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Adaptive backstepping control for an n-degree of freedom robotic manipulator based on combined state augmentation

N. Nikdel [a], M.A. Badamchizadeh [a,*], V. Azimirad [b], M.A. Nazari [c]

[a] Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran
[b] Faculty of Engineering Emerging Technologies, University of Tabriz, Tabriz, Iran
[c] Cognitive Neuroscience Laboratory, Department of Psychology, University of Tabriz, Tabriz, Iran

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ABSTRACT

The aim of this paper is to improve the tracking performance of a robotic manipulator by designing an adaptive controller and implementing it on the system. The proposed controller guarantees the system stability as well as good tracking performance in existence of nonlinearity and parameter uncertainties. The requirement to decrease the system response overshoot and steady state error as well as increasing speed of tracking for manipulators is essential to many manufacturers. To this mean, in this paper, the tracking error equations for an n-DOF manipulator are derived and the response characteristics are improved by augmenting a new state to the system equations. The stability of the closed-loop system is guaranteed based on the Lyapunov theory via backstepping control approach. The robotic manipulator model contains parametric uncertainties and many of the parameter values are unknown. To solve the problem, an adaption law is proposed via adaptive backstepping mechanism. Different experiments are carried out for a 2-DOF manipulator to show the effectiveness of the proposed approach and the results are compared with four of the recently revealed researches on control. Experimental results present the superiority of the state augmented adaptive backstepping in tracking the desired joint angles. Moreover, in order to present the industrial application of the proposed control method, it is simulated for a large industrial Scara manipulator.

1. Introduction

Robotic systems are mostly used in industries and are considered as research test beds in control field [1–3]. Output tracking control of robotic manipulators and mobile robots is one of the most challenging issues in control engineering [4]. In order to improve the tracking performances, many effective methodologies have been developed and applied on robotic systems [5–9]. Zhong et al. [10]. investigate a dynamic balance control method for mobile robots in order to enhance the closed-loop system stability and improve the robot dynamic balance. In [11] a variable structure controller based on fractional calculus is presented in order to eliminate the chattering problem for a class of systems including a hexapod robot. In [12] an adaptive controller is designed for an n-DOF manipulator based on neural networks in order to handle external disturbances and model uncertainties. He et al. [13]. propose an adaptive impedance controller for a robotic system with input saturation to confront model uncertainties. In [14] the undesirable effects of output constraint and deadzone are investigated for a robotic manipulator and a controller is designed based on adaptive neural networks to confront these effects. Backstepping is one of the most powerful control strategies which is considered as a highly effective design tool for systems of pure or strict feedback forms [15–17]. The investigation and development of adaptive control approaches have also a long history. Different adaptive controllers which use the complete state measurement are applied on robotic systems [18].

Adaptive backstepping control has gained significant attention during last years and several results have been acquired. In contrast to the conventional adaptive certainty-equivalence design strategies, adaptive backstepping is a powerful approach to enhance the efficiency of the controlled system by decreasing the tracking error as well as control effort [19]. However, the performance of adaptive controllers can be restricted by some challenges such as complexity, parameter uncertainties, unmodeled dynamics and external disturbances.

Adaptive backstepping controller is designed recursively and

* Corresponding author.
E-mail addresses: n_nikdel@tabrizu.ac.ir (N. Nikdel), mbadamchi@tabrizu.ac.ir (M.A. Badamchizadeh), azimirad@tabrizu.ac.ir (V. Azimirad), alinazari@tabrizu.ac.ir (M.A. Nazari).

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requires introducing different virtual control signals and Lyapunov functions which results in complicated calculations. In [17], adaptive backstepping is investigated by considering a command filtered implementation method which helps simplification of the controller design procedure. Song et al. [19]. address the problem of explosion of complexity in adaptive backstepping method. Zero tracking error as well as simplifying the design steps are benefits of the paper. However, the introduced controller is proposed for linear time invariant (LTI) and single-input single-output (SISO) systems.

Estimating the robot parameters is another essential problem because in most of the cases the system parameters are uncertain [20]. Many studies on adaptive controllers are carried out to address this problem. In [21], the tracking problem of a robotic system is investigated utilizing an adaptive control approach which takes advantage of the adaptive fuzzy approach and backstepping methodology. Nguyen et al. [1]. focus on designing an adaptive controller for an underactuated dynamic system which is a robotic manipulator placed on a mobile platform. The purpose of [15] is controlling a wheeled inverted pendulum utilizing an adaptive backstepping control approach. The nonlinear unknown functions are estimated as time variant functions. In order to construct the adaptive backstepping controller, a PI and σ-modification-type adaption rules are proposed which estimate the time variant functions of the system body angle. The dynamic model of the wheel angle is approximated and stabilized utilizing a PD type control approach. Homayounzade et al. [18]. propose a noncertainty equivalent adaptive approach in order to control a robotic manipulator. The adaption mechanism is based on output feedback and is derived by utilizing the attractive manifold design method.

