Enhancing trajectory tracking accuracy for industrial robot with robust adaptive control

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A B S T R A C T

A robust adaptive control method is systematically proposed in this paper to significantly reduce the relatively tracking errors of 6 degree of freedom (DOF) industrial robots under both external disturbances and parametric uncertainties. The robust adaptive control law is formulated based on the robot dynamics in the task space of the robot end-effector. The control law is designed by combining robust term and adaptive term to track the desired trajectory of the end-effector with sufficient robustness and accuracy in the presence of unknown external disturbances and parametric uncertainties. The trajectory tracking performances of the proposed control are finally guaranteed based on Lyapunov function and Barbabalat’s lemma. Furthermore, a stable online parametric adaption law is proposed to estimate the unknown parameters in the control law based on persistent excitation and residual estimation. Test results are obtained to show that the combined robust adaptive control reduces the final trajectory tracking error significantly as compared with conventional control.

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1. Introduction

Industrial robots are base-stationary, reprogrammable and multi-function manipulators that are designed to move material, parts, tools, or specialized devices through variable programmed motions to perform a variety of tasks. The industrial robots have replaced human beings in dangerous, monotonous, or strenuous tasks that humans do not want to do. These activities frequently take place in spaces that are poorly ventilated, poorly lighted, or filled with noxious or toxic fumes. The trend for future industrial robots has been toward the electric-motor powered, servo-controlled industrial robots that are typically floor-standing machines [1]. These industrial robots have proved to be the most cost-effective because they are the most versatile.

As a fundamental and essential subject of industrial robots, the trajectory tracking control has attracted considerable attention over the last few years. A variety of control approaches for high-precision trajectory tracking control of industrial robots have been presented in the literature. The proportional integral derivative (PID) controllers have been widely used for motion tracking control of industrial robots due to the simple structure and model free control design [2]. However, the PID controllers should be carefully tuned according to different operating conditions, which is usually time-consuming. A cooperative target tracking control algorithm was proposed in [3] for motion target tracking of a group of mobile robots. A distributed Kalman filter was also designed to estimate the target position. The effectiveness of the control algorithm was verified based on simulation and experimental results. An adaptive trajectory tracking controller was designed in [4] for robot motion tracking with unknown parameters and uncertain dynamics. The back-stepping controller was designed by using the learning ability of neural networks which avoid the knowledge of the robot dynamics. Simulations and experiments on a commercial robot platform were used to verify the performances of the designed control algorithm with classical back-stepping controller. A model predictive control scheme incorporating neural-dynamic optimization was presented in [5] for robotic trajectory tracking. The model predictive control approach was iteratively transformed as a constrained quadratic programming problem, and then a primal-dual neural network was used to solve this problem over a finite receding horizon. The effectiveness of the control approach was verified based on experiments. A model-free proportional derivative (PD) with sliding mode control law was proposed for robotic trajectory tracking control in [6]. The control law has features of simple linear control provided by PD control and the robust nonlinear control contributed by sliding mode control. However, only simulation results were provided to prove the effectiveness and robustness of the control law. An adaptive back-stepping control scheme was proposed in [7] for trajectory tracking of robot manipulators in the presence of external disturbances and uncertain parameters. The controller was synthesized by using adaptive technique for estimating.
robotic system uncertainties. The performances of the controller were
verified only based on numerical simulation results. A robust discrete-
time sliding mode controller was designed in [8] for trajectory tracking
of robotic manipulators by coupling with an uncertainty estimator. The
trajectory tracking performances and robustness were evaluated based
on experimental results. A decentralized adaptive robust controller was
proposed in [9] for trajectory tracking of robot manipulators. A dis-
turbance observer was introduced in each local controller to compen-
sate for the low-passed coupled uncertainties. An adaptive sliding mode
control term was also employed to handle the fast-changing compo-
nents of the uncertainties. However, simulation results were provided
to support the theoretical results of the proposed controller. The per-
formance of a fractional order PID controller tuned with evolutionary
algorithms was compared in [10] to that with a real coded genetic algo-
rum in robot trajectory tracking control. The robotic parameters and
the given trajectory were changed and white noise was added to test
the controllers. Simulation results were provided to show that the con-
troller tuned by PSO performed better than that tuned by the genetic
algorithm. Neural networks have also been widely employed for robot
trajectory tracking control. In [11], adaptive neural network tracking
control for the robotic system with full-state constraints was proposed.
The adaptive neural networks were adopted to handle external distur-
bances and system uncertainties while a Moore-Penrose inverse term
was employed to prevent the violation of the full-state constraints. In
[12], radial basis function neural network based adaptive impedance
controller was developed for robotic motion tracking control with input
saturation by considering both uncertainties and input saturation. Ex-
tensive simulations were conducted to verify the impedance controller.
In [13], a neural network controller was designed for robotic manipu-
lator with input dead-zone by approximating the unknown robotic
manipulator dynamics and eliminating the effects of input dead-zone.
The feasibility and control performance of the controller were verified
based on experiments. In [14], adaptive fuzzy neural network control
using impedance learning was designed for a constrained robot with
unknown system dynamics. Impedance learning was also introduced to
tackle the interaction between the robot and its environment to follow
a desired trajectory generated by impedance learning. The effective-
ness of the proposed scheme was illustrated by using some simulation
studies.

