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Dynamic modeling and obstacle-crossing capability of flexible pendulum-driven ball-shaped robots

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HIGHLIGHTS

- An extended dynamic model for a flexible rolling, slipping, sliding and bouncing ball-shaped robot.
- A simplified contact model for a flexible ball interacting with an obstacle.
- A model-based method to predict step-crossing capability of a flexible ball-shaped robot.

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ABSTRACT

Ball-shaped robots present a novel and widely studied approach for mobile robotics. Despite the essential benefit of the ball-robot that it cannot flip over or fall down, the robot's physical construction often severely limits the ball mobility in uneven terrain. The customarily applied quasi-static motion model makes the anticipated theoretical robot mobility even worse, because it completely ignores ball dynamics and therefore seriously under-estimates the robot's obstacle-crossing capability. The energy-based model, sometimes applied instead of the quasi-static model, over-estimates ball mobility and becomes inconvenient when an active driving motor is added to the system. This paper introduces a new extended dynamic model for flexible pendulum-driven ball-shaped robots, as well as a simulation-based method to predict the robot's step-crossing capability. The extended dynamic model allows rolling, bouncing and slipping of the robot, and it includes a simplified contact model for the ball-obstacle-interaction. The simulation results have been compared to experimental results obtained with a physical robot. The comparison shows that the new dynamic model and contact model outperform the traditionally applied quasi-static and energy-based models. The new dynamic model may be applied in mobility analysis of ball-robot designs, for path planning, as well as for control algorithm development.

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1. Introduction

Ball-shaped vehicles have been under development already over the last 120 years. The first patents on self-propelled spherical toys were filed in the end of 19th century [1,2]. Studies on dynamic modeling and steering of a motor-driven ball started in 1990's, leading into emergence of computer controlled ball-shaped mobile robots [1–7]. Recently, problems on modeling, path planning and controlling of non-holonomic rolling mobile systems have gained much interest in analytical mechanics and control community, while practical rolling robots have been also introduced to surveillance applications and entertainment [1–8].

Motivation behind this paper anticipates a domestic rolling robot providing surveillance and companionship at home. The familiar and friendly spherical figure of the ball-shaped robot has been found beneficial for robots interacting with people [5]. The essential asset of the ball-robot is that it cannot flip over or fall down. In addition, the entire surface of the rolling sphere provides propulsion, so the robot may not get stuck on its belly, -like wheeled robots may. However, the ball-robot's physical construction often severely limits the available driving torque and ball mobility in uneven terrain. While the structured environment usually provides a beneficial flat rolling surface for a ball-robot, such regular elements as door steps, carpets, or scattered toys may form a notable obstruction for ball-robot mobility at home.

In order to design a ball-robot to surpass the predictable obstacles, there exists a need to estimate and predict the dynamic step-crossing capability of a ball-shaped robot. Estimation of slope-climbing and step-crossing capability of ball-robots has been customarily conducted with a quasi-static analysis based on a static

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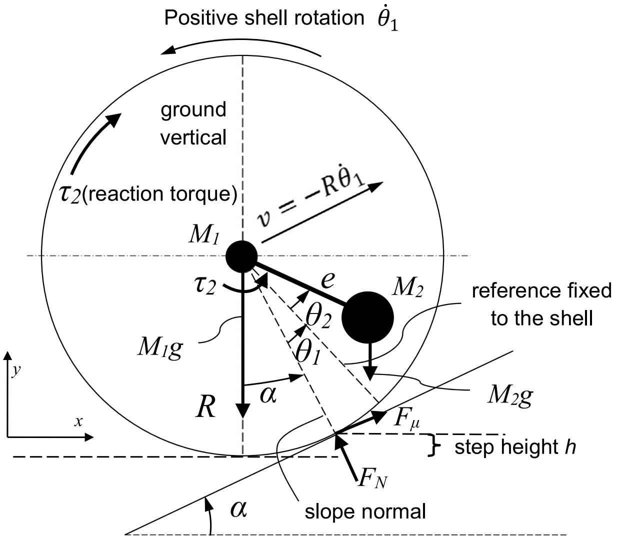

Fig. 1. A typical decoupled model of a pendulum-driven ball-robot crossing a step of height h, or a slope with a respective angle α. During forward rolling in positive x-direction, ball velocity v is positive and ball rotation angle θ_1 gets negative values, while pendulum angle θ_2 (relative to ball shell) is positive. Motor torque τ_2 drives the pendulum counter-clockwise and generates a reaction torque on ball shell in opposite direction. In quasi-static balance, the gravitational force M_2g on the pendulum balances the gravitational force M_1g on the shell. F_N and F_μ present the contact forces.

torque balance. With this approach, especially the step-crossing capability appears to be very limited being only some percent of the ball diameter [3,4,9–11]. Although some authors have noticed that the ball dynamic behavior could help in passing over large obstacles [4], no attempts have been presented to calculate the dynamic obstacle-overcoming capability of a motor-driven ball-robot. It may be anticipated that, if compared to a rigid-shelled ball, a flexible ball presents smoother rolling and softer interaction with environment. Intuitively thinking, a soft shell may allow easier obstacle overpassing due to softer contact and larger traction surface. Thus extension of the mobility model for flexible ball-robots is of interest.

