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Motion planning for a planar mechanical system with dissipative forces

Ahmad Ali [a,c], Sheraz Yaqub [a], Muhammad Usman [a,c], Khalil M. Zuhaib [a], A. Manan Khan [b], Ji-Yeong Lee [b], Chang-soo Han [b,*]

[a] Department of Mechatronics Engineering, ERICA Campus, Hanyang University, Ansan, Gyeonggi-do [425-791], Republic of Korea
[b] Department of Robotics Engineering, ERICA Campus, Hanyang University, Ansan, Gyeonggi-do [425-791], Republic of Korea
[c] Department of Mechatronics Engineering, University of Engineering &Technology, Lahore (Faisalabad Campus), Pakistan

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ABSTRACT

In this paper, the geometric motion planning problem is addressed for an under-actuated mechanical system with dynamic non-holonomic constraints. Such constraints are the result of conservation of momentum that limits the mobility of the system in ambient space. However, dissipation forces due to interaction with the environment play a role enabling the system to move in constrained directions. Geometric mechanics tools are used to represent system dynamics in a structured form, which help better understand the motion planning problem. The geometric structure can be utilized to choose appropriate gaits intuitively by considering the properties of functions involved in the system dynamics. In a similar manner, dissipation forces also show the same type of geometric properties in terms of Stokes' connection and Stokes' Gamma functions. We can choose a gait intuitively without the need for integrating the system dynamics to generate motion in ambient space. We achieve this by exploiting the geometric properties of the friction model along with the natural dynamics of the system. By the proposed gait selection methodology, gaits are devised to move the system along a fiber direction. The simulation results are consistent with the results predicted by the proposed motion planning method. The proposed methodology is validated using experimental demonstration which also supports the simulation results. The proposed Stokes' Height functions and Stokes' Gamma functions can help to better understand the contribution of the dissipative forces and their anisotropy in motion of biological snakes and their robotic counterparts.

1. Introduction

To overcome the limits of wheeled robots on uneven terrain, more versatile locomotion mechanisms inspired by nature have gained the attention of many robotics research groups. New designs for legged, flying, or crawling robots have been found to be more effective for specific applications. A particularly effective structure for mobility in confined spaces such as pipe inspection, collapsed buildings, and mine shafts is the snake robot. Hirose and colleagues pioneered the field of snake robotics by introducing an active cord mechanism for snake-like motion [1]. Mechanical designs of snake robots and the serpenoid curve were achieved through extensive experimentation on snakes for generating gaits to imitate a slithering motion [1,2]. Snake models built by many research groups are either wheeled to realize the kinematic non-holonomic constraints during the slithering motion [3] or have a un-wheeled modular design to comprehend real snakes [4,5].

Since a robotic locomotion system does not have direct control over position and orientation in an inertial frame, it is an under-actuated system. For this type of system, geometric mechanics provides a structured way to define reduced ordered Lagrangian dynamic model by representing system dynamics in the local body frame [6–8]. Geometric motion planning exploits the structure of the reduced order dynamic model of the locomotion system to design gaits to change position in ambient space [6,9–11]. The mobility of the robot can be achieved by cyclic changes in the shape of the robot [7,12,13] as observed in locomotion mechanisms existing in nature.

In the absence of external forces, mechanical locomotion systems without kinematic nonholonomic constraints are purely mechanical systems [14]. Such systems possess conserved quantities as Lagrangian symmetries such as linear or angular momentum.

* Corresponding author.
E-mail addresses: ahmadali@hanyang.ac.kr, ahmad.ali@uet.edu.pk (A. Ali), sheraz.yaqub@yahoo.com (S. Yaqub), musman@hanyang.ac.kr, m.usman@uet.edu.pk (M. Usman), kmzuhaib@gmail.com (K.M. Zuhaib), kam@hanyang.ac.kr (A.M. Khan), jiyeongl@hanyang.ac.kr (J.-Y. Lee), cshan@hanyang.ac.kr (C.-s. Han).

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Such quantities are considered as dynamic non-holonomic constraints [6,15]. The locomotion mechanics of such systems can be modeled by mechanical connection on the principle fiber bundle of the configuration space. However, for the above-mentioned class of mechanical systems in the absence of interaction with the environment, dynamic nonholonomic constraints limit mobility in ambient space. In contrast, friction forces due to interaction with an environment enable the system to move along the constrained directions. In [16,17], the effect of friction forces on the dynamics of a 2-link robot moving on the ground using dry friction was considered. The method used to generate motion was composed of the slow and fast motion of the rear smaller link. However, the motion of the systems is constrained with the difference in sizes of link lengths. The geometry of the viscous dissipative forces on the principle bundle structure of the configuration space can be represented by Stoke's Connection. In [18], Stoke's Connection was used to study the controllability of the deformable bodies in a viscous environment. In this paper, we introduce the Stoke's Height Function to represent the curvature of the Stoke's Connection. The Stoke's Height Function is utilized to quantify the net change in momentum along a fiber direction, in response to viscous dissipative forces, and the gait selection.

