Force Tracking Impedance Control with Moving Target

Houde Liu, Weifeng Lu, Xiaojun Zhu, Xueqian Wang, Bin Liang*

***Abstract*—Force control can help a robot to deal with unexpected events and uncertainty in applications such as flexible manufacturing. For example, motion of a workpiece can be handled by tracking the moving object with a manipulator. In this paper, we present a position-based force control scheme for tracking a moving target with the robotic manipulator using force feedback. Stability and convergence of the proposed control scheme are analyzed for a stable force tracking execution. Simulation studies are shown to demonstrate the robustness of the proposed scheme under unknown environment stiffness and variable environment position. The experimental results support the claim that the approach could be successfully applied to track a moving target with a constant force.**

Keywords—force tracking, impedance control, moving target, industry manipulator.

I. INTRODUCTION

As technology evolves, robot manipulators have been used extensively in applications requiring interaction with the environment, such as deburring, assembly and grinding tasks[1][2][3]. A robotic manipulator requires force control to perform complex operations and to deal with uncertainty in the environment[4]. The function of tracking a moving target has become an essential application for flexible manufacturing. This function is used for following a target with various purposes in robots[5].

Impedance force control is one of the main force control algorithms in the literature with the hybrid position/force control[6][7]. Impedance function is realized by the relationship between force and position error. The major difficulty of impedance control is how to keep robust with unknown environment stiffness and position. A robust force tracking impedance control scheme with uncertain environment position and stiffness has be proposed[8]. In [9], a velocity and force control scheme for tracking moving target has be proposed using both force sensor and vision sensor.

In this paper, we present a robust force tracking scheme based impedance control for tracking moving target with a robot manipulator using force sensor. The main idea is to adopt force error function to compensate the change of environment position. A case study for a test bench has been developed to analyze interactions with the environment.

The paper is structured as follows. Section 2 reviews briefly the conventional impedance control and a novel adaptive impedance control scheme is developed. Stability and convergence of the proposed control scheme are analyzed in Section 3. Simulations are presented in Section 4 to demonstrate the robustness of the proposed scheme under unknown environment stiffness and variable environment position. Experimental results using a 6-axis robot arm are presented in Section 5 to confirm the performance of the control scheme. Conclusions are given in Section 6.

II. FORCE TRACKING IMPEDANCE CONTROL

A position based impedance control scheme consists of an inner position control loop and an outer indirect force control loop. One of the common formulations for the target impedance is

$$M\ddot{X}_d + B\dot{X}_d + K(X_d - X_r) = F_d - F_e, \qquad (1)$$

where M, B and K are the $n \times n$ diagonal mass, damping and stiffness matrices of the target impedance specified by the user; X_r is the reference position trajectory; F_d and F_e denote the desired contact force and the actual contact force. In free space motion (zero contact forces F_e), the desired trajectory X_d is identical to the compliant trajectory X_r since no compliant motions are necessary. In constrained motions, however, a nonzero contact force modifies the desired trajectory in the outer impedance control loop resulting in the compliant desired trajectory, which is to be tracked by the inner motion control loop.

For simplicity, we consider that force is applied to only one direction. Let f_d, f_e, m, b, k, x_r be elements of F_d, F_e, M, B, K, X_r respectively. Further, assuming good tracking performance of the inner position control loop, the compliant trajectory can be reached by the end-effector ($x_d = x$). Then, (1) becomes

$$m\ddot{x} + b\dot{x} + k(x - x_r) = f_d - f_e. \qquad (2)$$

This work is supported by the National Natural Science Foundation of China (No.61673239), Natural Science Foundation of Guangdong Province (2014A030310318, 2015A030313881) and the Basic Research Program of Shenzhen (JCYJ20160301153317415、JSGG20150331151358134).

