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Adaptive control of underactuated robots with unmodeled dynamics

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HIGHLIGHTS

- An adaptive control formulation for underactuated robotic systems with unmodeled dynamics is proposed.
- The design allows for fast estimation while guaranteeing bounded deviation from a nonadaptive reference system.
- The proposed formulation is independent of detailed information about the system model.
- The proof of stability is established by the analysis based on input–output maps.
- The system's robustness to measurement noise and time delay is demonstrated.

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ABSTRACT

This paper develops an adaptive controller for underactuated robotic systems with unmodeled dynamics. The control scheme is motivated by the applications of manipulators operating on dynamic platforms. The design decouples the system's adaptation and control loops to allow for fast estimation rates, while guaranteeing bounded deviation from a nonadaptive reference system. The proposed formulation is independent of detailed information about the system model. The control scheme is tested in different trajectory-tracking scenarios: (i) a manipulator installed on a ship operating in a high-sea state with uncertain environmental disturbances and (ii) a mobile manipulator moving across a rough terrain of unknown geometry. The simulation results illustrate the tracking performance of the proposed control algorithm, its ability to deal with unmodeled dynamics, and its robustness to measurement noise and time delay, while maintaining smooth control signals.

1. Introduction

Robot manipulators are widely used in industry and have long been considered as testbeds for research in nonlinear control theory. Early work on adaptive control of fixed-base manipulators was mostly based on model-reference adaptive-control architectures [1–3], the linear-in-parameter property of dynamic structure [4–6] and the passivity of rigid robot dynamics [7–9]. Under relevant assumptions on the robots' dynamic properties, these controllers were demonstrated to estimate successfully certain types of unknown model parameters and achieve desired performance.

The extension of these classical control schemes to the context of a manipulator installed on a dynamic platform, however, is challenging and still an ongoing research area. Such systems are very popular in space robots, mobile manipulators, as well as underwater and offshore robotic systems [10–12]. Manipulators are used in space applications to perform maintenance operation, construction of structures, scientific experiments, or to collect debris. Mobile manipulators have a growing range of applications from exploration, such as the Mars rovers, to rescue missions, deactivation of explosive devices, and removal of hazardous materials. Recently, offshore and underwater platforms have become the new application territories for robotic technology, especially in rapidly-changing and challenging environments [13,14]. Examples include moving loads, maintenance, construction, and other unmanned tasks on ships, seaborne platforms, and underwater vehicles.

When the actuators driving certain degrees of freedom of the robotic systems in the aforementioned scenarios are turned off, the robotic systems become underactuated. In addition, the dynamics of the manipulator and the platform are mutually coupled due to conservation of momentum. This adds tremendous challenges as compared with fixed-based manipulators [15]. Firstly, the equations of motion for the unactuated degrees of freedom now act as constraints on the control design. As these are intrinsically nonholonomic, it is not possible to solve for the underactuated states in terms of the controlled states. Consequently, model-reduction methods fail to reduce the system dimension [16]. Moreover,

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according to Brockett's theorem [17], it is impossible to asymptotically stabilize a nonholonomic system to an equilibrium point by a continuous and time-invariant state-feedback control law, despite its controllability. Secondly, with complicated platform structures, or unknown terrain geometries in the case of mobile manipulators, or in challenging environments, including manipulators operating on ships and offshore platforms in high sea states, the platform dynamics are usually unmodeled and add large inertial terms and disturbances to the description of the manipulator dynamics. Example control designs include switching schemes based on support-vector-machine regression [18], a combination of fuzzy and backstepping control [19], adaptive control based on estimation of a bounded parameterization of the unknown dynamics [20,21], and adaptive variable structure control [22].

The most popular methods for controlling underactuated moving-base manipulators involve adopting the adaptive-control frameworks for fixed-base manipulators. Recent examples of control schemes in this category for free-floating space manipulators include [23] which constructs a dynamically equivalent model for parameterization and control of the original system dynamics, [24] which assumes passivity and other structure properties to eliminate the need for measuring the platform acceleration, [25] which proposes an adaptive controller based on the reaction dynamics between the active and passive parts in the system, and [26] which combines a recursive formulation of control torque and the platform's reference velocity and acceleration to achieve desirable tracking performance. For mobile manipulators, work in [27] designs an interaction control scheme, which is composed of an adaptation algorithm and an input–output linearizing controller. A trajectory and force tracking control problem is addressed in [28], which presents an adaptive controller based on a suitably reduced dynamic model to control a system with some unknown inertia parameters. Work in [29] employs a Frenét-like description to transform the kinematics of nonholonomic mobile platforms to generic driftless dynamics, which are then stabilized by two control schemes for the kinematics and dynamics, respectively. In the presence of disturbances, [30] combines a regressor-based adaptive scheme with an estimator for the disturbance to improve tracking performance of mobile manipulators. Work in [31] develops an image-based visual controller for mobile manipulators to track objects in three-dimensional space. The adaptive laws are designed based on the assumption that the robot dynamics can be parameterized linearly in terms of the unknown parameters in the model. In the context of marine robotics, an adaptive controller, which assumes passivity in the robot structure, and an adaptive-sliding control scheme are presented in [32] to compensate for model uncertainties. The analysis in [33,34] decomposes the system dynamics into control elements of individual bodies to derive a modular controller for manipulators mounted to an underwater vehicle. The control scheme in [35] allows underwater vehicle-manipulator systems to track both a prescribed sub-region as well as uncertain tasks.