Another important problem which can affect the tracking performance of a robotic system is the presence of external disturbances. Many of the traditional adaptive control approaches fail to perform well encountering the unbounded disturbances [20]. In [5], the decentralized control technique is analyzed and applied on a mobile robotic manipulator. The robot is divided into the manipulator and the mobile robot subsystems. The coupling between these two parts is considered as external disturbance. Compensating the uncertainties as well as the system stability are achieved by introducing a robust adaptive controller.

Successful parameter estimation as well as good tracking performance present the efficiency of the investigated control approaches [15,18]. However, in order to achieve a satisfactory tracking control of the robotic systems by improving the transient and steady state response characteristics in real application, the drawbacks of the conventional control approaches have to be overcome.

So, many problems which exist in real world applications, are engaged with designing an appropriate controller for a robotic manipulator. Unmodeled functions such as friction and backlash can deteriorate system response. Moreover, most of system dynamical parameters are not exactly known. External disturbances are also undesirable factors which affect the tracking performance. In addition, problems such as large inertia and varying loads can deteriorate industrial manipulator performance. Therefore, these problems are taken into account and the controller is designed for a general n-DOF manipulator in order to include a wide range of industrial applications. According to Su and Fu [22], state augmentation increases system robustness. So, based on this idea, the adaptive backstepping controller is reinforced by introducing an additional state and augmenting it into system equations. By this mean the controller is designed robustly to restrain external disturbances, unmodeled dynamics, large inertia, varying loads and compensate for parameters uncertainties. The augmented state is proposed such that it can enhance the closed-loop system robustness and improve system response by increasing response speed as well as decreasing response overshoot, steady state error and norm of control signal. Enhanced controller robustness as well as improved system response characteristics, make the proposed controller appropriate for an n-DOF industrial manipulator.

The paper is organized as follows. In Section 2, dynamic equations of the n-DOF robotic manipulator are formulated. The controller design steps and stability analysis are also addressed in this section. Section 3 contains the experimental results of applying the controller on a 2-DOF manipulator and system responses are analyzed. A comparison between the performances of the introduced controller and the previous studies is also made. Simulation results of applying the proposed control approach on a large industrial manipulator are illustrated in Section 4. Section 5 concludes the paper.

2. Manipulator dynamics and state augmented adaptive backstepping controller design

2.1. Manipulator dynamics

Deriving the dynamic equations of a manipulator is essential for analysis of robot motion and structure and also for designing an appropriate control approach for it. In order to implement the proposed controller, a general n-DOF robotic manipulator, presented in Fig. 1, is considered as the case study.

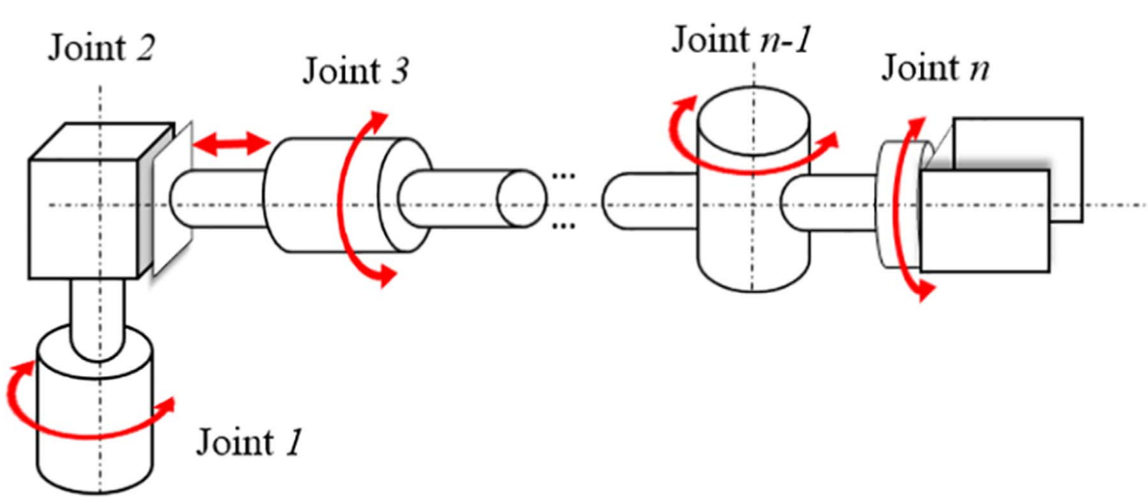

Fig. 1. The n-DOF manipulator.