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Dynamics and motion control of a chain of particles on a rough surface

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ABSTRACT

In this paper the mechanics and control of the motion of a straight chain of three particles interconnected with kinematical constraints are investigated. The ground contact is described by dry (discontinuous) or viscous (continuous) friction. Here, we understand this model as a methodological basis for the design of worm-like locomotion systems, i.e., non-pedal mobile robots. This kind of robots will prove an efficient form of locomotion in application to inspection of pipes or for rescue missions. In this paper, a number of issues related to the dynamics and control of artificial limbless locomotion systems are discussed. Simplest models of a limbless locomotor are two-body or three-body systems that move along a horizontal straight line. In the first part of the paper, the controls are assumed in the form of periodic functions with zero average, shifted on a phase one concerning each other. Thus, there is a traveling wave along the chain of particles. In the second part, actuator models are discussed. It is supposed that there are unknown actuator data or the worm system parameter are not known or exactly as well. The focus is on adaptive control algorithms for the worm-like locomotion systems in order to track given reference trajectories, like kinematic gaits. Finally, a prototype together with its signal processing and control software is presented. Theoretically (analytically and numerically) calculated results of the dynamical behavior of the mobile system are compared to experimental data.

1. Introduction

Recent developments in mobile robotics show that, especially in medicine, for inspection technology and for urban search and rescue scenarios, locomotion systems are needed, which can move through narrow tubular and complex environments, i.e., blood vessels, pipelines and ruins. For such applications the systems should be characterized by a relatively small size and weight, as well as by the possibility to move autonomously. To realize such artificial locomotion systems, the research focus in mobile robotics has been shifted more and more towards limbless and compliant locomotion systems that are inspired by snakes, worms and similar biological objects [1–3]. Thus, this paper relates to the mechanics and control of worm-like locomotion systems [4–6]. A key issue of mechanics of limbless locomotion is the identification of conditions of the physical interaction between the locomotion system and the environment, subject to which the system can move progressively in the environment. If the motion is possible, then the next question is finding out what specific control algorithms for the internal shape variables [7] lead to an optimal locomotion, e.g. a motion with a maximal velocity of the center of mass. The aim of the paper is twofold. First, to present a theoretical and methodological basis for the investigation of the motion and the control of worm-like locomotion systems. Second, to describe the

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experimental evaluation of theoretical results on a prototype developed by the authors.

Worm-like locomotion systems designed as a chain of links connected by powered prismatic and/or revolute joints are investigated in several publications [8–10]. The papers [9,11,12] deal with the analysis of the rectilinear motion along a rough plane of chains of bodies (*discrete mass points*) interconnected by elastic elements in the case that the normal pressure does not change and the system is driven by harmonically varying forces acting between the bodies. The asymmetry in the force of friction is provided by the dependence of the coefficient of friction on the direction of the velocity of the system's components. This can be provided, for example, by covering the contact surfaces of the robot with scaly or pinned plates with an appropriate orientation of scales. In comparison with the paper [12] this study presents also hard- and software developments for the evaluation of theoretical results. Focusing on the aim of autonomous locomotion, the studies [13,14] present the idea of making an elastic element using smart materials (a magneto-sensitive elastomer [15]). The harmonically varying force is created through a controllable magnetic field. In [16–18], for a particular model, it is shown that a one-dimensional *distributed-mass locomotor* can move progressively in a viscous medium with linear rheology. The motion was excited by a periodic extension-contraction deformation wave traveling through the worm's body.

Mechanisms of another type consist of a body with movable internal masses [19–25]. The inertial masses interact with the body by means of internal forces generated and controlled by drives. When the control force is applied to an internal mass, the reaction force is applied to the body and changes its velocity, which affects the resistance force exerted on the body by the environment. The investigations in [20] deal with the motion of a single body with an unbalanced vibration exciter along a straight line on a rough horizontal plane. A difference in the coefficients of forward and backward friction is not assumed. The dynamic asymmetry is provided by the phase shift between the horizontal and vertical components of the driving force produced by the exciter. A mobile system that consists of two identical modules connected by a spring is considered in [23]. Each module contains an unbalanced vibration exciter. The exciters rotate with the same frequency in one direction but have a phase shift. It is shown, that when the excitation frequency passes through the resonance with the natural frequency of the system, the direction of the motion changes.

The issue of the optimal control of the motion of a body with movable internal masses is considered in [19,26,21,27]. Adaptive control problems of finite degree of freedom worm-like locomotion systems which contact the ground with Coulomb dry friction are discussed in [28–31]. Gaits (i.e. the set of all prescribed time-dependent link length functions $l_i(t)$, see Fig. 1), based on kinematic equations are tracked by means of adaptive controllers. In [32] an extended admissible control for a two segmented worm with an asymmetric dry friction model is presented. Control problems in connection with the realization of artificial worm prototypes are discussed in [33–35].

2. Mechanical model of the worm-like locomotion system and methods of investigation

The basic model for the investigations in the following sections is a chain of three identical bodies (particles) moving along a straight line on a rough horizontal plane (see Fig. 1). The particles are denoted by 1, 2, and 3 consecutively from the left to the right end of the chain. Let x_1, x_2, and x_3 denote the coordinates of the respective particles measured along the line of motion of the chain from a fixed point 0. The motion is excited and controlled by changing the distances $l_i(t)$ between the particles.

The medium acts on the ith particle with the force $F(\dot{x}_i)$, depending on the velocity $\dot{x}_i$ of this particle relative to the environment that is assumed to be unmoved in an inertial reference frame. The force F is the force of friction between the particle and the medium.

By *viscous friction*, we understand the resistance characterized by a continuously, monotonically decreasing function $F(\dot{x}_i)$, vanishing at $\dot{x}_i = 0$. A typical example of the viscous friction is the power-law friction characterized by

$$F(\dot{x}_i) = \begin{cases} \mu_- |\dot{x}_i|^\alpha & \text{if } \dot{x}_i \le 0, \\ -\mu_+ |\dot{x}_i|^\alpha & \text{if } \dot{x}_i > 0, \end{cases} \tag{1}$$

where μ_- and μ_+ are positive coefficients of friction resisting the leftward ($\dot{x} < 0$) and rightward ($\dot{x} > 0$) motion, respectively, and $\alpha > 0$ is the power exponent of the resistance law, Fig. 2.

By *dry friction*, we understand the resistance characterized by the law:

$$F(\dot{x}_i) = \begin{cases} k_- N, & \text{if } \dot{x}_i < 0 \text{ or } \dot{x}_i = 0, \text{ and } \Phi < -k_- N, \\ -\Phi, & \text{if } \dot{x}_i = 0 \text{ and } -k_- N \le \Phi \le k_+ N, \\ -k_+ N, & \text{if } \dot{x}_i > 0 \text{ or } \dot{x}_i = 0, \text{ and } \Phi > k_+ N, \end{cases} \tag{2}$$

where k_- and k_+ are the coefficients of dry friction at the leftward ($\dot{x} < 0$) and rightward ($\dot{x} > 0$) motion, respectively, N is the force of normal pressure (in the case under consideration, N=mg, where g is the acceleration due to gravity), and Φ is the resultant of the forces, other than frictional ones, applied to the particle. The friction characterized by this law is sometimes called *Coulomb's*

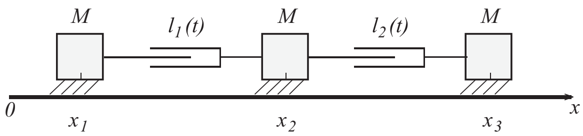

Fig. 1. A three particle system with controlled relative distances between the consecutive particles.