The adaptive-control algorithms in [23–35] rely on the *linear-in-parameter property* of Lagrangian systems. Specifically, they exploit the dynamic structure and the passivity of rigid robot dynamics to factor the model description in terms of a regression matrix and a vector of unknown parameters, and proceed to implement adaptive laws to estimate these parameters. While the linear-in-parameter property is an acceptable model parameterization for many fixed-based manipulators, it is not applicable to others, such as robots with complicated link and/or joint geometries, unknown lengths, or with nonlinear mass distribution, stiffness, or damping. Furthermore, these controllers require construction of a well-defined and complicated model regression matrix, which involves correct selection of the joint velocity coefficient matrix from among several options [36]. The use of the model regression matrix, which must contain no uncertainty, also implies high dependence of the control algorithms on system modeling.

In moving-base manipulators, the reliance on the linear-in-parameter property may further undermine system performance. Firstly, accurate modeling of the platform dynamics is much more challenging than modeling the manipulator. Platforms are often complex structures with many uncalibrated parameters and uncertainties. In addition, moving-platform robots often operate in challenging environments such as space, underwater, offshore, across uneven terrains, or on ships operating in high seas [13,14,37–40]. Even when the ship stands still, modeling of the ship's structure is a very difficult task. Constructing the ship's equation of motion under influence of waves, ocean currents, and wind is even more challenging, if not impossible. The treatment in [14] avoids these problems by assuming that the oscillations of the ship are known *a priori* for all time. This assumption is eliminated in [38,40] by two intriguing methods for predicting the ship's motion, including an auto-regressive predictor and a predictor that superposes a series of sinusoidal waves. However, these methods require re-calibration of the parameters in the algorithms for different sea locations. In addition, the prediction accuracy can only be achieved with advanced sensors, such as wave cameras and sensors that measure interaction forces on the ship from waves and wind [40]. Similarly, in the case of mobile manipulators, most adaptive controllers are formulated with the assumption that the robots are moving across perfectly even terrain.

In this paper, we design an adaptive controller which is independent of system modeling and can achieve desired tracking for manipulators that operate on an underactuated dynamic platform. The control scheme proposed here is inspired by the work in [41], which proposed the use of a filter in the control input of a reference model adaptive controller to improve the robustness of a linear single input system. The architecture decouples the estimation loop from the control loop to facilitate a significant increase in the rate of estimation and adaptation, without a corresponding loss of robustness. Following the design method presented in [41], this paper develops a control scheme for an underactuated system consisting of a manipulator mounted on a moving platform with unmodeled dynamics. The proposed controller employs a fast adaptation scheme while maintaining bounded deviation from a nonadaptive reference system. In particular, the control design is tolerant of time delays in the control loop, and maintains clean control channels even in the presence of measurement noise due to the use of a low-pass filter structure in the control input. Tuning of the filter also allows for shaping the nominal response and enhancing the time-delay margin.

The proposed controller is implemented for two example underactuated robotic systems in two trajectory-tracking contexts: (1) a manipulator mounted on a ship operating in a high-sea state under uncertain environmental disturbances on the ship dynamics from wind, waves, and ocean currents; and (2) a mobile manipulator moving across a rough terrain of unknown geometry. The first task is used to assess the tracking performance when the platform motions contribute large inertia and nonlinearity to the manipulator dynamics. The second task demonstrates the proposed controller's effectiveness when the manipulator dynamics are mutually coupled with the platform dynamics, whose high-frequency motions are induced by both the manipulator motions and traversal across a rough terrain via a suspension system. The control objectives in these two tasks are achieved under both velocity-measurement noise and time delay in the control signal.

The remainder of this paper is organized as follows. A template dynamic model of an underactuated robotic system is described in Section 2. The text presents a broad-strokes description of a popular approach for adaptive control of such systems, including its potential shortcomings. The proposed adaptive control design