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

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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.

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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

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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

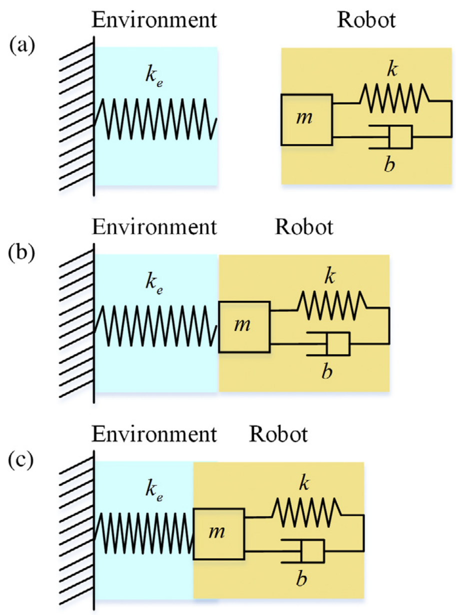

Fig. 1. System model of robot and rigid environment: (a) without any contact between robot and environment, (b) critical point when contact occurs but $f = 0$ and (c) contact with $f \neq 0$.

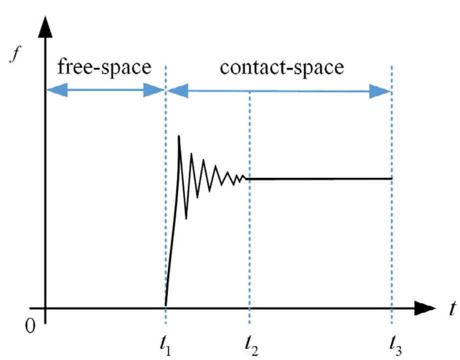

Fig. 2. The diagram of robot and environment contact force.

a practical approach to achieve compliant interaction of position-controlled manipulators. The position-based impedance control schematic for force tracking is shown in Fig. 3.

In Fig. 3, X_r, X_c and X_m represent for the reference position trajectory, the commanded position trajectory which is sent to the robot, the measured position trajectory, respectively. Assuming that $X_c = X_m$ in the position control mode, the position perturbation due to the contact force can be represented as $E = X_m - X_r = X_c - X_r$. X_e refers to the location of the environment. Because the environment is assumed to be rigid, so the environment is represented by a linear spring with stiffness K_e. The contact force between the robot and the environment is then simplified as $F_e = K_e(X_e - X_m) = K_e(X_e - X_c)$. Denoting F_d the desired contact force, then the force tracking error is $\Delta F = F_e - F_d$.

Typically, the impedance model is chosen as a linear second-order system with the transfer-function $K(s) = 1/(Ms^2 + Bs + K)$, so the dynamical relationship between the force tracking error ΔF and the position perturbation E can be expressed as

$$M\frac{\mathrm{d}^2E(t)}{dt^2} + B\frac{\mathrm{d}E(t)}{dt} + KE(t) = \Delta F(t) \tag{1}$$

where M is the mass, B is the damping, K is the stiffness. The perturbation E is used to modify the reference position trajectory X_r to produce the commanded trajectory $X_c = X_r + E = X_r + \Delta F \cdot K(s)$, which is then tracked by the servo driver system.

Each Cartesian variable is independent. Without loss of generality, taking one dimension for example, the force tracking error Δf can be written as

$$\begin{aligned} \Delta f &= f_e - f_d = k_e(x_e - x_c) - f_d \\ &= k_e x_e - k_e(x_r + k(s)\Delta f) - f_d \end{aligned} \tag{2}$$

Substituting $k(s) = 1/(ms^2 + bs + k)$ into (2), yields

$$\begin{aligned} &\Delta f(ms^2 + bs + k + k_e) = \\ &(ms^2 + bs + k)[k_e(x_e - x_r) - f_d] \end{aligned} \tag{3}$$

The steady-state force tracking error is then obtained from Eq. (3) as

$$\Delta f_{ss} = \frac{k}{k + k_e}[k_e(x_e - x_r) - f_d] \tag{4}$$

From Eq. (4), the reference position must satisfy the following equation in order to make the force tracking error converge to zero in the steady state.

$$x_r = x_e - \frac{f_d}{k_e} \tag{5}$$

Eq. (5) shows that if the precise location of the environment x_e and the exact value of environment stiffness k_e are known, the reference position trajectory x_r could be computed according to Eq. (5) to exert the desired contact force f_d on the environment. However, in practice the values of x_e and k_e are not known in advance. According to the analysis in [4], it is difficult to directly compensate the environment location x_e and the environment stiffness k_e. There will be an infinite steady-state force tracking error, because the force error always exists.

Based on the above problems, a new adaptive variable impedance is proposed to realize force tracking in the case of uncertain environment information in the next section.

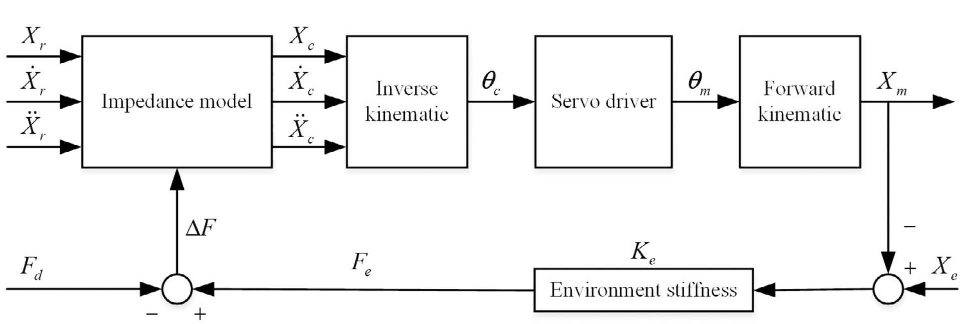

Fig. 3. The position-based impedance control schematic.

3. The dynamic force tracking based on adaptive variable impedance control

This section will address two problems in uncertain environments. (1) The environment stiffness is unknown or dynamic. (2) The environment location changes dynamically.

3.1. Unknown environmental stiffness

The following is an analysis of unknown or dynamic variation of the environmental stiffness. Substituting $E = X_c - X_r$ and $\Delta F = F_e - F_d$ into Eq. (1), yields

$$F_e - F_d = M(\ddot{X}_c - \ddot{X}_r) + B(\dot{X}_c - \dot{X}_r) + K(X_c - X_r) \tag{6}$$

According to the analysis in Section 2, it is difficult to obtain accurate reference trajectory X_r, because of the unknown environment information. Therefore, replacing X_r with the initial environment location X_e, the new impedance equation is then converted to

$$F_e - F_d = M(\ddot{X}_c - \ddot{X}_e) + B(\dot{X}_c - \dot{X}_e) + K(X_c - X_e) \tag{7}$$

Now the position perturbation E can be written as $E = X_c - X_e$. For simplicity, we take one-dimensional interaction force for example in the latter analysis. Then Eq. (7) can be expressed as

$$\Delta f = f_e - f_d = m\ddot{e} + b\dot{e} + ke \tag{8}$$

where $e = x_c - x_e$.