Even though various control methods have been presented for tra-
jectory control of robots, only a few of them target the motion trajectory
control of the six degree of freedom (6DOF) industrial robots. Most of
the control methods were designed in the joint angle space of the robots,
which may not achieve the final trajectory tracking in the end-effector
of the robots. Furthermore, the proposed back-stepping and neural net-
work controllers always necessitate time-consuming and complicated
calculations such as repeated partial derivatives, which significantly im-
pede their real-time applications.

Therefore, this paper proposes a systematic method to combine adap-
tive control and robust control to formulate a robust adaptive control
for trajectory tracking of 6 DOF industrial robot under both paramet-
ric uncertainties and external disturbances. A stable online parametric
adaptation law is also proposed to estimate the robot parameters based
on persistent excitation. Unlike the existing robot controllers that are
primarily designed based on the joint angle spaces, the proposed ro-
 bust adaptive controller is designed in the task space of the robot’s end-
effector, which has the potential to significantly enhance the accurate
trajectory tracking performances superior to existing controls. The pro-
posed controller also has explicit structure and is easy to implement in
industrial robot for real time control due to its relatively lower compu-
tational burden as compared with the existing controls in the literature.
Furthermore, the proposed control and parametric adaptation law are ver-
ified based on 6 DOF MITSUBISHI RV-4F industrial robot, which solidly
justifies the significantly enhanced control accuracy of the proposed
controller.

2. Dynamics analysis of industrial robots in the task space

The 6 DOF industrial robots are commonly constituted by 6 moving
links coupled by 6 kinematic pairs of the prismatic types. The motion
dynamics of the robots can be readily described in the task space of the
end-effector [15]. The governing equations of the motion dynamics are
usually second-order ordinary differential equations that are useful and
required for the real-time feedback control of the robots. Therefore,
\[ M(x)\ddot{x} + C(x, \dot{x})\dot{x} + G(x) + d = F \]

where \( M(x) \) denotes the inertial properties of the robot, \( C(x, \dot{x}) \) rep-
resents the centrifugal and Coriolis force, \( G(x) \) is the gravitational force,
\( d \) represents the effects from un-modeled dynamics and external distur-
bances, \( F \) denotes the end-effector force vector, which can be designed
based on feedback control law, \( x \) is the end-effector position vector in
the task space with three rotational and three translational positions.

The parameters of the robot dynamics \( M(x), C(x, \dot{x}) \) and \( G(x) \) in the
above equation play a vital role in the control law design of the indus-
trial robot. However, the exact values of these parameters usually cannot
be known in advance due to the time-varying working conditions and
uncertain environment. The boundaries of these uncertain parameters
are generally known or can be calculated prior to implementation.

The forward dynamics of the industrial robot in the task space as
described in Eq. (1) can be readily derived from the joint space since
each joint angle of the industrial robot can be measurable. For this
dynamics equation, the following two properties [16] will be commonly
utilized for controller design.

**Property 1.** \( M(x) \) is a symmetric and positive definite matrix.

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

The paper aims to synthesize a control law for the input force vector
\( F \) to ensure that the position vector of the end-effector tracks its desired
trajectory \( x_d(t) \) closely while the desired trajectory \( x_d(t) \) is of at least
second-order differentiable. The actual control inputs for each joint of
the industrial robot can then be calculated from the designed input force
vector \( F \) based on inverse dynamics and Jacobin matrix [17].

3. Control design

A robust adaptive tracking controller is designed in this section to ac-
curately track the desired trajectory of the end-effector with sufficient
robustness and accuracy in the presence of unknown external distur-
bances and parametric uncertainties.

The tracking error \( e \) of the end-effector can be defined as
\[ e = x_d - x \]

A switching manifold \( s \) can thus be defined based on the tracking
error as
\[ s = \dot{e} + Ae = (\dot{x}_d + Ae) - \dot{x} = \dot{x}_q - \dot{x} \]

where \( A \) is a constant positive definite diagonal matrix, \( x_q \) is the equi-

alent position vector of the end-effector and its orientation with respect
to the task space coordinate for specifying an assembly task, \( x_d \) is the
desired motion trajectory.

The equivalent position vector of the end-effector can be defined as
\[ \dot{x}_q = \dot{x}_d + Ae \]

Therefore, the robot dynamics on this manifold can be formulated based
on Eq. (1) as
\[ M(x)\ddot{x}_q = M(x)(\dot{x}_q - \dot{x}) = M(x)x_q - F + C(x, \dot{x}_q) + G(x) + d \]

In order to design the control law, a positive semidefinite Lyapunov
function is defined as
\[ V(t) = \frac{1}{2} x^T M(x)x \]

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