A generalized geometric motion planning framework was proposed by Shammas et al. in [10,11,14] for different classes of systems with spectrum of kinematic and dynamic nonholonomic constraints. However, this method does not consider the effect of the external forces, like dissipative forces, which are the main agent enabling the systems without kinematic nonholonomic constraints to move in ambient space. This paper highlights how the effect of dissipative forces can be considered in the geometric motion planning and gait selection. In order to quantify the dynamic phase shift, we need to evaluate the momentum evolution equation in the reduced order dynamics of the system. In [11], scaled momentum was introduced to simplify the momentum evolution equation and evaluate the dynamic phase shift. However, this simplification is conditioned by the existence of the integrating factor for the momentum evolution equation. This simplification has limitation that integrating factor and scaled momentum were presented with the assumption that generalized momentum is one dimensional. However, there is no general way to find integrating factor and hence scaled momenta terms for simultaneous coupled nonlinear differential equations with more than one generalized momenta as in our case. Alternatively, our work exploits the geometric structure of the dissipative forces by defining the Stoke's Height function and Stoke's Gamma function to quantify dynamic phase shift. This helps evaluate explicitly and easily the effects of centrifugal and Coriolis forces, coupling of the generalized momenta and joint (shape) velocities in dynamic phase shift. This work is more consistent with the geometric motion planning framework to intuitively find and evaluate a closed curve gait in joint space) for a system with dissipative forces.

In [19], McIsaac et al. investigated the motion planning problem for a body moving in high Reynolds number. However, they ignored the longitudinal friction forces and also the coupling between the generalized momenta. In contrast, our proposed method considers both aspects in the system dynamic equations. Furthermore, McIsaac et al. in [19] evaluated various gaits. However, gait selection is not intuitive and the trajectory followed by system in the shape space to execute the motion in ambient space was not considered. To overcome this problem, our work addresses both aspects of the motion planning.

Motion planning problem for a two link system moving in viscous medium was also studied by introducing friction pads, and the gait design method was proposed in [20]. The geometric structure of the dynamic forces are represented explicitly as push, drift, and cross terms in the dynamic model of the system. However, the gait design method is represented only for two link system with single degree of freedom. Furthermore, this gait design method does not give direct intuition about gait selection but using the constraints on the push and cross terms to nullify motion in undesired direction. This paper represents similar structure of the viscous dissipative forces as Dissipative Gamma Functions matrix, Dissipative Connection matrix and Centrifugal, and Coriolis terms, respectively. Furthermore, motion planning using the geometric structure properties of the dissipative forces, as proposed in this paper is easier and more intuitive.

In this paper, we address the geometric motion planning problem for a snake robot moving on the ground. For the sake of simplicity, each link is assumed to have point contact with the environment under conditions of frictional anisotropy. This assumption can be realized by an elongated oval shape of the link with point contact with the ground during motion [21]. The link profile is responsible for maintaining the anisotropic nature of the friction model due to different coefficients of friction along longitudinal and lateral axes for each link. The properties of the geometric structure of dissipative forces along with that of system dynamics are also exploited to choose appropriate gaits for an unconstrained 3-link snake model moving on a flat surface.

1.1. Contribution

This paper makes three major contributions to the geometric motion planning:

- The first contribution of this article is to analyze the effect of dissipative forces in reduced order dynamics using the Stoke's Height function and Stoke's Gamma functions. These functions can be formulated by integrating the momentum evolution equation using Stoke's Theorem. These functions are helpful in quantifying the change in momentum for a closed curve gait.
- Second, we examine how the coupling between the generalized momenta can be analyzed intuitively using Stoke's Gamma functions.
- Third, using Stoke's connection and Stoke's Gamma functions, the equations of motion with the dissipative forces as external forces can be analyzed easily for motion planning problem. Gait selection becomes simple and intuitive by analyzing properties of the Stokes' Height Functions and Stokes' Gamma Functions along with Height Functions and Gamma Functions from reconstruction equation rather than solving the differential equations using integrating factor (which may exist but is difficult to find).
- Fourth, the proposed methodology is demonstrated experimentally, which supports the simulation results.

1.2. Organization of the paper

The structure of this article is as follows. Section 2 outlines a summary of the reduced order dynamics based on Lagrangian mechanics. Section 3 details the dynamic model formulation for the system used in this paper and how the conserved quantities due to Lagrangian symmetries limit the evolution of motion in some directions. The friction model with its geometric structure is presented in Section 4. Section 5 provides the evaluation of the robot motion using reduced order dynamics model of the system for a given closed curve gait in base space. In Section 6, gait selection rules are described, which are based on exploiting the geometric structure of a system's reduced dynamics along with that of the friction model. The simulation tests and experimental demonstration are given in Sections 7 and 8, respectively. Finally, a discussion on results and proposed future work in Section 9.