If the desired force $f_d = 0$, the situation is satisfied $\Delta f_{ss} = 0$ when $x_c = x_e$. It means robot just come into contact with the environment, the contact force f_e is zero. In this case, Eq. (8) is always satisfied for any environmental stiffness k_e.

If the desired force $f_d \neq 0$, the desired force f_d serves as the driving force to enable the robot to exert a force on the environment, so $x_c \neq x_e$, which means $\Delta f_{ss} \neq 0$ when the system is stable. As [24] shows that setting the stiffness k to zero will satisfy the ideal steady state condition in $f_e = f_d$ for any k_e.

So the proposed control law is to set stiffness $k = 0$, Eq. (8) yields

$$\Delta f = f_e - f_d = m\ddot{e} + b\dot{e} \tag{9}$$

Substituting $f_e = k_e(x_e - x_c) = -k_e e$ into Eq. (9), the contact impedance law is

$$m\ddot{e} + b\dot{e} + k_e e = -f_d \tag{10}$$

The analysis shows that, even if the environment stiffness k_e is unknown, the proper m and b based on approximation of k_e can be chosen to satisfy Eq. (10), so that when the system is stable, we have $\Delta f_{ss} = 0$.

Therefore, we can conclude that when the environmental stiffness is unknown or dynamic changes, the desired force tracking effect can be achieved by setting $k = 0$.

3.2. Dynamic environmental location

The situation of dynamic change of environment location is analyzed as following. Substituting $e = x_c - x_e$ into Eq. (9) results in

$$f_e - f_d = m(\ddot{x}_c - \ddot{x}_e) + b(\dot{x}_c - \dot{x}_e) \tag{11}$$

If the operation is on a plane, where $\ddot{x}_e = \dot{x}_e = 0$, we have $\Delta f_{ss} = 0$, which means the system is definitely stable.

If the operation is on a slope or a more complex unknown surface, x_e is time-varying, and $\dot{x}_e \neq 0$ or $\dot{x}_e \neq 0, \ddot{x}_e \neq 0$. So the environmental location needs to be estimated. Suppose the estimation of the environment location is $\hat{x}_e = x_e - \delta x_e$. The position error is then expressed as $\hat{e} = e + \delta x_e$. Replacing e with $\hat{e}$ in Eq. (9) yields

$$f_e - f_d = m\ddot{\hat{e}} + b\dot{\hat{e}} = m(\ddot{e} + \delta\ddot{x}_e) + b(\dot{e} + \delta\dot{x}_e) \tag{12}$$

In Eq. (12), $f_e, f_d, \ddot{\hat{e}}, \dot{\hat{e}}$ are time-varying. In other words, the force tracking error exists at any time with the previously-used control law. In order to obtain $\Delta f_{ss} = 0$, an adaptive variable impedance control is introduced to compensate the error of time variation. Considering the stability of the system, the damping coefficient in the impedance model is adjusted, but it is not recommended to modify the mass coefficient because it is easy to cause the system to oscillate. So the adaptive variable impedance law is proposed as

$$f_e(t) - f_d(t) = m\ddot{\hat{e}}(t) + (b + \Delta b(t))\dot{\hat{e}}(t) \tag{13}$$

$\Delta b(t)$ is adjusted online according to the force error, having the form as

$$\begin{cases} \Delta b(t) = \dfrac{b}{\dot{\hat{e}}(t)}\Phi(t) \\ \Phi(t) = \Phi(t-\lambda) + \sigma\dfrac{f_d(t-\lambda) - f_e(t-\lambda)}{b} \end{cases} \tag{14}$$

where λ is the sampling period of the controller and σ is the update rate.

For convenient applications in the control of industrial robots, Eq. (13) can be converted to its discrete format as

$$\begin{cases} \ddot{X}_c(t) = \ddot{X}_e(t) + \dfrac{1}{M}[\Delta F(t) - B(t)(\dot{X}_c(t-1) - \dot{X}_e(t))] \\ \dot{X}_c(t) = \dot{X}_c(t-1) + \ddot{X}_c(t)\mathrm{T} \\ X_c(t) = X_c(t-1) + \dot{X}_c(t)\mathrm{T} \end{cases} \tag{15}$$

where T is the system communication cycle between the robot controller and the servo driver.

The proposed force tracking structure is shown in Fig. 4.

4. Stability and convergence of adaptive variable impedance law

The form of adaptive variable impedance is given in Eqs. (13) and (14). The constraint conditions for the stability of adaptive variable impedance are given below, and the force tracking error is proved to be zero when the system is asymptotically stable. Substituting Eq.(14) into Eq. (13), yields

$$\begin{aligned} &f_e(t) - f_d(t) = m\ddot{\hat{e}}(t) + b\dot{\hat{e}}(t) + b\Phi(t-\lambda) \\ &+\sigma\,[f_d(t-\lambda) - f_e(t-\lambda)] \\ &= m[\ddot{e}(t) + \delta\ddot{x}_e(t)] + b[\dot{e}(t) + \delta\dot{x}_e(t)] \\ &+ b\Phi(t-\lambda) + \sigma\,[f_d(t-\lambda) - f_e(t-\lambda)] \end{aligned} \tag{16}$$

Reorganizing Eq. (16) yields,

$$\begin{aligned} &m\ddot{e}(t) + b\dot{e}(t) + b\Phi(t-\lambda) - [f_e(t) - f_d(t)] \\ &+\sigma\,[f_d(t-\lambda) - f_e(t-\lambda)] \\ &= -m\delta\ddot{x}_e(t) - b\delta\dot{x}_e(t) \end{aligned} \tag{17}$$

According to the stiffness model between the robot and the environment, which is $f_e = k_e(x_e - x_c) = -k_e e$, it becomes

$$\begin{cases} \dot{e} = -\dot{f}_e/k_e \\ \ddot{e} = -\ddot{f}_e/k_e \end{cases} \tag{18}$$

Substituting Eq. (18) into Eq. (17), yields

$$\begin{aligned} &-m\ddot{f}_e(t) - b\dot{f}_e(t) + bk_e\Phi(t-\lambda) - k_e[f_e(t) - f_d(t)] \\ &+\sigma k_e\,[f_d(t-\lambda) - f_e(t-\lambda)] = -mk_e\delta\ddot{x}_e(t) - bk_e\delta\dot{x}_e(t) \end{aligned} \tag{19}$$

