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Robust tracking control of uncertain dynamic nonholonomic systems using recurrent neural networks ☆

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ABSTRACT

The tracking problem for a class of dynamic nonholonomic systems with uncertainties is considered. First, under the assumption that the dynamics of the nonholonomic systems are exactly known without uncertainties, a simpler model-based controller is proposed by means of cascade design approach, in which the virtual velocity controller is linear, and the actual torque controller is derived by conventional computed-torque law. Then, to deal with uncertainties, a recurrent neural network control system is developed without requiring explicit knowledge of the system dynamics. The closed-loop stability analysis is presented based on a technical lemma developed for nonlinear cascaded systems with vanishing disturbances. Comparing with the existing results, the resulting control system has a simpler structure, and can deal with parametric uncertainties as well as non-parametric uncertainties, yet guarantees asymptotic stability of the tracking error dynamics. Simulation results for a wheeled mobile robot verify the good tracking performance and robustness of the proposed control system.

1. Introduction

In recent years, much attention has been devoted to the problem of controlling nonlinear mechanical systems with nonholonomic constraints [1,2]. Depending on whether the nonholonomic system is presented by a kinematic or dynamic model, the control problem can be classified as either kinematic control or dynamic control. Due to Brockett's theorem [3], it is well known that a nonholonomic system cannot be asymptotically stabilized to an equilibrium point via smooth or even continuous pure-feedback laws. However, several approaches have been proposed for tackling the stabilization problem at kinematic level [4–8] or dynamic level [9–11].

The tracking problem has also received a great deal of attention because of its practical importance. Several authors have studied the kinematic tracking problem in which velocity acts as the control input. In [12], a linearization-based tracking control was proposed for nonholonomic systems under the assumption that the linearized system is uniformly completely controllable along the desired trajectory. In [13,14], based on dynamic feedback linearization, controllers with structural singularity were proposed for the tracking problem of mobile robots. However, these controllers only solve the local tracking problem. There are mainly two methods to deal with the global tracking problem: backstepping method [15,16] and cascade design approach [17,18]. The main difference of these two methods lies in the way of dealing with the coupling terms between subsystems. Unlike the backstepping method, the coupling terms are neglected and the control law is chosen without canceling the coupling terms in cascade design to reduce complexity of the controllers.

In practice, however, it is more realistic to consider the tracking problem at dynamic level, where the torque and force are taken as the control inputs. The dynamics of the systems usually cannot be neglected if high performance of the control systems is required. With the assumption of known dynamics, model-based controls can be obtained for the dynamic nonholonomic systems using backstepping [19]. However, there often exist uncertainties in the dynamics of the nonholonomic systems inevitably, such as unmolded dynamics, parameter perturbations and load variation. To confront this, some adaptive controls and robust controls have been developed. In [20,21], adaptive control techniques were employed to solve the tracking problem of nonholonomic systems with unknown inertia parameters. However, the major problem of the adaptive control approaches is that certain functions must be assumed "linearity in the parameters", and tedious preliminary computation of "regression matrices" is needed [22]. In [23], a robust adaptive controller was designed for nonholonomic mechanical systems with model uncertainties. In [11,24], robust

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adaptive controllers were proposed for dynamic nonholonomic systems with parametric and non-parametric uncertainties, in which adaptive control techniques were used to compensate for the parametric uncertainties and sliding mode control was used to suppress the bounded disturbances. In [25], robust control strategies were presented systematically for both holonomic mechanical systems and a large class of nonholonomic systems in the presence of uncertainties and disturbances. Li et al. [26–28] have studied the motion/force control for a mobile manipulator under both holonomic and nonholonomic constraints, and some adaptive robust control strategies have been proposed. In order to cope with highly uncertain nonlinear systems, as an alternative, the applications of neural networks (NNs) were also studied for the control of nonholonomic robotic systems. A multilayer perception network-based controller was suggested by Fierro and Lewis [29] to deal with parametric or non-parametric uncertainties for a nonholonomic mobile robot without any prior knowledge of the uncertainties. Other feedforword neural networks, like radial basis function (RBF) neural network [30] and wavelet network [31,32], were also adopted for the robust control of mobile manipulators and mobile robots.

In the past decade, a great progress has been achieved in the study of using neural networks to control uncertain nonlinear systems. Extensive works demonstrate that adaptive neural control is particularly suitable for controlling highly uncertain, nonlinear, and complex systems [33–35]. In these neuro-adaptive control schemes, the neural network is used to compensate the effects of nonlinearity and system uncertainties, so the stability, convergence and robustness of the control system can be improved [36]. According to the structure, the neural networks can be mainly classified as feedforward neural networks (FNNs) and recurrent neural networks (RNNs). It is well known that FNN is capable of approximating arbitrary continuous function closely. However, FNN is a static mapping and unable to represent a dynamic mapping without the aid of tapped delays [37]. On the other hand, he RNNs, which comprise both feedforward and feedback connections, have superior capabilities than the FNNs. Since the RNN has a feedback loop, it can capture the past information of the network and adapt rapidly to sudden changes of the control environment [38]. The RNNs have the ability to deal with time-varying input or output though their own natural temporal operation [39]. For this ability, the structure of the neural network is simplified. Due to its dynamic characteristic and relative simple structure, the RNN is a useful tool in real-time application [40].

