Time-varying Force Tracking in Impedance Control
A Case Study for Automatic Cell Manipulation

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Abstract—Compared with the general compliance control problem where the manipulator-environment interaction force is often assumed to be a fixed value, a time-varying manipulation force of impedance control is studied upon a newly automatic cell injection system. The position-based impedance control method is deeply discussed, and two new controllers, a nonlinear PID controller for inner-loop position tracking and an adaptive impedance regulator for the outer force control loop, are well talked and introduced. Two conditions for time-varying force tracking in position-based impedance control are preliminarily given, and large amount of simulations are performed to verify the efficacy of the proposed methods in both trajectory and force control.

Index Terms—Time-varying force control; Automatic cell injection; Robust position control; improved target impedance

I. INTRODUCTION

Biological cell microinjection has always been a key method applied in gene injection, in-vitro fertilization, drug development and intracytoplasmic sperm injection since it was developed. Conventional microinjection methods performed manually suffers from a low success rate for its low precision and complex operation. Over the past decades, continued efforts have been made to semiautomate or automate the cell injection process. Recent advances in 3-D cell manipulation, microforce sensor, and sophisticated cell holder etc. help the process of full automatic batch microinjection. Some prototypes of full automatic batch microinjection systems have been proposed by a number of research groups [1]-[3]. Given the soft and fragile characteristic of the injected cells, excessive injection force or vibration may easily cause damage to the cell membrane and eventually a potential failure in micromanipulation. Hence, proper measurement and direct control of the time-varying injection force, namely, the general compliance control, is an important work during the robotic manipulation [4].

Much work have been done towards the problem of compliance control within which the position, the force and their interactive relation all necessitate respective regulation, such as assembling a workpiece, grinding and deburring. A remarkable and effective method is the impedance control proposed by Hogan [5], who definitely gave the dynamic relation between the manipulator motion and the interaction force for the first time. Another popular control algorithm is the hybrid position/force control [6], which decomposes the end-effector Cartesian coordinates into a “position subspace” and a “force subspace”, and a position controller and a force controller in each subspace is specified, correspondingly. However, the switch between different modes of control and an accurate information about the shape and elasticity of the environment are required. Besides, this hybrid method ignores the dynamic manipulator-environment coupling, which may be sometimes beneficial to the system. As a result, the hybrid position/force control is not possible to control the commanded position or force accurately and may also cause some unstable response [7]. However, the impedance control method not only establishes a user-specified dynamical relationship between the end-effector position and force, but also provides a unified framework for controlling a manipulator both in free space motion (without environmental contact) and in compliant motion (with environmental contact) [8].

To date, impedance control has been implemented in various forms, depending on how the measured signals, i.e. velocity, position or force are used [9]. Two common approaches, torque-based impedance control (TBIC) and position-based impedance control (PBIC), are generally discussed in the frame work of impedance control. However, most of the approaches of impedance control are neither without a direct control of the manipulation force nor can be used for time-varying force control, namely, the desired end effector position and the desired force exerted on the environment should be specified as time-varying terms (ramp force or other high order force functions), rather than fixed values [8][9][10]-[12]. Preliminary exploration of time-varying cell injection regulation has also been carried out [3]-[4]. However, these works may fall into position-based cell microinjection method, which are incapable to directly control the injection forces [4].

In papers [13]-[15] where a newly automatic cell injection system is developed and the time-varying force tracking is implemented via a visual-based impedance control method. Improved studies have also been found to achieve a ramp force tracking in the position-based impedance control [4]. Inspired by their contributing work, more valuable work can be done. First, the ramp force tracking problem can be extended to a more general case in which the tracking of any twice continuously differentiable reference injection force can be achieved in the position-based impedance control. Then, a more simple and easy-implemented position controller can be applied as the basis of the force control.

The present work thus makes the following contributions:
1. An indirect adaptive impedance controller which can deals with the uncertain environment stiffness is presented and the corresponding stability analysis is also given.

2. Two conditions guaranteeing the tracking of any twice continuously differential force function are preliminarily proposed.

The time-varying force control method proposed for cell injection purpose in this paper can actually be extended to a more general case where a time-varying force tracking is required.

This article is organized as follows. First, we analyze the fundamental characteristics of the general position-based impedance control theoretically. Next, as to the theoretical analysis, a simple and easy-implemented nonlinear proportional-integral-differential (NPI) controller for the inner trajectory tracking manipulator system is proposed. Then, an indirect adaptive impedance controller is presented to deal with the uncertainties from the cell membrane, and finally, simulations are performed to verify the effectiveness of the proposed methods in trajectory tracking and time-varying force control.