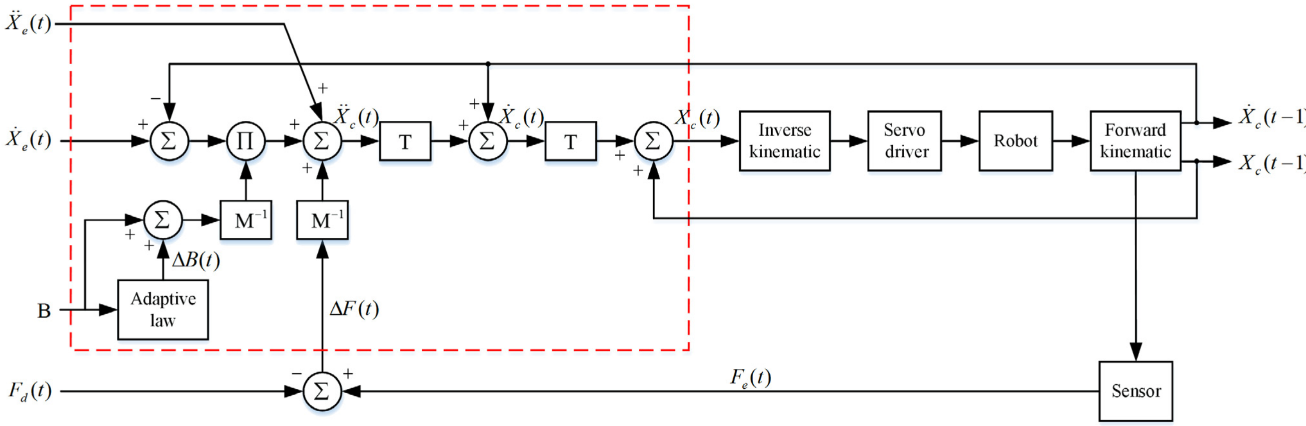

Fig. 4. The adaptive variable impedance control schematic.

Let $\hat{f}_e(t) = k_e\delta x_e(t)$, and then Eq. (19) could be represented as

$$\begin{aligned} &m\ddot{f}_d(t) - m\ddot{f}_e(t) + b\dot{f}_d(t) - b\dot{f}_e(t) + bk_e\Phi(t-\lambda) \\ &+\sigma k_e\left[f_d(t-\lambda) - f_e(t-\lambda)\right] - k_e[f_e(t) - f_d(t)] \\ &= m\ddot{f}_d(t) - mk_e\delta\ddot{x}_e(t) + b\dot{f}_d(t) - bk_e\delta\dot{x}_e(t) \\ &= m\ddot{f}_d(t) - m\ddot{\hat{f}}_e(t) + b\dot{f}_d(t) - b\dot{\hat{f}}_e(t) \end{aligned} \tag{20}$$

Marking $c(t) = f_d(t) - f_e(t)$ and $r(t) = f_d(t) - \hat{f}_e(t)$, rewrite Eq. (20) as

$$m\ddot{c} + b\dot{c} + bk_e\Phi(t-\lambda) + \sigma k_e c(t-\lambda) + k_e c = m\ddot{r} + b\dot{r} \tag{21}$$

According to the principle of dispersion, n elements of Φ series can be expanded as [24]

$$\begin{aligned} &b\Phi(t-\lambda) = b\Phi(t-(n+1)\lambda) \\ &+\sigma c(t-(n+1)\lambda) + \cdots + \sigma c(t-2\lambda) \end{aligned} \tag{22}$$

In general, set the initial value of adaptive compensation $\Phi(t-(n+1)\lambda) = 0$, so Eq. (21) can be rewritten as

$$\begin{aligned} &m\ddot{c} + b\dot{c} + k_e c + \sigma k_e(c(t-(n+1)\lambda) + \\ &\ldots + c(t-\lambda)) = m\ddot{r} + b\dot{r} \end{aligned} \tag{23}$$

According to the delay property of the Laplace transform $\mathcal{I}[f(t-\tau)] = e^{-\tau s}F(s)$, the following equation is obtained by Eq. (23).

$$\frac{c(s)}{r(s)} = \frac{ms^2 + bs}{ms^2 + bs + k_e + \sigma k_e(e^{-(n+1)\lambda s} + \cdots + e^{-\lambda s})} \tag{24}$$

The stability of Eq. (24) can be assured by the characteristic Eq. (25)

$$ms^2 + bs + k_e + \sigma k_e(e^{-(n+1)\lambda s} + \cdots + e^{-\lambda s}) = 0 \tag{25}$$

Under the assumption that n is a sufficiently large number, it can be expressed as

$$\sum_{n=1}^{\infty} e^{-\lambda ns} = \frac{e^{-\lambda s}}{1 - e^{-\lambda s}} \tag{26}$$

When the sampling rate λ is sufficient, the delayed term can be approximated as $e^{-\lambda s} \simeq 1 - \lambda s$ by Taylor expansion. Eq. (25) can be written as

$$\lambda ms^3 + \lambda bs^2 + k_e\lambda(1-\sigma)s + \sigma k_e = 0 \tag{27}$$

According to the Routh criterion, we get the Routh array as illustrated in Eq. (28). To ensure the stability of the system, the coefficients of the first column and the coefficients of the characteristic equation must be positive, representing as in Eq. (29).

$$\begin{array}{lll} s^3 & \lambda m & k_e\lambda(1-\sigma) \\ s^2 & \lambda b & \sigma k_e \\ s^1 & \dfrac{\lambda bk_e\lambda(1-\sigma) - \lambda m\sigma k_e}{\lambda b} & 0 \\ s^0 & \sigma k_e & 0 \end{array} \tag{28}$$

$$\begin{cases} \dfrac{\lambda bk_e\lambda(1-\sigma) - \lambda m\sigma k_e}{\lambda b} > 0 \\ k_e\lambda(1-\sigma) > 0 \\ \sigma k_e > 0 \end{cases} \tag{29}$$

Simplifying Eq. (29), yields

$$0 < \sigma < \frac{\lambda b}{m + \lambda b} \tag{30}$$

For a stable system, the steady-state error e_{ss} defined based on the Laplace transform. For convergence, the steady-state error e_{ss} can be obtained as

$$\begin{aligned} e_{ss} &= \lim_{t\to\infty} e(t) = \lim_{s\to 0} sE(s) = \lim_{s\to 0} s(c(s) - r(s)) \\ &= \lim_{s\to 0} s\left[\frac{ms^2 + bs}{ms^2 + bs + k_e + \sigma k_e(e^{-(n-1)\lambda s} + \cdots + e^{-\lambda s})} r(s) - r(s)\right] \end{aligned} \tag{31}$$

When the input is a step function with the form as $r(s) = (1/s)$. Eq. (31) yields

$$e_{ss} = \lim_{s\to 0} s(c(s) - r(s)) = -1 \tag{32}$$

According to the Eq. (32), the following conclusion can be drawn.

$$\lim_{s\to 0} sc(s) = 0 \tag{33}$$

$$\lim_{t\to\infty} c(t) = 0 \tag{34}$$

Therefore, when $t \to \infty$, $f_e \to f_d$. The contact force between robot and environment converges to the dynamic desired force. Actually, even if $r(s)$ is not a constant, like a sine function as in experiment, we can always prove that the tracking error goes to zero.

