Mechatronics 45 (2017) 110–118

Contents lists available at ScienceDirect

Mechatronics

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

Stability enhancement of admittance control with acceleration feedback and friction compensation☆,☆☆

Myo Thant Sin Aung[a,*], Ryo Kikuuwe[b]

[a] Department of Mechatronic Engineering, Yangon Technological University, Insein, Yangon, Myanmar
[b] Department of Mechanical Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

ARTICLE INFO

Article history:
Received 4 October 2016
Revised 4 April 2017
Accepted 22 June 2017

Keywords:
Admittance control
Noise filter
Sliding mode
Position control
Overdamped behavior

ABSTRACT

This paper presents an experimental investigation of a new position control scheme that enhances the stability of admittance control by using: (a) PDD^2 (proportional, derivative, and second derivative) feedback, (b) dither-based friction compensation and (c) sliding-mode-based noise filter with a variable gain. The PDD^2 structure and the friction compensation are for expanding the bandwidth of the internal position-controlled subsystem. The sliding-mode-based filter is for the attenuation of noise in the acceleration signal without producing a large phase lag. The variable gain of the filter is for suppressing acceleration-measurement noise at low velocity. The proposed controller is validated by employing a 1-DOF device.

1. Introduction

For many robotic manipulation tasks, such as force guided assembly, where robots are required to work in contact with the environment or external objects, appropriate controllers are needed to regulate the contact force between the robot and the environment. There exist many control schemes for force control of robots as surveyed in [2–4]. Among them, admittance control is a well-suited option when a force sensor is available in the end-effector because the effects of the nonlinearities such as joint friction are suppressed by the internal position controller of the admittance controller.

The block diagram of a common implementation of admittance control is illustrated in Fig. 1. In this control scheme, the motion of a virtual object with simple dynamics is generated from the measured force and an input (desired) force. The robot tracks the virtual object's position under the internal position controller. In this framework, one requires an accurate position controller so that the robot's response to external forces is sufficiently close to that of the virtual object. Admittance control has been implemented in many robotic tasks, e.g., rehabilitation [5,6], haptic rendering [7], human-robot cooperation [8], and robotic surgery [9].

As noted in [10,11], a primary source of the instability of admittance control is the limited bandwidth of the internal position controller. In order to enhance the stability, the virtual mass can be set as high as the device mass [12,13] at the cost of the system being less responsive.

Several previous research works have shown that the use of acceleration signal is effective in expanding the bandwidth of force control systems. Morbi et al. [5] proposed acceleration-limited proportional derivative controller to enhance the stability of admittance control. Xu et al. [14,15] showed that the joint acceleration feedback by using an accelerometer damps out the oscillations substantially in explicit force control. One of the authors [16] employed a feedforward term of the desired acceleration in combination with a sliding mode-like position controller in admittance control. Aguirre-Ollinger et al. [17] showed that acceleration feedback by using an accelerometer extends the bandwidth of admittance control.

Other approaches that enhances the stability of admittance and impedance controllers have been proposed. Duchaine and Gosselin [18] implemented variable damping to enhance the stability of admittance control. Hashimoto et al. [19] applied a nonlinear admittance controller in which the stiffness is varied according to the displacement of the leg in a biped robot. By using an adaptive controller, Tee et al. [20] proposed a variable admittance control scheme to deal with unmodeled dynamics. Osa et al. [21] proposed

☆ The paper extends the authors' previous conference publication [1] by including an improved position controller and new experimental results. The difference between the improved position controller and the previous position controller in [1] is explained in Section 3.3, and some experimental comparisons between the two controllers are included in Section 4.

☆☆ This paper was recommended for publication by Associate Editor Stefano Longo.

* Corresponding author.
E-mail addresses: nayaye1@gmail.com, aung@ctrl.mech.kyushu-u.ac.jp (M.T.S. Aung).

http://dx.doi.org/10.1016/j.mechatronics.2017.06.011
0957-4158/

a hybrid controller that switches between rate control and admittance control for use in bilateral operations. Dimeas et al. [22] implemented an online learning controller with neural network backpropagation training in the inner loop of the admittance controller. An interaction controller that combines friction compensation and disturbance observer was proposed in [23].

Our preliminary work [1] investigated the use of acceleration feedback and friction compensation in the position control loop for enhancing the stability of admittance control. In this paper, we propose a new position controller that produces better force control performance by allowing higher acceleration feedback gain than our previous controller [1]. The proposed control scheme comprises three components: (a) PDD^2 (proportional, derivative, and second derivative) position controller, (b) dither-based friction compensator [24] and (c) sliding-mode-based noise filter with a variable gain. The D^2 term is used to enhance the stability because its phase-lead effect theoretically extends the bandwidth of the position-controlled subsystem, i.e., the subsystem with the input p_d and the output p indicated in Fig. 1. The friction compensator proposed by the authors [24] is also used to extend the bandwidth of the position-controlled subsystem by reducing the phase lag caused by the hardware. The sliding-mode-based filter, which is also the one presented by the authors [25], is employed to smooth the acceleration (second-derivative) signal from the optical encoder without producing a large phase lag. The effect of the noise at low velocity is mitigated by setting the filter gain low when the velocity is low. Experimental results show that the proposed position controller enhances the stability of admittance control.

