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Optimal motion planning and control of a nonholonomic spherical robot using dynamic programming approach: simulation and experimental results

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ABSTRACT

Optimal motion planning and control of a nonholonomic spherical mobile robot is studied. Dynamic Programming (DP) as a direct and online approach is used to navigate the robot in an environment with/without obstacles. The optimal trajectory, which corresponds to the minimum cost, is determined in the case of presence of obstacles in the environment, and the robot can move towards the target optimally, without colliding with obstacles. DP yields optimal control inputs in a closed-loop form. In fact, a traditional control system is no longer needed to track the obtained trajectory since the resulted DP table includes optimal control inputs for every state in the admissible region. The effect of different final states and alternative intervals of the allowable state and control values are also studied. Results from several simulations show that the proposed method enables the robot to find an optimal trajectory from any given state towards a predefined target. An experimental setup is designed wherein a real spherical robot is driven according to the developed algorithm. A vision system monitors the robot and outputs the location/orientation of the robot at each step via image processing. Experimental results are then compared with simulations to validate the model and evaluate the control strategy.

1. Introduction

Spherical mobile robot basically consists of a ball-shaped outer shell including its driving mechanism to roll the sphere. As compared to usual wheeled robots or walking robots, a spherical rolling robot offers certain advantages. The major advantage due to the spherical shape is that it is not overturned. Therefore, it can face obstacle cluttered environment and irregular surfaces. Such robots can thus survive in harsh or dangerous environments such as outer planets, deserts and earthquake ruins for exploration or reconnaissance tasks [1–5]. Different constructions have been suggested for a spherical robot [6].

From control point of view, spherical robot is a kind of nonholonomic system; the number of control inputs is smaller than the dimensions of the state space. This makes the motion planning and control problem difficult [7]. The stable full-state tracking problem was investigated for nonholonomic wheeled mobile robots under output-tracking control laws [8]. An adaptive output feedback tracking controller for nonholonomic mobile robots was proposed to guarantee that the tracking errors are confined to an arbitrarily small ball [9]. Control schemes, based on the flatness property and the concept of virtual vehicles, for a group of nonholonomic kinematic mobile robots for maintaining a desired formation along a time-parameterized path were proposed in [10]. Obstacle avoidance policies were introduced for cluster space control of nonholonomic multirobot systems [11].

In fact, spherical robots are not yet popular due to the complexity involved in motion planning and control of nonholonomic robots. However, researchers have done significant works for navigation and control of these robots. Li and Canny proposed a three-step algorithm for motion planning of a sphere rolling on a flat surface [12]. In the first step of the algorithm, the position coordinates of the sphere are converged to the desired values. Next, two of the three orientation coordinates are converged applying Lie Bracket-like motion. A polhode is used to converge the last orientation coordinate in the third step. Two algorithms were presented for partial and complete reconfiguration of the sphere by using individual control inputs in [13]. In the first algorithm, spherical triangles are utilized to bring the sphere to the desired position and orientation. The second strategy generates a trajectory comprised of straight lines and circular arc segments. Two simple and effective algorithms for reconfiguration of the sphere are given in [14,15]. One algorithm that uses spherical trigonometric concepts is similar to the second step of the Li and Canny algorithm. Another

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algorithm effectively uses the final configuration of the sphere at the singularity of the ZYZ Euler angle description, thus reducing the number of configuration variables. It however uses control inputs in a rotating reference frame. Bhattacharya and Agrawal deduced the first-order mathematical model for a kind of spherical robot from the non-slip constraint and the conservation of angular momentum. The authors studied the trajectory planning based on optimal time and energy strategy, and presented both simulations and experimental results [16,17]. Bicchi et al. [18,19] established a simplified dynamic model for a spherical robot and discussed its motion planning on a surface with obstacles. Joshi and Banavar proposed the kinematics model of a spherical robot using Euler parameters and investigated the path planning problems [20,21]. Two different algorithms for motion planning of a rolling sphere, the circle-based and the generalized Viviani-curve-based ones, were also proposed [22]. Based on Ritz approximation theory, the near-optimal trajectory of a spherical robot was planned with the Gauss-Newton algorithm [5]. Path tracking control of a spherical robot, focusing on the simultaneous converges of both position and orientation, was studied in [4]. Wilson's eXtended Classifier System was utilized for motion planning of a spherical robot [23,24]. A motion planning strategy, composed of two trivial and one nontrivial maneuver, was devised for a spherical rolling robot driven by two internal rotors [25]. Using computational fluid dynamics, Alizadeh et al. studied the motion of a spherical robot on the surface of water and called it an amphibious robot [26].