In this paper, the tracking problem is considered for a class of dynamic nonholonomic systems in which the nonholonomic kinematic subsystem is assumed to be capable of being transformed into the chained form and the dynamic subsystem is completely unknown. First, a simpler model-based controller is proposed for dynamic nonholonomic systems without uncertainties, in which the virtual velocity controller is linear, and the actual torque controller is derived by conventional computed-torque law. The stability of the closed-loop systems is presented based on the results on nonlinear cascaded systems with vanishing disturbances. To deal with disturbances and unstructured unmodeled dynamics in the nonholomonic system, a robust control system is then developed based on recurrent neural networks. On-line weights tuning algorithms that do not require off-line learning yet guaranty asymptotic stability of the tracking error dynamics are utilized. Simulation results for a wheeled mobile robot are provided to demonstrate the effectiveness of the proposed control method.

The remainder of this paper is organized as follows. Problem is formulated in Section 2. In Section 3, a model-based controller is presented and the closed-loop stability analysis is given based on a technical lemma developed for nonlinear cascaded systems with vanishing disturbances. A RNN-based control system is developed in Section 4. In Section 5, the effectiveness of the proposed approach is verified by simulation on a wheeled mobile robot. Section 6 concludes the paper.

2. Problem formulation

In general, a mechanical system with nonholonomic constraints can be described as

$$J(q)\dot{q}=0 \tag{1}$$

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+G(q)+d(t)=J^T(q)\lambda+B(q)\tau \tag{2}$$

where $q\in R^n$ denotes the generalized coordinates, $M(q)\in R^{n\times n}$ is the symmetric, positive definite inertia matrix, $C(q,\dot{q})\in R^{n\times n}$ is the centripetal and coriolis matrix, $G(q)\in R^n$ is the gravitational vector, $d(t)\in R^n$ denotes unknown disturbances including unstructured unmodeled dynamics, $J(q)\in R^{m\times n}$ is the constrained matrix, $\lambda\in R^m$ is the associated Lagrange multipliers which expresses the contact force, $\tau\in R^r$ is the vector of control input, $B(q)\in R^{n\times r}$ is the input transformation matrix, and is assumed to be known because it is a function of fixed geometry of the system. The dynamic system (2) has the following properties.

Property 1. *$M(q), C(q,\dot{q}), G(q)$ and $d(t)$ are bounded.*

Property 2. *$\dot{M}-2C$ is a skew-symmetric matrix, i.e. $x^T(\dot{M}-2C)x=0,\ \forall x\neq 0$.*

Let $S(q)\in R^{n\times(n-m)}$ be a full rank matrix formed by a set of smooth and linearly independent vector fields spanning the null space of $J(q)$, i.e.

$$S^T(q)J^T(q)=0 \tag{3}$$

According to (2) and (3), there always exists an auxiliary vector of independent generalized velocities $v\in R^{n-m}$, that make the system (1) and (2) be transformed in to a more appropriate representation for control purposes:

$$\dot{q}=S(q)v \tag{4}$$

$$M_1(q)\dot{v}+C_1(q,\dot{q})v+G_1(q)+d_1(t)=B_1(q)\tau \tag{5}$$

where $M_1(q)=S^TM(q)S$, $C_1(q,\dot{q})=S^T(M(q)\dot{S}+C(q,\dot{q})S)$, $G_1(q)=S^TG(q)$, $B_1(q)=S^TB(q)$, $d_1(t)=S^Td(t)$. It should be noted that the reduced system consists of a reduced state dynamics (5) and the so-called kinematic model (4) of nonholonomic systems in the literature. It is assumed that $B_1(q)\in R^{(n-m)\times r}$ is a full rank matrix and $r\geq n-m$ to completely actuate the nonholonomic system.

For ease of controller design, the existing results for the control of nonholonomic canonical forms in the literature are exploited. We assume that there exists a coordinate transformation $x=T_1(q)$ and a state feedback $v=T_2(q)u$, so that the kinematic model of the nonholonomic system given in Eq. (4) can be converted to the chained form. Since most of non-holonomic robotic systems (such as wheeled mobile robots) often include two pseudo-velocities, we only consider two independent generalized velocities $(n-m=2)$ case for the sake of simplicity; however, the results can be extended to more general case. That is, the nonholonomic chained system considered in this paper is the 2-input, single-chain, single-generator chained form

$$\begin{aligned}&\dot{x}_1=u_1\\&\dot{x}_i=u_1x_{i+1}\quad(2\leq i\leq n-1)\\&\dot{x}_n=u_2\end{aligned} \tag{6}$$

The necessary and sufficient condition for the existence of the transformation can be founded in [41–43]. Based on the above