5. Simulations and experiments

To verify the proposed force tracking approach and analysis, a series of simulation and experimental studies are conducted

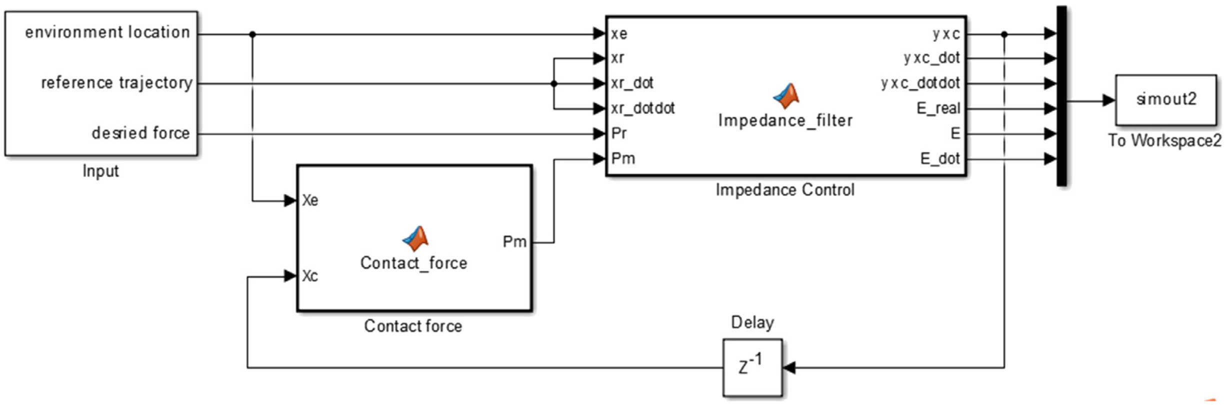

Fig. 5. The block diagram of simulation.

and presented in this section. The performance of the proposed schemes is first tested by simulations. The simulations include a variety of force tracking scenarios which basically cover most of the actual situations. Three experimental studies are carried out to test the feasibility of practical application.

5.1. Simulation studies

In the following simulation experiments, the classical constant impedance control as shown in Eq. (11) and the adaptive variable impedance control as shown in Eqs. (13) and (14) are tested and compared in a variety of uncertain environments. The simulation environment is based on Matlab Simulink which including two parts: the impedance control and the model of contact force. The block diagram of simulation is shown in Fig. 5, the simulation does not consider any disturbance.

5.1.1. Force tracking on planes

If the contact environment is a plane, then it satisfies $\dot{x}_e = \ddot{x}_e = 0$. Assume that $m = 1, k = 0, x_e = 0.1$ m, $f_d = 5$ N. Set x_c to a value bigger than x_e, for instance $x_c = 0.2$ m in this paper. In other words, the robot is not in contact with the environment in the beginning. In order to test the robustness of the Eq. (11) to uncertain environment stiffness, abruptly changing the environment stiffness to be

$$k_e = \begin{cases} 1000\,(\mathrm{N/m}), 0 \le t \le 6 \\ 3000\,(\mathrm{N/m}), 6 \le t \le 8 \\ 5000\,(\mathrm{N/m}), 8 \le t \le 10 \end{cases} \tag{35}$$

Figs. 6 and 7 show us the result of position tracking and force tracking on a plane with the fixed impedance control, respectively. The damping coefficient $b = 42$ can obtain the ideal effect. Fig. 6 shows that robot moves from free space to constrained space between 0 $\sim$ 0.4 s. Once the end-effector contacts with the environment, it can be seen from Fig. 7 that when the environment stiffness changes, the desired force can be tracked after a brief force adjustment.

The above experimental results show that constant impedance control is robust to the varying environmental stiffness. Therefore, the classical constant impedance control can achieve good force tracking effect when the robot operates on a plane or the environment stiffness varies.

5.1.2. Force tracking on slope surface

If the contact environment is a slope surface, then it satisfies $\dot{x}_e \neq 0, \ddot{x}_e = 0$. This experiment is to compare the adaptability of classical impedance control and adaptive variable impedance control to the dynamic changes of the environment, so set the

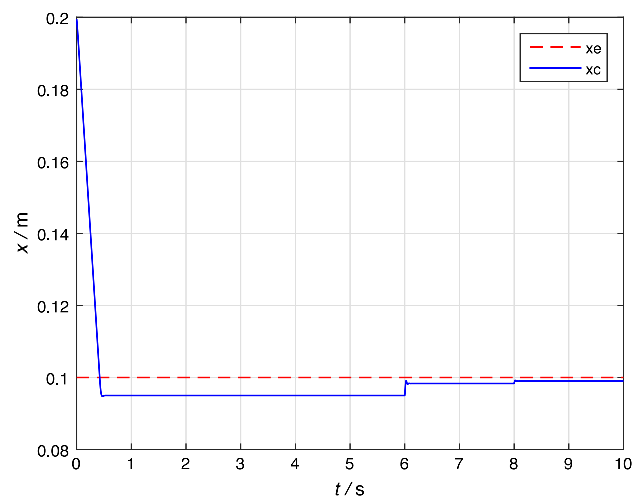

Fig. 6. Position tracking on planes based on constant impedance control.

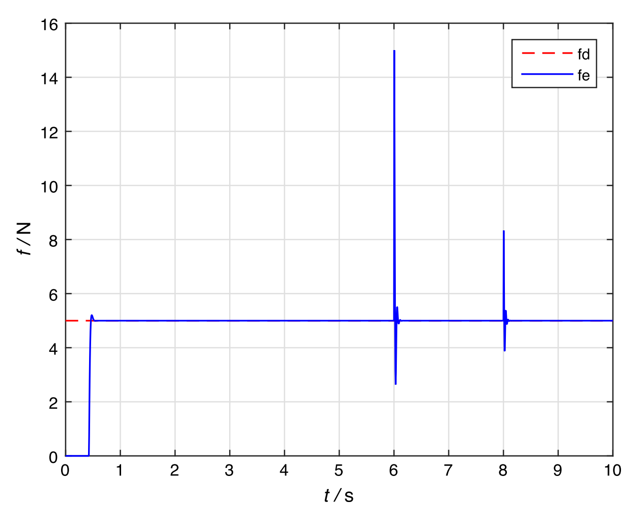

Fig. 7. Force tracking on planes based on constant impedance control.

initial location $x_c = x_m = 0$, $k_e = 5000$ (N/m), $f_d = 50$ N, the other assumptions are the same.

Figs. 8–11 show us the simulation results of position and force tracking when the robot operating on a slope flat surface with the

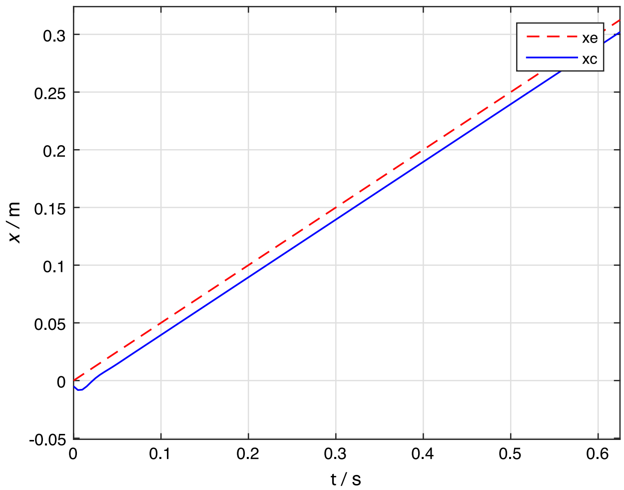

Fig. 8. Position tracking on a slope surface based on constant impedance control.