Motion analysis of spherical robots has thus been studied in two directions: one is the motion planning of these robots and the other is tracking the desired trajectory [27,28]. In almost all of the previous researches, the optimal trajectory obtained offline should be tracked by control actions. The control inputs were not limited in motion planning and could not be implemented on a real robot. There is also a lack of experimental work for closed-loop control of the spherical robot.

In this paper, the direct and online approach of dynamic programming, introduced by Bellman, is used to find the optimal trajectory and closed-loop control of a nonholonomic spherical robot in an environment with/without obstacles. In fact, DP is used to find the optimal trajectory to reach the target without colliding with obstacles. The control inputs have certain bounds in our proposed procedure and could easily be implemented in real world. Here, designing a traditional control system and tracking the obtained optimal trajectory are eliminated since DP yields the optimal control inputs in a feedback form. In other words, in the proposed method, the robot can find the optimal control inputs according to its state at each step and the completed DP table. The effect of presence of obstacles, variation of final states and intervals of the allowable state and control values are also studied. An experimental setup is designed to implement the proposed closed-loop algorithm. A vision system is utilized to monitor the state of the robot at each step via image processing. The closed-loop control system implemented here is explained and experimental results are compared with simulations to validate the model and evaluate the control strategy.

The outline of the paper is as follows. The kinematic model of the spherical robot is described in the next section. In Section 3, a brief description of DP and its implementation for the spherical robot are presented. Section 4 provides the simulation results. Experimental works and implementation of control loop are discussed in Section 5.

2. Modeling

This paper focuses on a simple spherical mobile robot developed using a pendulum-based design. This type of spherical robot uses gravitational force to move. Fig. 1 shows a schematic of the internals of a kind of spherical robot called Rotundus [6]. This design consists of two perpendicular motors attached to the inside of the sphere. One of them, stepper motor 1 in Fig. 1, is attached to the horizontal axis (the main shaft) that goes through the sphere and changes θ. In the center of the main shaft there is a pendulum that can move with respect to the shaft. When this motor is activated, position of the mass center of the robot changes, and hence, the sphere moves as long as the weight of the pendulum has enough inertia as it is easier for the casing to spin than the pendulum to go around. The pendulum can move in a direction perpendicular to the shaft for changing ϕ by the other motor (stepper motor 2 in Fig. 1), causing the robot to turn in other directions. Therefore, it has a pendulum with two DOFs [29–31]. Fig. 2 shows the fabricated spherical robot in our laboratory.

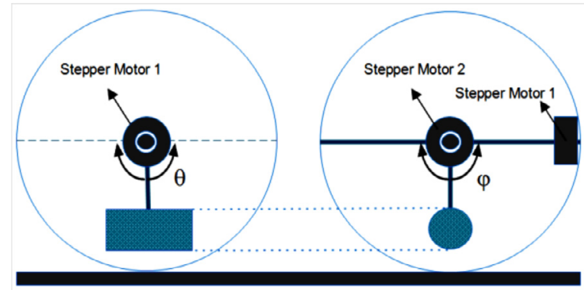

Fig. 1. Schematic of the intervals of a pendulum-driven spherical robot.

Fig. 2. The fabricated spherical mobile robot.

Consider the motion of a sphere on a flat plate, rolling without slipping. The contact point can be represented in the coordinate system attached to the sphere center as follows. ρ is the radius of the spherical shell.

$$f(\theta,\phi) = \begin{pmatrix} \rho\cos\phi\cos\theta \\ \rho\cos\phi\sin\theta \\ \rho\sin\phi \end{pmatrix} \quad (1)$$

where ρ,ϕ,θ are variables specifying a point in the spherical coordinates. The contact trajectory on the plate is specified by $C=(x,y)$ in the xyz-coordinates attached to the plane. The contact trajectory on the sphere is indicated by $C' = (\theta,\phi)$ in the coordinates attached to the sphere. In Cartesian coordinates, the rotation angle of the sphere with respect to the surface is the angle between two coordinate systems at the contact point (see Fig. 3). This angle is known as the "holonomy angle", indicated by ψ. The solution of the forward problem in which we seek C with knowledge of C' is obtained as follows [29,30]:

$$\begin{cases} \dot{x} = \rho\left(-\dot{\theta}\cos\phi\sin\psi + \dot{\phi}\cos\psi\right) \\ \dot{y} = \rho\left(\dot{\theta}\cos\phi\cos\psi + \dot{\phi}\sin\psi\right) \\ \dot{\psi} = -\dot{\theta}\sin\phi \end{cases} \quad (2)$$