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Fuzzy adaptive hybrid impedance control for mirror milling system[☆]

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ABSTRACT

In this paper, a fuzzy adaptive hybrid impedance control scheme designed for the supporting side of mirror milling system is proposed, which is capable of solving the force supporting problem with time-varying environment stiffness. In the process of milling large thin-walled sides, maintaining a constant supporting force is crucial both for suppressing vibration and for reducing deformation. Moreover, a superior impedance control scheme is beneficial in terms of enhancing the system stability, which is characterized by easy-implementation in the industrial robots. Hence, the force error triggered by the time-varying stiffness environment can be compensated by using our fuzzy adaptive algorithm. Simulations are tested on a parallel robot, *i.e.*, Tricept, in order to verify the force control accuracy as well as its robustness in terms of a time-varying stiffness environment. Both the simulation and the experiment show that our proposed support scheme has a better performance on maintaining the desired contact force than hybrid impedance (HI) control and adaptive hybrid impedance (AHI) control.

1. Introduction

Robot compliant control plays a critical role in the manufacturing industry, which is proposed to resolve both the position control and the force control. Recently, a novel technology, *i.e.*, mirror milling, is invoked for manufacturing large thin-walled sides characterized with a range of specific features [1], such as large area, easy deformation, complex shape, low structure stiffness, etc. It has been deemed to be as a research focus during the last decades. However, mirror milling requires the end-effector both to support the workpiece perpendicularly, and to realize precise control of the supporting force and the supporting position, *i.e.*, compliant control. A variety of compliant control models have been proposed in the literature. Zeng et al. [2] categorized the compliant control into fundamental robot force controls and advanced robot compliant controls. The fundamental robot compliant control, which relies on the relationship between the position and the force, can be further classified as impedance control and hybrid force/position control [3]. Specifically, Hogan [4] first proposed the concept of impedance control, where manipulator control was invoked for tracking a motion trajectory by means of adjusting the target impedance. Besides, hybrid force/position control conceived two complementary orthogonal workspaces on the displacement and the force relying on Manson's concept in [5]. In many cases, impedance control outperformed the others in terms of controlling the dynamic contact between manipulators and the environment, as well as presented more robustness in an unknown stiffness environment [6]. Based on work in [4], several research papers were proposed to solve the major issue in impedance control, *i.e.*, force tracking error. Due to its easy implementation of the hybrid force/position control and superior dynamic force tracking performances, a variety of literatures combined the concept of hybrid force/position control and the impedance force scheme, *i.e.*, Hybrid impedance (HI) control scheme [11–12]. The adaptive hybrid impedance (AHI) control was deemed to be as a new stable force tracking impedance control scheme, which is capable both of tracking a desired force and of compensating for uncertainties in environment location and stiffness [7–10]. Moreover, several schemes were proposed to study the position-based impedance controller and to analyze the performance and stability [13–15]. Komati et al. [16] presented a new position-based impedance control scheme to estimate the environment, which was able to estimate the environment stiffness according to the past value of the position measurement. Considering the adverse working conditions of the milling manufacture, a position-based force control scheme is implemented to achieve constant milling force with an internal model controller [17]. Mendes [18] used an optimal fuzzy-PI force controller to increase industrial robot autonomy. Gudur and Dixit 's work [19], the roll force and roll torque in a cold flat rolling process were modeled using first order Takagi-Sugeno (T-S) fuzzy models.

However, few studies aforementioned have concentrated on the compliant control designed for mirror milling system (MMS) due to its

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novelty and complication. The most of previous research works applying to the no deformed or slowly deformed environment focused more attention on the theoretical analyses, while it is difficult to realize in practical industrial robots directly. Moreover, the accurate model of the workpiece in the MMS cannot be achieved, because the parameters of the workpiece are time-varying during milling process. Considering with the AHI scheme has superior performance in compensating the force tracking error, and fuzzy control can realize parameters adjusting on line easily, therefore, we conceive fuzzy adaptive hybrid impedance (FAHI) control for MMS which do not require measurement of the environment. Our contributions can be summarized as follows. To the best of our knowledge, we first propose a compliant control designed for MMS. Moreover, the FAHI is presented in order to cater for the time-varying milling environment, and meanwhile ensure there is no overshoot to damage thin-wall. Furthermore, it is easy to be implemented in the practical industrial robots. Both the simulations' and experiments' results show that our scheme has a superior dynamic performance on tracking desired contact force.

The remainder of the article is outlined as follows. The system model and the environment assumptions are introduced in Section 2. Our FAHI scheme is discussed in Section 3. Simulation and experiment results are presented in Section 4, followed by a range of future work and our conclusion in Section 5.

2. System configuration

The mirror milling technology proposed in recent years is seen as the main method of the large thin-walled parts processing in the future, due to the characteristic of good generality and high efficiency. Large thin-walled parts are usually produced to be the propellant tank wall in aerospace. Its thickness is generally around 1 mm millimeters, and its shape is a cylinder wall with a radius of several meters. As shown in Fig. 1, MMS are composed by two sides, *i.e.*, the milling side as well as the supporting side. The MMS utilizes one industrial robot to mill the workpiece on one side, and the other robot supports the large thin-walled unit in the opposite normal direction. The support end-effector maintains a constant supporting force which plays a critical role in preventing the deformation of the workpiece and suppressing the vibration. In this way, our paper focuses its attention on the compliance control on the supporting side rather than the issues on the milling side.