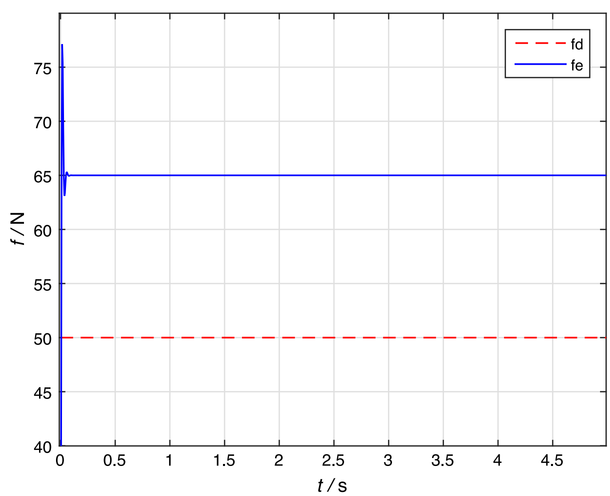

Fig. 9. Force tracking on a slope surface based on constant impedance control.

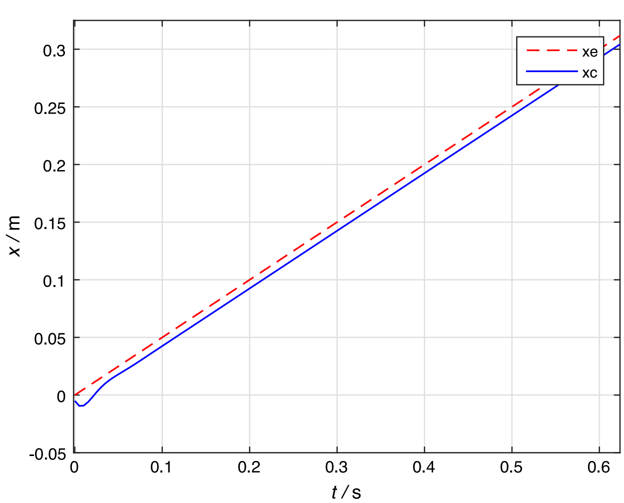

Fig. 10. Position tracking on a slope surface based on variable impedance control.

constant impedance control and the adaptive variable impedance control, respectively.

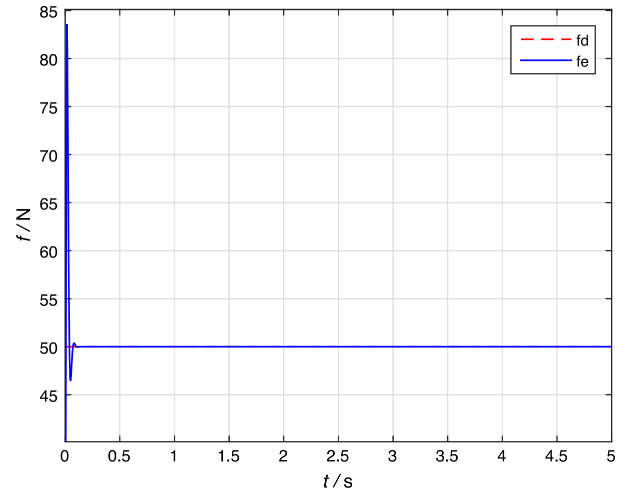

Fig. 11. Force tracking on a slope surface based on variable impedance control.

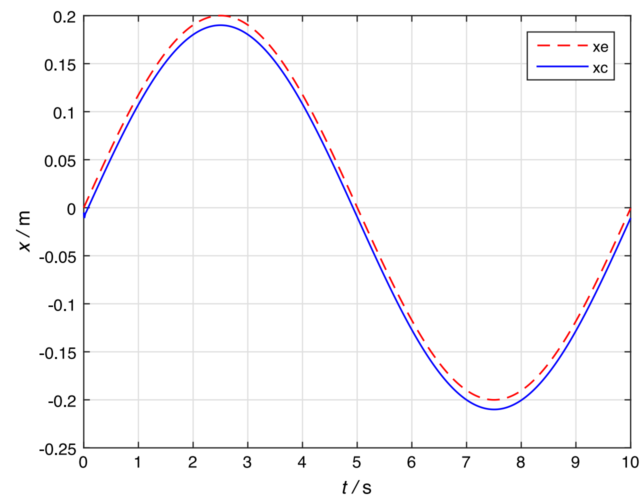

Fig. 12. Position tracking on a sine surface based on constant impedance control.

For the constant impedance control, the damping coefficient $b = 60$ can be used to obtain the stable force tracking value. But Fig. 9 shows that the stable value is $\hat{f}_d = 65$ N, there is a large error in expectation. For the adaptive variable impedance control, the initial damping coefficient $b = 100$ and the update rate $\sigma = 0.5$ can be used to obtain the stable force tracking value, and Fig. 11 shows that the adaptive variable impedance control can achieve the desired stable value after the short adaptive adjustment.

By the above experimental results, we can conclude that although the constant impedance control can achieve a stable value, it cannot track the desired force. Therefore, the adaptive variable impedance control outperforms the constant impedance control.

5.1.3. *Force tracking on sine surface*

If the contact environment is a sine surface, then it satisfies $\dot{x}_e \neq 0, \ddot{x}_e \neq 0$, the other assumptions are the same. Figs. 12–15 show us the simulation results of position and force tracking when the robot operating on the sine surface.

Fig. 13 shows that whatever b is chosen, the force tracking error always exists, and the estimated force trends sideways. Hence, the force tracking in this case is non-convergent. But Fig. 15 shows that the adaptive variable impedance control can achieve the desired stable value after the short adaptive adjustment.

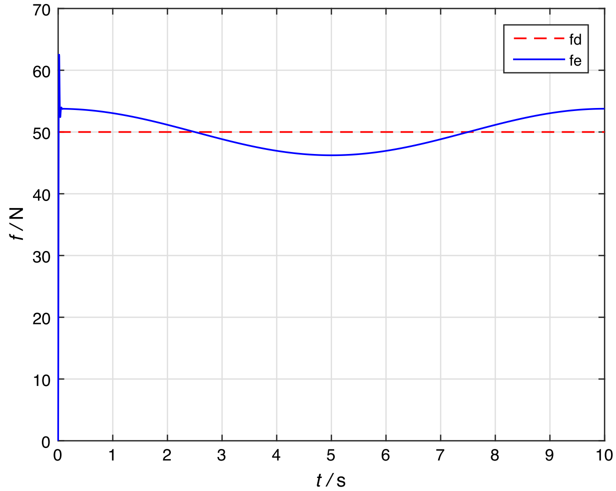

Fig. 13. Force tracking on a sine surface based on constant impedance control.

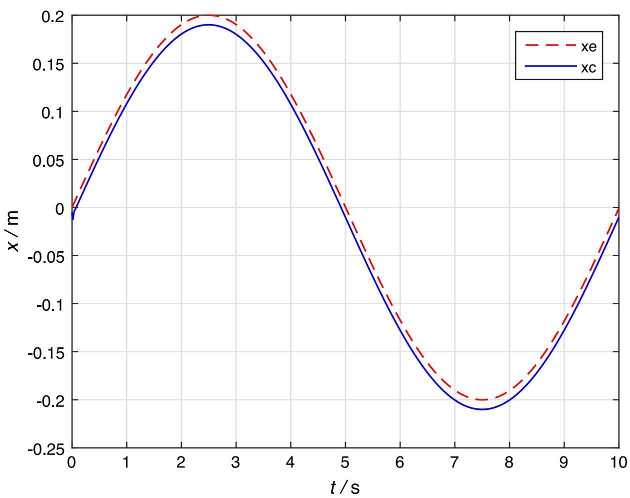

Fig. 14. Position tracking on a sine surface based on variable impedance control.

