Robotics and Autonomous Systems 102 (2018) 54–65

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Adaptive variable impedance control for dynamic contact force tracking in uncertain environment

Duan Jinjun, Gan Yahui *, Chen Ming, Dai Xianzhong

School of Automation, Southeast University, Nanjing, 210096, PR China
Key Lab of Measurement and Control of Complex Systems of Engineering, Ministry of Education, Nanjing, 210096, PR China

HIGHLIGHTS

- Adaptive variable impedance control for dynamic force tracking in uncertain environment is discussed.
- It combines the idea of variable impedance control with the advantage of the adaptive control.
- It is achieved by adjusting tracking error to compensate the unknown environment and dynamic desired forcet.
- Stability and convergence of the method are demonstrated for a stable force tracking execution.

ARTICLE INFO

Article history:
Received 25 October 2017
Received in revised form 8 December 2017
Accepted 22 January 2018
Available online 1 February 2018

Keywords:
Adaptive variable impedance control
Contact force tracking
Uncertain environment
Modified impedance control
Uncertainties

ABSTRACT

The traditional constant impedance control is a simple but effective method widely used in many fields including contact force tracking. Using this method, the location of the environment relative to the robot and the stiffness of the environment must be known, and usually the desired force is constant. However, for applications in dynamic contact force tracking in uncertain environment, it is not an effective solution. In this paper, a new adaptive variable impedance control is proposed for force tracking which has the capability to track the dynamic desired force and compensate for uncertainties (in terms of unknown geometrical and mechanical properties) in environment. In this study, the contact force model of robot end-effector and the environment is analyzed. Specifically, the contact force is used as the feedback force of a position-based impedance controller to actively track the dynamic desired force in uncertain environment. To adapt any environment stiffness uncertainties, a modified impedance control is proposed. To reduce the force tracking error caused by environment location uncertainty, an adaptive variable impedance control is implemented for the first time by adjusting the impedance parameters on-line based on the tracking error to compensate the unknown environment and the dynamic desired force. Furthermore, stability and convergence of the adaptive variable impedance control are demonstrated for a stable force tracking execution. Simulations and experiments to compare the performance of force tracking with the constant impedance control and the adaptive variable impedance control, perspectively, are conducted. The results strongly prove that the proposed approach can achieve better force tracking performance than the constant impedance control.

1. Introduction

With the development of the robot technology, contact operation is becoming an important area of robot application. Typical examples include assembly, polishing, deburring, dual-arm coordination or dexterous hand manipulations. For these applications, control of interaction between a robot and the environment is crucial for successfully executing the tasks, since the robot (or certain parts) has to contact and operate on the surface of objects. In these cases, purely using a motion control strategy for controlling contact force is unreasonable, because when the robot interacts with environment, the desired force should be maintained while following the desired trajectories.

The interaction task can be executed successfully by using the motion control only when the entire task can be planned accurately and completely, which requests both of the robot and the environment are properly modeled and all the parameters are accurately known. Usually, robot modeling can be known with enough accuracy [1], but an accurate model of the environment

* Corresponding author at: School of Automation, Southeast University, Nanjing, 210096, PR China.
E-mail addresses: duan_jinjun@yeah.net (J. Duan), ganyahui@yeah.net (Y. Gan), chenming317@yeah.net (M. Chen), xzdai@seu.edu.cn (X. Dai).

https://doi.org/10.1016/j.robot.2018.01.009

is difficult to obtain. In practice, the modeling error leads to the existence of planning error, thereby the planning error reflects to the contact force causing a deviation from the desired trajectory. Along with the accumulation of contact force errors, the saturation of the joint actuators is reached or breakage of the parts in contact occurs. If a compliant behavior is ensured or the environment information can be estimated accurately during the interaction, the above drawback can be overcome. The contact force can describe the properties of the interaction in most cases. Usually, a force/torque sensor is mounted between the wrist and the end-effector to achieve the contact force. The robot with the sensor means that it has the ability to control the force, and the most essential problem of force control is the force tracking.

Force tracking has attracted a wide number of researchers over the past decades. For the static environment which the environmental information is certain or the applications are known, the classical force control strategies can achieve good performance. The classical force control includes impedance control [2] and hybrid position and force control [3]. But for the uncertain environment, the environment stiffness and location are unknown, it is difficult to obtain a perfect model for the various unknown features, so it is more difficult for force tracking.