Previous work presents experiments and a model for the dynamic step-crossing capability of a rigid-shelled pendulum-driven ball-robot [12]. This paper continues the work and introduces a method to predict the dynamic step-overcoming capability of a flexible pendulum-driven ball-robot. We validate the results with practical experiments.

2. Related work

Plenty of prior work has been conducted on kinematic and dynamic modeling, path planning, and control of ball-shaped robots with different constructions. A motor-actuated pendulum as a driving mechanism has been presented in [3,5,10,11,13–16], while an omni-wheeled platform drives the ball in [17]. A *coupled model,* that presents the full motion of the complete system, is applied in [16–24]. On the other hand, a *decoupled model* considers the steering and forward-driving motions separately in [3,25–34]. Rolling without slipping is investigated in [35], and a review on decoupled models is available in [36].

2.1. Mobility of internally propelled robots

In the related literature, there exists some papers discussing the motion of a pendulum-driven ball-robot on a sloped surface, sometimes addressing also the quasi-static obstacle-overcoming capability. Fig. 1 illustrates a typical model of a pendulum-driven ball on a slope, or against a step-shaped obstacle.

In analysis of ball mobility, Koshiyama and Yamafuji include the slope angle in the dynamic equations [3]. Halme et al. calculate the quasi-static torque balance about the contact point at the step corner [4], as shown in (1).

$$h_{\max} = R - \sqrt{R^2 - \left(\frac{M_2 e}{M_1 + M_2}\right)^2} \tag{1}$$

where: $h_{\max}$ = traversable maximum step height, R = ball radius, e = driving mass-center off-set from the ball center, M_1 = mass of the spherical shell, M_2 = driving mass.

While (1) presents the maximum obstacle height for a quasi-static balance, which has been adopted as a regular measure for ball-robot mobility, Halme et al. note that any initial rolling velocity of the robot would help to overcome an obstacle also larger than this model implies. Identical results have been presented also in [9–11]. They all ignore any dynamic effects and notify the significantly small passable step height, being only 0.5%–2% of ball radius. Yu et al. present the dynamics of a spherical shell rolling along an inclined slope [21,33], while Zhao et al. place the robot on Moon surface and study the rolling on Lunar soil [37].

2.2. Flexible, wind driven, and deformable robots

Flexible ball-robots include a number of wind-driven balls as well as deformable ball-robots. Based on the concept presented by Jacques Blamont, *Tumbleweed* is a spherical wind-propelled robot designed to travel on the surface of Mars [38]. Different conceptual designs, testing and modeling are presented by Wilson et al. in [39]. Kolacinski and Quinn apply the quasi-static model, energy based model, and a dynamic simulator to study Tumbleweed obstacle-crossing [40]. They show that the quasi-static model under-estimates the ball mobility while the energy-based model over-estimates it. Flick and Toniolo apply as well a quasi-static torque balance for Tumbleweed mobility [41], while Wilson et al., Hartl, and also Li and Liu use the collision model of Kane and Levinson, but do not draw conclusions about the over-passable obstacle size [42–45]. Liang et al. study the mobility of a deformable ball-robot constructed with a wire frame and airbags [46]. Hogan and Forbes model a wind-driven ball while harvesting energy with an internal generator [47]. Zhou et al. present a soft-shelled inflatable ball-robot that becomes immobilized when not full [48], in a similar manner as NASA JPL Tumbleweed and Heimendahl's Windball [38,49,50]. Jiang et al. include the ball flexion in calculation of the quasi-static balance for an inflatable ball trapped between obstacles [51,52]. Due to the flexibility of the spherical shell, the model of Zhang et al. allows the mass-center to move inside the ball, as if suspended by elastic springs inside a rigid-shell [53]. Li et al. and Basic present separately inflatable wind-driven ball-robots but ignore discussions about ball flexibility [54,55]. Apostolopoulos et al. report experimental test results for a spherical inflatable rover wheel, which in structure is similar to the rolling Tumbleweed-robot [56]. Marsh presents an inflatable Tumbleweed rover, operation of which was demonstrated on US-television [57,58]. Sugiyama et al. introduced circular and spherical wire-frame-like robots, powered by shape-memory actuators [75]. Wait et al. present a ball-robot actuated with pressurized air [59] and rolling in a similar manner as the pneumatically driven wheel of Arizona University [60], Wormsphere of Kangi [61], and silicone-rubber ball of Mozeika et al. [62]. Artusi et al. apply dielectric materials for ball deformation [63].

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