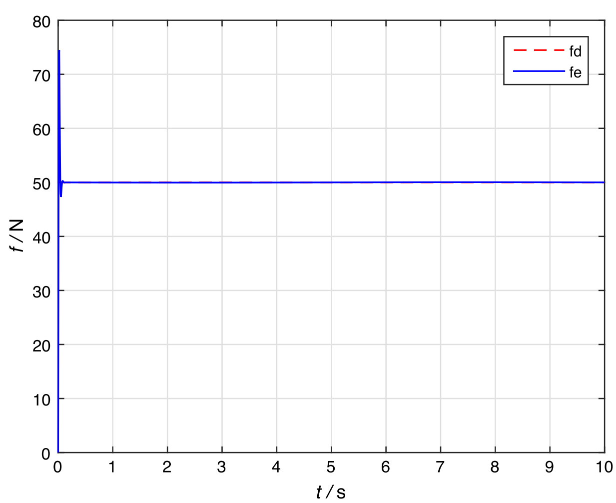

Fig. 15. Force tracking on a sine surface based on variable impedance control.

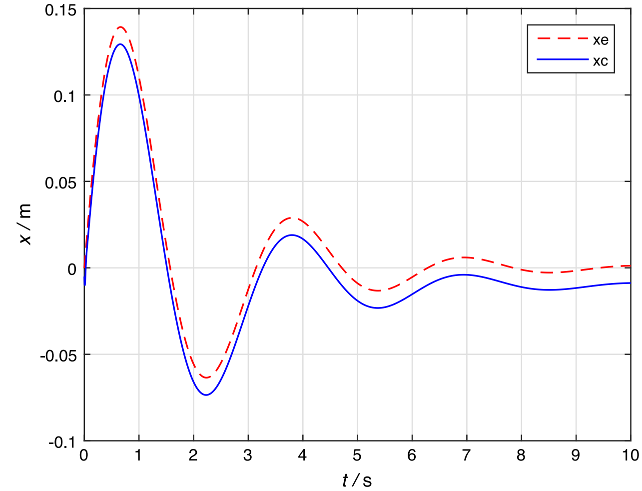

Fig. 16. Position tracking on a complex surface based on variable impedance control.

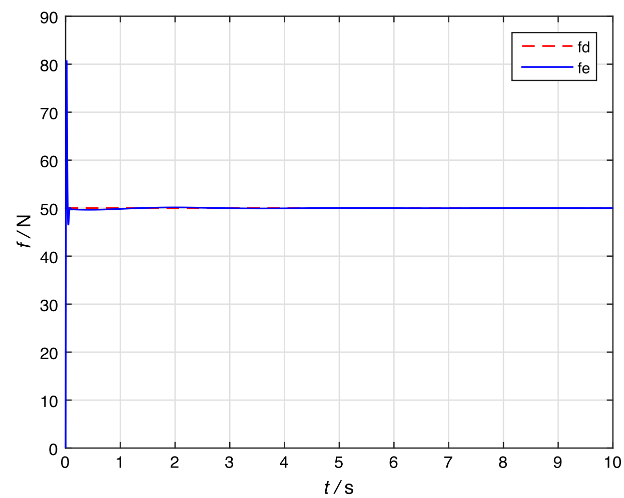

Fig. 17. Force tracking on a complex surface based on variable impedance control.

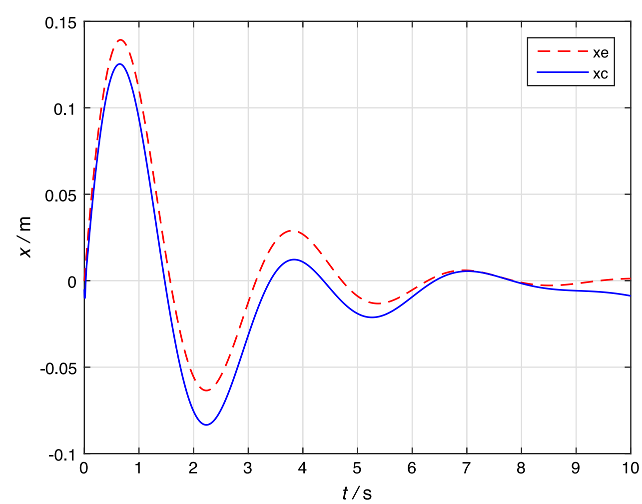

Fig. 18. Position tracking on a complex surface based on variable impedance control where f_d is time varying.

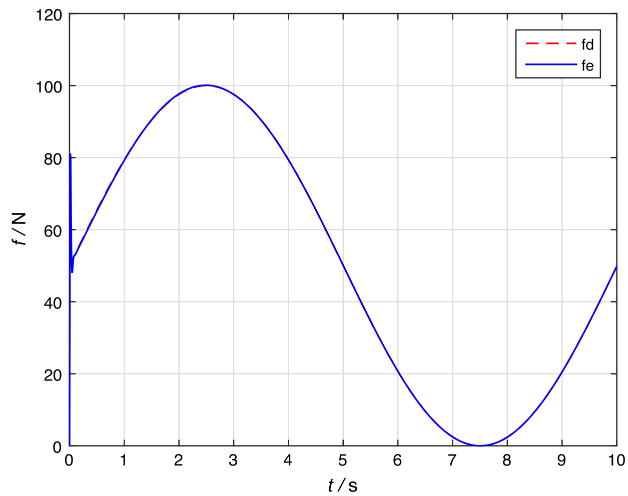

Fig. 19. Force tracking on a complex surface based on variable impedance control where f_d is time varying.

5.1.4. Force tracking on complex surface

The aim of this experiment is to test the robustness of the adaptive impedance control to the complex surface for force tracking. Figs. 16 and 17 show us the simulation results of position and force tracking when the robot operating on the complex surface based on adaptive variable impedance control. It shows that force tracking error is zero when the system is stable.

Furthermore, in order to test whether adaptive variable impedance control can adapt to the dynamic desired force, so f_d is set a time-varying series. Figs. 18 and 19 show us the simulation results of position and force tracking when the robot operating on the complex surface based on adaptive variable impedance control where f_d is time varying. The simulation results show the force tracking error is zero when the system is stable.