The current research of force tracking control in uncertain environment can be classified into three categorizes. (1) Indirect adjustment of reference trajectory. The basic idea is to identify the environmental information including stiffness and location. A simple trajectory modification scheme using adaptive techniques to estimate environment stiffness or adjust controller gains to compensate for unknown environment stiffness based on the force error has been proposed in [4]. The shape and the local surface normals of the environment are estimated in [5]. The adaptive environmental parameters estimation has been studied in [6] to actively track the reference force based on a position-based impedance controller. The force tracking has been implemented by defining the control gains analytically based on the estimation of the stiffness using an Extended Kalman Filter in [7]. Some authors proposed an intelligent force control algorithm using a neural network to compensate for uncertainties [8]. Fuzzy-neuro techniques have been used for force control of unknown objects [9]. However, the identification process often has errors. Sometimes the past information is only used to estimate the environment information, these factors can also lead to the existence of force tracking error. In practice, the experiment in [1] has showed that the force can be tracked accurately only under the circumstance that the estimated environment location is within a certain limitation. (2) Direct adjustment of reference trajectory. The basic idea is to update the reference trajectory directly by prior information. The model-reference adaptive control (MRAC) has been used to generate the reference location on-line as a function of the force tracking error in [4]. The prediction was also used to generate the reference trajectory according to the force error [10,11], such as an Extended Kalman Filter is used to estimate. There is often a large force tracking error using this method, because the dynamic physical properties of the robot and environment are often ignored. (3) Variable impedance control. The basic idea is to adjust the impedance parameters according to the force feedback information. Recently, many researchers have studied the benefit of variable impedance control during the task [12,13]. Variable impedance control has been first demonstrated its stability for the control system in [14], where a state-independent stability constraint that relates the stiffness and the time derivative of the stiffness to the damping have been proposed. Several works have addressed the problem of the specification of varying impedance through learning by demonstration [13,15], reinforcement learning [12,16,17]. Using the learning methods, it requires a huge amount of training data, which is not always convenient to collect for the force tracking systems.

In summary, the first category and the second category of approaches are based on the estimation and prediction of the environment location. Therefore, the force tracking error is unavoidable. What is worse, the dynamic physical properties of contact are always ignored. The third category considers the dynamic physical properties of contact, but the learning method requires a lot of data, it is not suitable for real-time system. The optimal control [18–23] like adaptive control and adaptive neural network are robust to uncertain systems and dynamically changing systems, the system can be achieved according to adjust the gains by the feedback information. To the best of our knowledge, no research has been reported to combine adaptive control and variable impedance control. Based on the existing problems of the above research, a new force tracking strategy which is called adaptive variable impedance control is proposed. It combines the idea of variable impedance control with the advantage of the adaptive control at the same time. The adaptive variable impedance control considers the dynamic physical properties of contact, and it stabilizes the system just by adjusting the gains on-line using the force feedback.

This paper aims at introducing the adaptive variable impedance control for dynamic force tracking in uncertain environment. The remaining of this paper is organized as follows. The interaction model of the system and the basic position-based impedance control with force tracking strategy are introduced in Section 2. The adaptive variable impedance control and the control block diagram are given in Section 3. The stability and convergence of the proposed control algorithm are analyzed in Section 4. A series of experiments are carried out in Section 5, followed by conclusions in Section 6.

2. System model and control

In this section, the interaction model of the system used in this paper is discussed. Then position-based impedance control with force tracking strategy is presented.

2.1. Model of robot and environment

For modeling the contact force of the robot and environment, the robot is presented by a second order mass–spring–damper system, the environment is also presented by a second order mass–spring–damper system as in other literatures. But in this paper, to begin with a simple case, let us consider the environment to be rigid. Denote k_e the stiffness of the environment, m, b and k the mass, damping and stiffness of the robot end-effector, respectively. Let f be the current contact force applied by the robot to the environment once a contact between both is established.

The contact process between the robot and the environment can be illustrated as two phases, as shown in Fig. 1. In the first phase, the robot is approaching toward the environment. While in the second phase, the end-effector is in contact with the environment. Fig. 2 shows a contact force diagram of a robot when it comes in contact with the environment.

As shown in Fig. 2, from $0 \sim t_1$, there is no contact during the free-space. From $t_2 \sim t_3$, the system will be stable after a process of collision. Collision is inevitable, however the collision time is transient and strongly nonlinear.

2.2. Position-based impedance control for force tracking

In the majority of the literature, force-based impedance control for force tracking has been widely studied. However, most commercialized robots emphasize the accuracy of position trajectory following, and do not provide a force control mode. Therefore, force-based impedance control was impossible on these robots. Alternatively, position-based impedance control is recognized as