to the levels of kinematics and dynamics and solving the planning problem separately was impossible because kinematically admissible trajectories can be dynamically unrealizable. As a result, the motion planning problem can be addressed only dynamic formulation. In addition, the problem features a singularity when the contact trajectory goes along the equatorial line in the plane of the two rotors.

A motion planning strategy composed of two trivial and one nontrivial maneuver was then devised. The trivial maneuvers implement motion along the geodesic line perpendicular to the singularity line. The construction of the nontrivial maneuver can be realized by three different techniques. The first one is based on the optimal control formulation and results to a contact point trajectory that can be classified as an Euler's dynamic *elastica* curve. This technique, however, comes with higher computational cost. The second technique employs the nilpotent approximation of the originally nonnilpotent robot dynamics, and is based on an iterative steering algorithm. At each iteration, the control inputs are constructed with the use of geometric phases. This technique can be on-line implementable but it results a large number of movement steps. The third technique, is based on tracing spherical figure eights (circles, in our case) with precomputed radii of circles matching the desired non-holonomic shift and holonomy phase. This technique can be regarded as trade-off between the computational cost and mechanical efficiency of movements (the number of movement steps). The motion planning strategy, with three different techniques for realizing non-trivial maneuver, was verified under simulation.

Next, we analyzed a spherical rolling robot, actuated by a controlled pendulum with two degrees of freedom. A dynamic model for the robot, featuring 12 states and 2 control inputs, was developed. Based on the dynamic model it was shown that, in general, not all feasible kinematic trajectories of the rolling carrier are dynamically realizable if there are only two control inputs. However, we established that if the kinematic trajectory admits pure rolling mode (pure rolling, i.e., rolling without spinning), the motion planning problem can be efficiently decoupled into kinematic and dynamic levels. The former can be realized by conventional planners, while the latter is reduced to steering an underactuated system (hoop-pendulum system) system along the contact curve. The hoop-pendulum system is described by two differential equations of second order with one control input. Thus, for pure rolling motion the planning can be reduced to solving a boundary value problem for 4 states-1 control input system.

To steer the hoop-pendulum system in rest-to-rest mode along the contact curve, a simple technique, based on the linearized optimal control problem with the minimum control effort criterion and featuring an illustrative connection to geometric phase method, was developed. The technique admits the analytical solution (the second derivative of Beta function for the pendulum angle in the contact plane) and is easy to implement. Limitations of this technique and the practical ways to deal with them were established. Overall, this technique was verified under simulations for different spherical curves (geodesic lines, circles, Viviani's curve, and the Loxodrome).

In addition, a trajectory tracking problem for the hoop-pendulum was also considered and an adaptive feedback controller was proposed. To deal with time-varying uncertainty of the system dynamics, an adaptation mechanism was included in the trajectory tracking controller by using an auxiliary square system and applying a function approximation technique, i.e. by parameterizing the system uncertainty with a chosen basis function, weighted by unknown constant parameters adjustable by the defined update law. As a result, the variation between the auxiliary square system and the original non-square underactuated system can be eliminated. The asymptotic stability of the controller was established and the feasibility of the proposed control method was verified under simulation.

Finally, it should be also noted that the byproducts of this research (methods and algorithms of optimal control of nonlinear systems) have been applied also to modeling and prevention of infection diseases for certain biological species, and to the prediction of rest-to-rest natural human-like reaching movements.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

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６．研究組織

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