From the above four simulation experiments, we could conclude that (1) For the flat surface, even if the environment stiffness is uncertain, the constant impedance control can achieve the desired force tracking effect. (2) But for the slope or more complicated unknown surface, the constant impedance control cannot achieve the desired force tracking. (3) The adaptive variable impedance control not only can achieve the desired force tracking

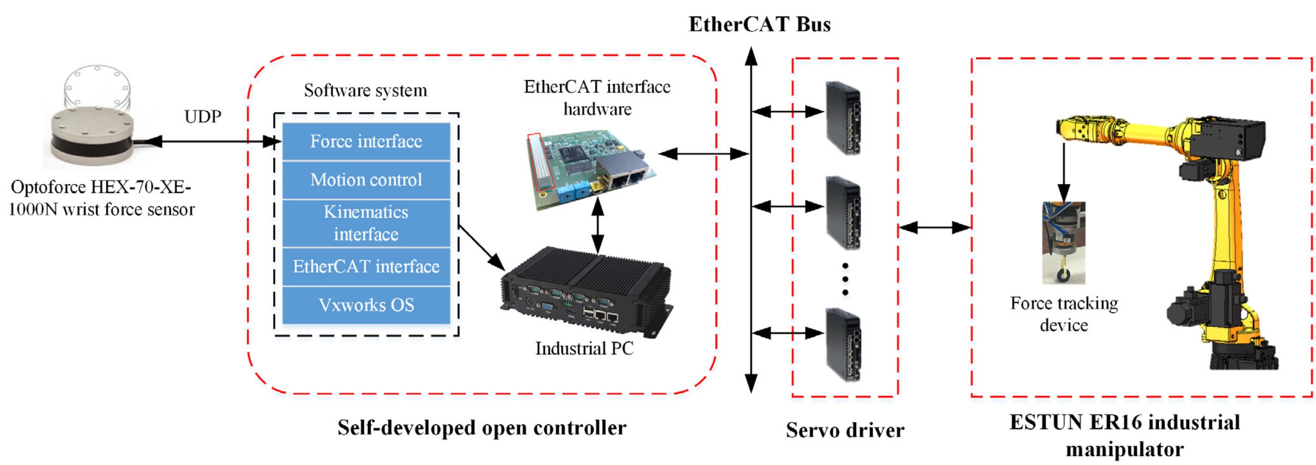

Fig. 20. Hardware architecture of test-bed.

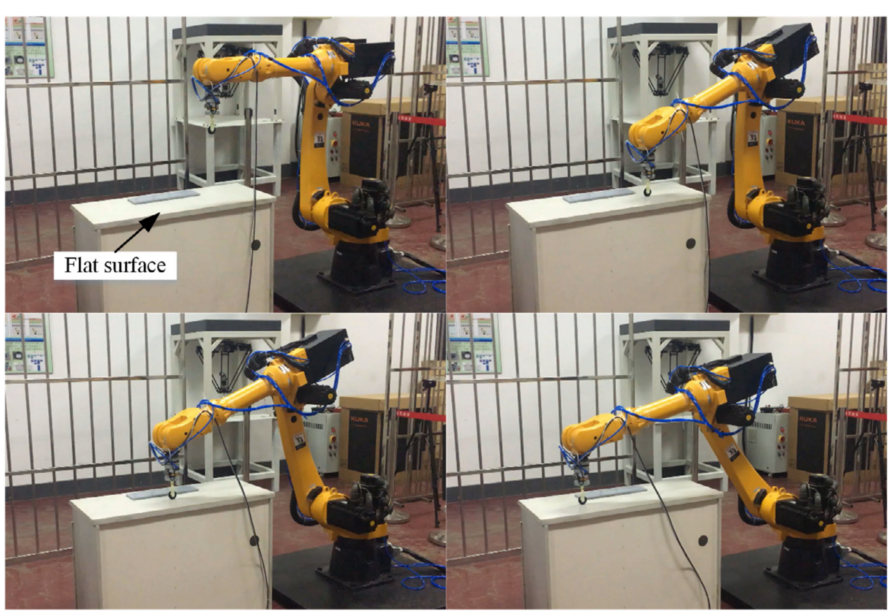

Fig. 21. Experimental setup — flat surface.

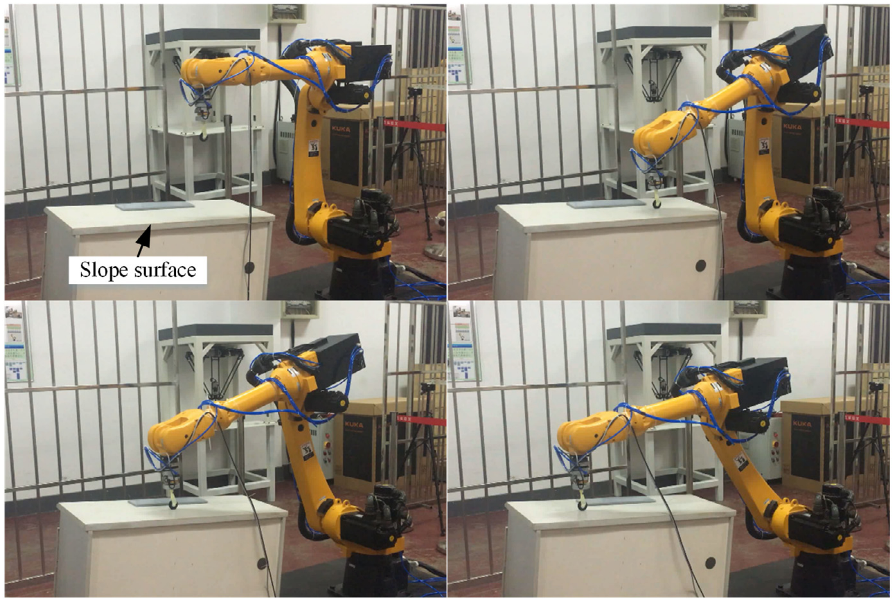

Fig. 22. Experimental setup — slope surface.

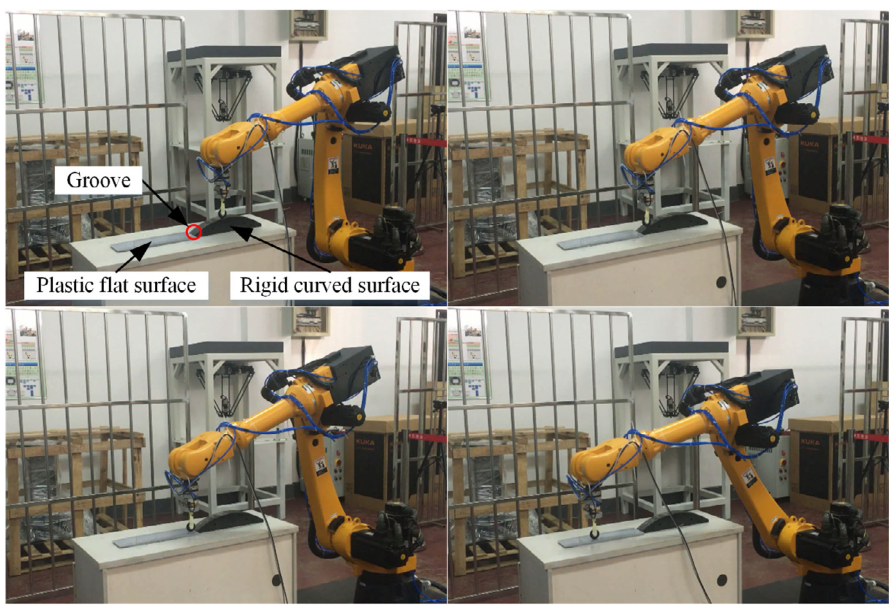

Fig. 23. Experimental setup — curved surface.

performance on whatever surface, but also can adapt the dynamic desired force.