The present research is distinct from previous works mainly in that it does not require accelerometers, in contrast to [14,15,17], or the acceleration estimation based on precalibrated joint's dynamics, in contrast to [5]. In addition, the acceleration feedback presented in this paper can be readily combined with conventional PD or PID position controllers in any admittance control scheme.

The rest of this paper is organized as follows. Section 2 discusses the theoretical necessity of the second order controller and friction compensation in the new position controller. Section 3 proposes the new controller. Section 4 shows its effectiveness through experimental results and Section 5 provides some concluding remarks.

2. Preliminary analysis

2.1. One-DOF system

Here, we discuss the motivation of the new position controller based on an analysis on a one-dimensional robot under admittance control in contact with an environment. The block diagram of such a system is shown in Fig. 1.

A typical admittance-controlled robot with the desired force input f_d comprises a virtual object motion generator and a position servo for controlling the robot to track the motion of the virtual object. A common type of such a controller can be described as follows:

$$\ddot{p}_d = \frac{-b\dot{p}_d - f + f_d}{m} \tag{1a}$$

$$\tau = K(p_d - p) + B(\dot{p}_d - \dot{p}). \tag{1b}$$

Here, f denotes the measured external force, the desired force f_d and the measured position p are the inputs to the controller while τ is the torque command sent to the actuator. The virtual object dynamics is modeled as in (1a), where the constants m and b represents the inertia and the viscosity of the object. One can regard (1a) as a controller to make the measured force f track the desired value f_d, where the virtual object position p_d is the desired input to the internal position controller, of which K and B are P-, and D-gains, respectively.

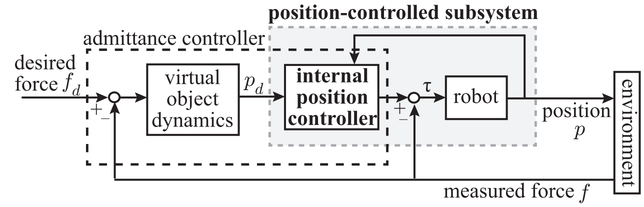

Fig. 1. Block diagram of an admittance-controlled robot in contact with an environment.

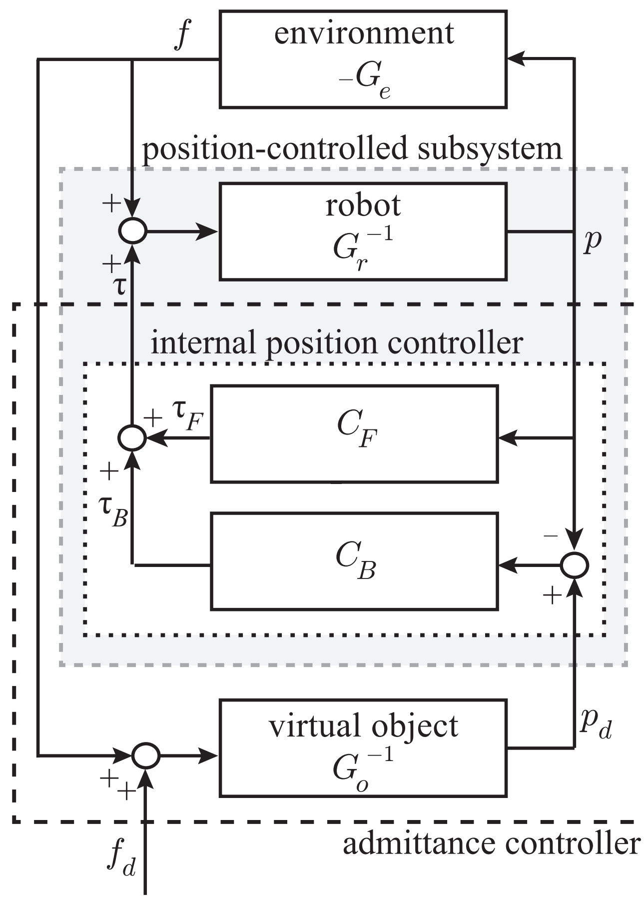

Fig. 2. Detailed block diagram of the system of Fig. 1.

2.2. Phase lag and instability

The analysis in this section follows a similar path to the analysis in [26], where a bilateral master-slave system is analyzed. Fig. 2 is a more detailed block diagram of the system of Fig. 1. Hereafter, all symbols are defined in the Laplace transform domain and are functions of the Laplace operator s. In Fig. 2, G_o is the dynamics of the virtual object, C_B and C_F are the components of the position controller, G_r is the dynamics of the robot and G_e is the dynamics of the environment. We describe the dynamics of the virtual object as follows:

$$G_o p_d = f_d + f. \tag{2}$$

We also assume that the robot is a single mass and its dynamics can be described as follows:

$$G_r p = \tau + f \tag{3}$$