II. TIME-VARYING FORCE TRACKING

The common formulation of target impedance is given as

\[ M(\ddot{X} - \ddot{X}_r) + B(\dot{X} - \dot{X}_r) + K(X - X_r) = -F_e \]  

(1)

where \( X \) and \( X_r \) are, respectively, the actual and reference location of the end-effector in Cartesian space, \( M, B \) and \( K \) are the diagonal mass, damping and stiffness matrices and \( F_e \) denotes the actual contact force from the environment.

In order to endow the traditional impedance controller the force-tracking ability, Goldenberg [16] modified the impedance function by adding a reference force, \( F_r \), to the original target impedance function. Therefore, a specified force set-point, \( F_r \), is introduced to execute the force tracking and the target impedance is then driven by the force tracking error, \( E = F_r - F_e \) [8].

Since the model (1) is decoupled in every direction, for simplicity, we consider the injection force in only one direction. Let \( m, b, k, f_r, f_e \) be the elements of \( M, B, K, F_r, F_e \), respectively. Then, we can rewrite (1) as

\[ m(\ddot{x} - \ddot{x}_r) + b(\dot{x} - \dot{x}_r) + k(x - x_r) = e \]  

(2)

During the free space motion where there is no contact between the manipulator and the environment, the force error term \( e = 0 \). The target impedance function (2) is modified as

\[ m(\ddot{x} - \ddot{x}_r) + b(\dot{x} - \dot{x}_r) + k(x - x_r) = e \]  

(3)

Clearly, the system (3) is a stable differential equation, that is, \( x(t) \rightarrow x_r(t) \) as \( t \rightarrow \infty \).

Once the interactive contact is occurred, the dynamic interaction between the manipulator and the environment will change into the dynamics depicted in (2), which leads to a compromise between the position error, \( x - x_r \), and the force error, \( e \), which means neither accurate position control nor accurate force control can be achieved. Therefore, impedance control itself is incapable of force tracking [17].

Further, to produce a constant force, \( f_r \), the reference position, \( x_r \), is specified into the environment by a constant amount [17], thus, \( \ddot{x}_r = \dot{x}_r = 0 \), and the target impedance model (2) is modified into

\[ m\ddot{x} + b\dot{x} + k(x - x_r) = e \]  

(4)

As has been discussed, the force tracking capability largely depends on the accuracy of the inner position controller. Additionally, problems about the trajectory tracking with or without uncertainties have been proved to be asymptotic stable or globally exponential stable, and have found extensive and successful industrial applications [19]. That is, we can find a position controller which is proved to be asymptotic stable or globally exponential stable even when the uncertainties are considered, given the assumption that the uncertainty be within a bounded value.

As a result, two steps are found to be necessary to guarantee the time-varying force tracking in the framework of position-based impedance control. Trying to minimize the force error \( e \) in (2) or restrict it to a small bounded value, within which the position controller can tolerate (keep stable), is a natural and simple method which is able to contribute to the precision of the inner position controller, so will the force error. Thus, a new force tracking impedance function to accomplish ramp force tracking by employing a PI compensator to eliminate the steady-state error while tracking a ramp force [4], namely, a PI compensator is added to the right side of (4), i.e.

\[ m\ddot{x} + b\dot{x} + k(x - x_r) = k_p e + k_i \int_0^t e \, d\tau \]  

(5)

where \( k_p \) and \( k_i \) are chosen to be positive diagonal constants for system decoupling.

Here, in view of the time delay included in the system mentioned above, we additionally add the differentiation element to the PI compensator to remove oscillation and enhance the system stability. Thus, we have

\[ m\ddot{x} + b\dot{x} + k(x - x_r) = k_p e + k_i \int_0^t e \, d\tau + k_d \dot{e} \]  

(6)

The force tracking performance is believed to be much improved through the above modification, mainly due to the following two reasons:

1) Through routine analysis, (As can also be seen in (8)) it is noted that the three parameters of the introduced PID controller only influence the dominator of the force tracking error, specifically, the parameters \( k_p, k_i, k_d \) merely appear in the dominator of the steady state force tracking error, thus facilitating the zero tracking error.