Therefore, the simulation experiments show that the adaptive variable impedance control can achieve very good tracking effect in uncertain environment.

5.2. Experimental studies

To demonstrate the performance of the proposed algorithm, experiments were conducted using the test-bed as shown in Fig. 20. The test platform consists of four parts, self-developed open controller, servo driver, an ESTUN ER16 industrial manipulator and an Optoforce HEX-70-XE-1000N wrist force sensor (The nominal capacity of F_z is 1000N, the deformation is 1 mm and the accuracy is 3%FS). The servo driver communicates with the controller through EtherCAT. The force sensor and the controller are communicated through UDP, both of the communication cycles are 5 ms. At the end-effector of the robot is a pulley-based device for tracking the contact position and force accurately.

To confirm simulation studies, three experiments were conducted to test the feasibility of the proposed algorithm as show from Figs. 21 to 23. The flat and slope surface are hard desk surface as show in Fig. 21 and Fig. 22. The complex surface is a blend curved surface which includes a sine surface and a flat surface as show in Fig. 23, the sine surface is rigid, and the flat surface is plastic, there is a groove in the connection between the sine surface and the flat surface. The exact location and stiffness of each surface are uncertain. Consider the robot moving in the negative z direction onto a surface, and then moving 40 cm along the surface in the y direction with $f_d = -12$ N in z direction.

The constant impedance control strategy is tested in the first experiment, and the adaptive variable impedance control algorithm

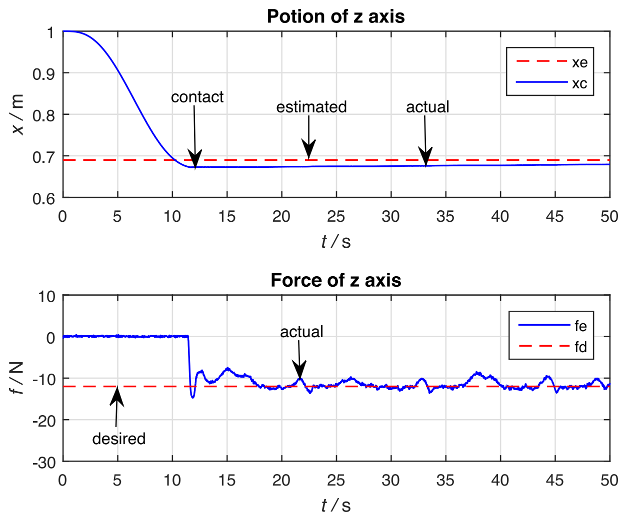

Fig. 24. Results of constant impedance control — flat surface.

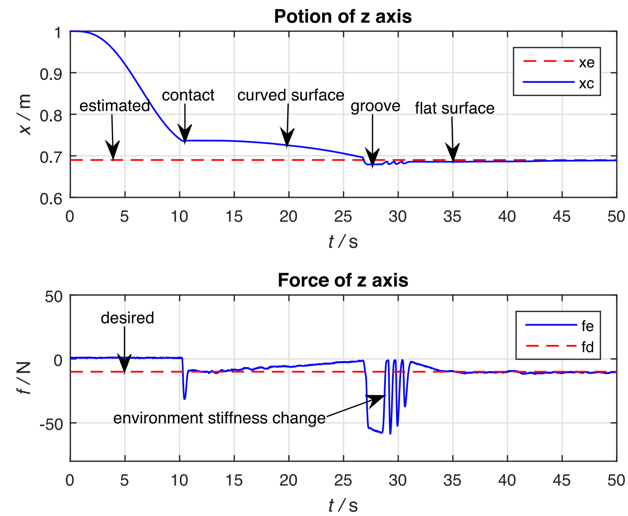

Fig. 26. Results of adaptive variable impedance control — curved surface.

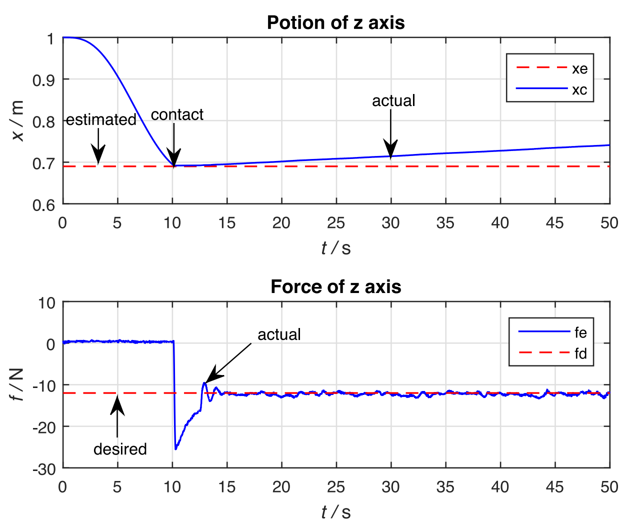

Fig. 25. Results of adaptive variable impedance control — slope surface.

is tested in the second and third experiments. The results of the experiments are shown from Figs. 24 to 26. In the initial state, the end-effector moves from the free space to a point beyond the surface. f_d is used to drive the robot in contact with the surface. In contact with the surface, the desired force is tracked smoothly after a brief adjustment.

Fig. 24 shows that once the end-effector contacts with the surface, the initial overshoot is happening, and the force settles to -12 N in approximately 15 s. Fig. 25 shows that after a brief force adjustment, the tracking is stable at -12 N in approximately 15s. Fig. 26 shows that from 10 s to 27 s the adaptive variable impedance control can track the curved surface although the force has a bit error. From 27 s to 28 s, the end-effector through the groove in the junction between the sine surface and flat surface. At time 28 s, the environment stiffness changes. After a brief adjustment from 28 s to 31 s, the force can be tracked. In the whole experiments, the initial damping coefficient $b = 100$ and the update rate $\sigma = 0.5$ are used to obtain the stable force tracking value.

6. Conclusion

Force tracking is one of the most important issue in contact operation. A new adaptive variable impedance control for dynamic force tracking in uncertain environment was proposed.

Two key factors for the uncertain environment were analyzed: unknown environmental stiffness and dynamic environmental location. The dynamic physical properties of the robot and the environment were modeled. A modified impedance control law which was based on the traditional impedance control was improved to adapt any environmental stiffness. In order to solve the problem of the dynamic environmental location, an adaptive variable impedance control strategy based on force feedback by adjusting impedance parameters to compensate for the location error was studied.

To verify the feasibility of the proposed algorithm, both simulation and experimental studies were conducted and tested. Test results showed that the constant impedance control only can be applied to the flat surface force tracking, but the adaptive variable impedance control can be used to a variety of uncertain environments such as slope surface or another complex unknown surface. The proposed algorithm was not only used to track static desired force, but also can be used to dynamic desired force tracking. It can be extended to a lot of situations involving force tracking, and it provides a more effective solution to the contact operation.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.robot.2018.01.009.

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