Parallel robots are well known for their high rigidity and low positioning errors. In our work, the Tricept [20], a three degree of freedom (DOF) parallel robot, is chosen as a supporting actuator as Fig. 2(a) shown. Though the working area of Tricept is limited, it can be installed on a movable unit to extend its working area. The designed end-effector, as shown in Fig. 2(b), is composed of a force sensor, three eddy current sensors as well as a supporting bar. Specifically, when the supporting bar touches the thin-walled unit, the force sensor will immediately detect the three-dimension force vector. Besides, the three eddy current sensors are used to detect the distance between the end-effector and the thin-walled unit. Thus, our end effector has the following functions: (1) Supporting the thin-walled unit, (2) detecting the real-time supporting force by means of the force sensors and (3) measuring the surface normal vector of the thin-walled unit relying on the eddy current sensors. The information obtained by the eddy current sensors contributes to helping the end-effector to keep normal direction to the thin-walled unit (see Fig. 1). Hence, the supporting side follows the trajectory of the milling side and maintains the supporting force.

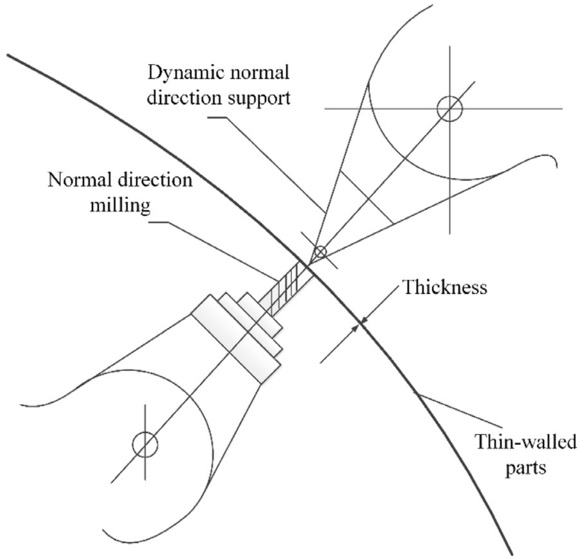

Fig. 1. A sketch map of the MMS.

In the process of milling large thin-wall, its stiffness is weak and changeable. Then, the force control should be as accurate as possible (less than 1 N usually in MMS). Moreover, in order to prevent damaging the large thin-wall, a large overshoot must be avoided. To address these two key issues, an FAHI algorithm is proposed.

3. Compliant controller

3.1. Hybrid impedance controller

As shown in Fig. 3, the coordinate system {c} is associated with the end-effector. f_x represents the force along X axis and τ_x denotes the torque around X axis. Moreover, v_x is the velocity along X axis, and ω_x represents the angle around X axis. The notification of X axis is similar to Y and Z axis. According to the analyses in the Fig. 3, Z axis is the direction of force control, while along X, Y axis and around X, Y, Z axis need position control. The velocity vector V and the force vector F can be denoted as:

$$\begin{aligned}\mathbf{V} &= [v_x \;\; v_y \;\; v_z \;\; \omega_x \;\; \omega_y \;\; \omega_z] = [c_1 \;\; c_2 \;\; c_3 \;\; 0 \;\; 0 \;\; 0],\\ \mathbf{F} &= [f_x \;\; f_y \;\; f_z \;\; \tau_x \;\; \tau_y \;\; \tau_z] = [0 \;\; 0 \;\; c_4 \;\; 0 \;\; 0 \;\; 0],\end{aligned}$$

where $c_4 \approx 0$ after achieving the desired constant supporting force.

As shown in Fig. 4, the force controller receives the force error between the desired force and the environment force in the Z axis direction and then sends displacement commands to the position controlled robot to modify the position of the end-effector in order to maintain a constant contact force. Therefore, the compliance selection matrix in Fig. 4, namely [**S**], can be denoted as:

$$\mathbf{S} = \mathrm{diag}[1 \;\; 1 \;\; 0 \;\; 1 \;\; 1 \;\; 1]. \tag{1}$$

By means of compliance selection matrix [**S**], only along Z axis need force control. Therefore, to be simply, combining hybrid force/position with impedance control to be hybrid impedance (HI) control, the impedance dynamic Equation in Z axis direction can be given by:

$$f_d - f_r = m_d \Delta\ddot{z} + b_d \Delta\dot{z} + k_d \Delta z, \tag{2}$$

where $\Delta z = z_d - z_r$, and z_r represents the end-effector actual position. z_d is the desired position. Moreover, f_r denotes the actual force contact on the workpiece, while f_d is desired force. The parameters m_d, b_d and k_d are desired inertia, damping, and stiffness gains, respectively.

The environment model is shown as following:

$$f_e = k_e z_e, \tag{3}$$

where f_e is the force that the thin-wall acted with supporting bar. Moreover, k_e is the stiffness of thin-wall, and z_e denotes the displacement of thin-wall. When supporting bar contacts with the thin-wall, the z_e is equal to z_d. Because of the f_r exerting on the workpiece, f_r is equal to f_e. Then, the force tracking error can be obtained as:

$$e = f_d - f_e = f_d - k_e z_e. \tag{4}$$