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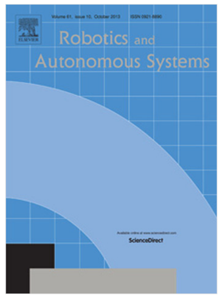

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Curved Path Following Control for Planar Eel Robots

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Abstract— **The dynamic models of the eel robots are under-actuated, highly nonlinear and coupled. It is thus a challenging work to design the path following controller for the eel robots. This paper proposes a framework of general curved path following control for planar eel robots. An implicit equation is used for describing the general 2D curved path. For simplicity, the eel robots are assumed to have smaller lateral displacement compared to the forward motion. A modified feedback control law based on the kinematic approximation model is combined with the gait controller to realize the curved path following of the eel robots. The eel robots with different gait patterns starting from an arbitrary initial position can guarantee asymptotic convergence to any given position. The simulation results show its effectiveness to apply the path following controller to the eel robot.**

Keywords— **Biologically inspired robot; eel robots; path following; non-inertial frame; gait; asymptotic convergence**

I. INTRODUCTION

Bio-eel has a high swimming efficiency and strong flexibility. Inspired by the bio-eel, the researchers have been working on the development of the physical prototypes [1], [2], the kinematic and dynamic modeling methods [3], [4], and motion control methods [5], [6], [7], [8], [9] of the eel robots or chain structure robots without a fixed pedestal. However, the dynamic models of eel robots are highly nonlinear and coupled; the degree of under-actuation is greater than two. What is more, there are random perturbations and periodic disturbances in the underwater environment, those increase the difficulties of design of path following controller. This paper considers the curved path following control problem of planar eel robots.

At present, there are a few literatures about the path following control of eel robot or snake-like robot [1], [10]. The path following control of eel robot or snake-like robot can be divided into with or without nonholonomic constraints. The planar eel robots with nonholonomic constraints mainly considers the forward and turning locomotion [10]. Perturbation methods were adopted to derive approximate expressions for the effect of internal shape changes on the motion of the system [11], but only the planar straight line and circular paths were analyzed. These approaches for path following control of eel robots are based on dynamic model of the swimming robots where ocean current effects are neglected. The eel robot without nonholonomic constraints, however, mainly focuses on straight linear path following. Solving the problem of optimal control, the Nonlinear Model Predictive Control (NMPC) control method was utilized to achieve the snake-like robot linear path following under bounded disturbances [12]. The simulation was time-consuming. Thus it is not appropriate to apply the NMPC method to snake-like robots directly. The method of virtual holonomic constraints (VHCs) [13], [14] are used to investigate the problem of maneuvering control. Inspired by the path following algorithms developed for terrestrial or marine vehicles [15], [16], [17], [18], [19], the line-of-sight (LOS) guidance law and integrated line-of-sight(ILOS) guidance law were utilized to implement the path following control in 2D spaces [20], [21], [22], [23], [24]. The integral effect of the ILOS guidance law was utilized to compensate for the oceanic fluid effect and the Poincaré maps were used to analyze the exponentially stable periodic orbits of the state variables. Then the ocean currents effect was also considered [24], [25]. The methods mentioned above exist the problem that the projection of the robot position is non-unique. A kinematic model of the serret-frenet frame description was combined with the virtual target principle to achieve curved paths following [26]. However, this method has a minimum limit of curvature radius. In general, most of studies mainly focus on straight line paths following, seldom considering the curved paths following control. The curved paths following method mentioned above exists curvature limitation. The path following control for eel robots still remains an open problem.

In order to simplify the controller design process, the eel robots are analogous to the unicycle robots by assuming that the normal velocity is much less than the tangential velocity. Combined with the gait controller, a path following controller based on kinematic model [27] is adopted and modified to accurately follow arbitrary paths. The method in this paper differs from the above-mentioned methods. This method neither requires the computation of a projection of the robot position on the path (When the projection of robot position is not unique, the robot cannot converge to and follow the path), nor does it need to consider moving the virtual target to be tracked [25]. It can guarantee asymptotic convergence to a 2D curve. Firstly, the dynamic model of an eel robot under non-inertial system is established by using the analytical Newton-Euler modeling method, which decouples parameters of the dynamic model. Whereafter, the mathematical model for evaluating the performance of the proposed path following controller is rewritten in the form of partial feedback linearization. Then the curved path following control framework is designed for an eel robot, which consists of gaits controller and path following

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