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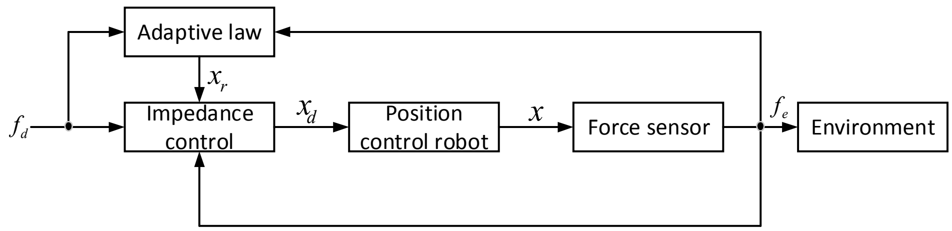

Fig. 1. Force control structure for tracking moving target

We propose a two-stage control algorithm: the first stage is free-space control when the robot is approaching toward the environment and the second stage is contact-space control in which the end-effector is in contact with the environment.

In free space control, the control law can be obtained from (2) for $f_d = 0$ and $f_e = 0$ as follows:

$$m\ddot{x} + b\dot{x} + k(x - x_r) = 0 . \tag{3}$$

We assume that the environment position is x_e. We note that if $x_r > x_e$, then the robot would always make contact with the environment.

In contact space, the environment can be represented by a linear spring model with stiffness k_e and location x_e. Then the contact force f_e can be expressed as

$$f_e = k_e(x - x_e) . \tag{4}$$

However, in the case of tracking moving target the environment stiffness k_e is unknown and the environment position x_e is variable.

First of all, we assume that the tracking target is stationary where x_e is constant, but the environment stiffness k_e is unknown. Then (2) becomes

$$m\ddot{x} + b\dot{x} + k(x - x_r) + k_e(x - x_e) = f_d . \tag{5}$$

Consider for the practical case that we have an inaccurate environment position estimate x_e' and $x_e' = x_e + \delta x_e$ in which δx_e is the uncertainty of x_e. Replacing x_r with x_e' then (5) becomes

$$m\ddot{e} + b\dot{e} + (k + k_e)e = f_d + k\delta x_e , \tag{6}$$

where $e = x - x_e$.

We see that (6) is progressively stable. Even though k_e is unknown accurately in practice, the proper parameters m and b based on approximation of k_e can be chosen to achieve a good transient response of (5). Therefore, the impedance function is stable and robust in force tracking under unknown environment stiffness condition.

For contact space (6), we can easily show that the exact force tracking can be achieved if the target is stationary where x_e is a constant and δx_e is also a constant. However in the case of tracking moving target which x_e is time varying, a force tracking error will occur.

So, we propose a new adaptive impedance equation as

$$m\ddot{x} + b\dot{x} + k(x - x_r) = f_d - f_e , \tag{7}$$

$$x_r(t) = x_r(t-\lambda) + k_d\left(f_d(t-\lambda) - f_e(t-\lambda)\right) , \tag{8}$$

where k_d is the proportional coefficient and λ is the sampling period of the controller. The proposed robust force tracking control structure shows in Fig.1.

In the following section, we will show that in the case of tracking moving target the impedance control algorithm (7) with (8) is stable and the force tracking error is approximately zero.

III. STABILITY AND CONVERGENCE OF CONTROL LAW

It is necessary to see whether the control law (7) and (8) remain stable when tracking the moving target. From the relationship $f_e = k_e\left(x - x_e\right)$, we can express

$$x = x_e + \frac{f_e}{k_e}, \dot{x} = \dot{x}_e + \frac{\dot{f}_e}{k_e}, \ddot{x} = \ddot{x}_e + \frac{\ddot{f}_e}{k_e} . \tag{9}$$

Substituting $x, \dot{x}, \ddot{x}$ into (7) yields the second-order force error equation as

$$\begin{aligned} &m\left(\ddot{f}_d - \ddot{f}_e\right) + b\left(\dot{f}_d - \dot{f}_e\right) + \left(k + k_e\right)\left(f_d - f_e\right) \\ &+ kk_e x_r = m\ddot{f}_d + b\dot{f}_d + kf_d + mk_e\ddot{x}_e \\ &\qquad + bk_e\dot{x}_e + kk_e x_e \end{aligned} \quad .(10)$$

Defining $\varepsilon = f_d - f_e$ and $\mu = f_d + k_e x_e$, then rewrite (10) as

$$m\ddot{\varepsilon} + b\dot{\varepsilon} + \left(k + k_e\right)\varepsilon + kk_e x_r = m\ddot{\mu} + b\dot{\mu} + k\mu . \tag{11}$$