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Neural adaptive tracking control for an uncertain robot manipulator with time-varying joint space constraints

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ABSTRACT

This paper presents a control design for a robotic manipulator with uncertainties in both actuator dynamics and manipulator dynamics subject to asymmetric time-varying joint space constraints. Tangent-type time-varying barrier Lyapunov functionals (tvBLFs) are constructed to ensure no constraint violation and to remove the need for transforming the original constrained system into an equivalent unconstrained one. Adaptive Neural Networks (NNs) are proposed to handle uncertainties in manipulator dynamics and actuator dynamics in addition to the unknown disturbances. Proper input saturation is employed, and it is proved that under the proposed method the stability and semi-global uniform ultimate boundedness of the closed-loop system can be achieved without violation of constraints. The effectiveness of the theoretical developments is verified through numerical simulations.

1. Introduction

Constrained control is becoming increasingly important due to safety issues and performance degradation in the instance of humanoid robots [1,2], physical human-robot collaboration [3,4], and assistive robots that guide the motion of the patient's limb in the rehabilitation therapy [5]. In these human-robot interacting tasks, the robotic motions are required to be constrained to avoid the potential of damage to humans. For example, in the rehabilitative robotic arm therapy application, the motion needs to be restricted according to the human partner physical upper-limb dimensions and reaching limits to avoid patient injuries. Therefore, rigorous constraint handling should be carefully managed within the adaptive interactive robotic control.

Numerious techniques for control of the robotic systems have been developed to accommodate various forms of constraints. Some are based on adaptive position/force control [6], adaptive vision and force tracking control [7] or impedance control [8]. In addition, several researchers developed unconventional methods to handle constraints in robotic control. For example, danger field quantity was introduced in [9] for safety-oriented control and danger assessment of robotic manipulators, and the distributed distance sensor approach was proposed in [10] to improve human safety in industrial environments by assessing the level of danger induced by the robot. Also, error transformation technique was used to asymptotic tracking controller design for uncertain robotic systems with external disturbances and time-varying constraints on the system state [11].

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Motion planning has also been extensively studied to deal with robot constraint avoidance [12,13]. Potential field method was developed to deal with the robot safety issue on the path planning and the real-time control [14]. The quadratic programming based optimal control method was developed for redundant robot manipulators with variable joint-velocity constraints [15]. Optimal motion planning was proposed for mobile robots in static and dynamic obstructed environments combining open-loop optimal control and the potential field method [16,17]. However, the trajectory in online optimization methods has to be calculated for various situations, which significantly increases the computational burden. In addition, these methods typically suffer from the implementation of the control inputs at the kinematic level, resulting in them not being able to cope with the dynamic uncertainties.

Barrier Lyapunov Functions (BLFs) have been developed to bound and suppress the propagation of system error [18–20]. Different from the conventional Lyapunov functions, BLFs escape to infinity when associated limits are exceeded. Hence, bounding the BLFs in closed loop systems can prevent violation of constraints along the system trajectories [21]. In addition, as the BLFs control design is constructive based on the direct method of Lyapunov, its computational burden is significantly reduced compared with online motion planning and optimization methods [22]. Different types of BLFs are exploited like logarithm BLFs [20], integral BLFs [23], tangent BLFs [24,25], secant BLFs [26], and cotangent BLFs [27]. The BLFs based control has been utilized to handle several practical systems with constraints like direct current (DC) motors [28,29], wind turbines [30], flexible structure systems [31–34], and aerial vehicles [19,35–37]. Logarithm BLF is employed to solve the trajectory tracking control problem of a fully actuated surface vessel with asymmetric output and input constraints [38]. In addition, this method is used for leader–follower formation control for a group of underactuated surface vessels subject to asymmetric range and bearing constraints [39].

The BLFs based control has been employed for constrained control of robotic manipulators. In [40,41], task space constraints were handled by considering the linearly-in-parameter conditions in robot dynamics. However, when the robot inverse Jacobian matrix is non-linear, e. g. in the case where the kinematics of the robot manipulator is uncertain [42], the linearly-in-parameter conditions do not hold. To solve the problem, [43,44], and [45] applied BLFs to the tracking control of robot manipulators with output and full state constraints. However, in these studies, only the static bounds for upper and lower constraints were considered while most practical robotic systems are subject to time-varying constraints. In addition, using the BLFs based control, the input control signals would approach infinity as the states approach their constraint limits. This means that the input control signals are not bounded. These problems were tackled in [25], which developed input and state constrained control using tangent-type time-varying BLFs for MIMO systems and verified the method via a two-link robot manipulator. However, the saturated type input constraint with sharp corners was used, which may prevent the backstepping technique to be applied directly [46]. In addition, this study only assumed the upper constraints to bind the states and errors, which is not an appropriate assumption for most practical applications. Furthermore, in all the works mentioned above, the dynamics of the joint actuator was neglected in spite of the actuator dynamics being a significant part of the real robot dynamics. More recently, BLFs were used to address actuator dynamics in control of robot manipulators in the constrained task space [47] and joint space [23]. However, both works were restricted to static constraints and unbounded inputs.

On the other hand, generally, NNs [48] and the fuzzy logic [49] have been widely incorporated into adaptive controller design to account for uncertainties in different mechanical systems like wind turbines [50], DC motors [51], unmanned vehicles [52], underwater vehicles [53], and marine vehicles [54]. Due to their outstanding approximation abilities, such methods afford robust and efficient frameworks to accommodate uncertainty and imprecision [55]. Accordingly, adaptive neural [11,56] or fuzzy [57] control schemes have been developed to address the stability problem of the unknown robotic systems. In addition, reviewing recent literature on adaptive control outlined the interest of using radial basis functions NNs among robotic researchers [58]. This method has a simple and fixed three-layer (input, hidden, and output) architecture. The output linearly combines neuron parameters with the radial basis function of the inputs [59]. Such networks are easy to design and train and compared to other methods in the literature, this approximation approach forms a composite adaptation law in terms of the tracking error and a model prediction error [60]. Furthermore, enjoying advantages of having strong tolerance to input noise, and the ability of online learning, this method has been extensively employed in control of robotic systems [26,61–64].

Motivated by the aforementioned considerations, in this paper, asymmetric tangent tvBLFs are developed to prevent the joint space constraint violation in control of robotic systems. Both manipulator dynamics and actuator dynamics uncertainties are considered and radial basis function NNs are employed to approximate the system uncertainties and the unknown disturbances. Also, a proper input saturation is developed to address the tracking problem and to ensure uniform boundedness of the system while all signals in the closed-loop system remain bounded.

Compared with the existing literature, the main advantages of this work are as follows. (*i*) the proposed tvBLFs can handle both time-varying and asymmetric constraints. Also, by defining a new state constraint in this paper, different initial conditions can be relaxed effectively on the starting values of the movement. By that means, more flexible constraints can be modelled for various practical transitions. (*ii*) a new approach in stability analysis of the closed-loop system using tangent tvBLFs is developed by introducing the Lemma 1. By that means, compared to previous works on tangent BLF like [25,65–67], the control design procedure required fewer parameters to ensure the prevention of constraint violation. (*iii*) in addition to studying the unknown robotic manipulator dynamics as in [45,68,69], unknown actuator dynamics have been considered. Moreover, utilizing NNs unknown disturbances have been incorporated into designing of the controller. Also, the unknown interaction force has been compensated without developing additional estimators.