2) The introduced PID force controller will have a rapid exertion of the force tracking response, rather than waiting to be controlled by the position controller. This is very similar to the idea of cascade control framework, where the added secondary/slave controller has a rapid amendment over the response, and disturbance, of the outer control loop.
For more information about such an improvement, see [18], where the force control method is implemented upon a 2nd order robotic system and more comprehensive illustrations are given.

Assuming the environment to be a linear spring system to mimic the real-time manipulation force, has been a widely adopted method in modeling of the environment by many researchers, that is

\[ f_e = k_e(x - x_e) \]  

(7)

where where \( k_e \) is the environment stiffness and \( x_e \) denotes the location of the undeformed cell surface before injection, we usually assume \( x_e = x_0 \), which considers the case where the manipulator (injector) environment (cell membrane) interaction force is zero.

Substituting (7) and its derivatives into the impedance dynamics equation (6) yields the force error function

\[ E(s) = \frac{(ms^3 + bs^2 + ks)F_r(s) + skkk_s[e_s - X_r(s)]}{ms^3 + (b + k_e k_a)s^2 + (k + k_e k_p)s + k_e k_i} \]  

(8)

Let the reference force input be the twice continuously differential function, which can be regarded as the approximate function of the practical relationship between the injection force and the cell membrane deformation, namely,

\[ f_r(t) = At^2 \]  

(9)

where A is a fixed value which can be specified artificially, and in the following analysis we try to extend the ramp force tracking to any twice continuously differential force trajectory.

Now, we can obtain the steady state force error

\[ e_s = \lim_{s \to 0} s E(s) \]

\[ = \lim_{s \to 0} \frac{(ms^4 + bs^3 + ks^2)\frac{2A}{s} + s^2 k_e k_s[e_s - X_r(s)]}{ms^3 + (b + k_e k_a)s^2 + (k + k_e k_p)s + k_e k_i} \]  

(10)

It is seen that the steady state force error tends to zero only when the numerator of (10) equals zero, namely,

\[ X_r(s) = \frac{2A}{kkk_e} \left( \frac{m}{s} + \frac{b}{s^2} + \frac{k}{s^3} \right) \frac{x_e}{s} \]  

(11)

that is,

\[ x_r(t) = \frac{2A}{k_e k_s} \left( \frac{k}{2} t^2 + bt + m \right) + x_e \]  

(12)

Clearly, the reference trajectory \( x_r \) is the function of both \( k_e \) and \( x_e \). When the environment, here, the cell membrane stiffness, \( k_e \) and environment, \( x_e \), are known a prior, then, we can calculate \( x_r \) which will eventually result in a zero steady state force tracking error.  

Unlike some other manipulation circumstance where the parameters of \( x_e \) and \( k_e \) were both not known perfectly, the environmental location \( x_e \) here was a fixed value which denoted the location of the undeformed cell without any injection force while \( k_e \) was still an inaccurate environment stiffness [13]-[15]. Especially, the cell membrane stiffness \( k_e \) changes at different stages of life. Thus, for the sake of perfect time-varying force tracking, an adaptive algorithm towards uncertain environment should be developed.

III. INDIRECT ADAPTIVE FORCE TRACKING ALGORITHM

We now turn to the development of the indirect adaptive method employed to estimate the environment stiffness online. Assuming the estimated value of the environment stiffness to be \( \hat{k}_e \), we have the estimation of the sensed contact force as

\[ \hat{f}_e = \hat{k}_e(x - x_e) \]  

(13)

where \( \hat{f}_e \) is the prediction of the \( f_e \) based on the current estimate of \( k_e \). It is actually assumed that the variables \( f_e, x, x_e \) are all \( 2 \times 1 \) vectors containing information in both X and Y directions.

We hope to find an update law for \( \hat{k}_e \) that guarantees \( \hat{k}_e \rightarrow k_e \) and thus \( \hat{f}_e \rightarrow f_e \) and eventually \( f_e \rightarrow f_r \) is achieved.

Differencing Equations (13) and (7) yields

\[ \dot{\hat{f}}_e - f = \hat{k}_e(x - x_e) \]  

(14)

where \( \hat{k}_e \) is defined as \( \hat{k}_e = \hat{k}_e - k_e \) and \( x - x_e \) is exact value.

Obviously, this is a linear system and an quadratic function of the uncertain parameter is commonly utilized as the Lyapunov function. Thus, we specify the Lyapunov function as

\[ V = \hat{k}_e^T P \hat{k}_e \]  

(15)

where \( P \) denotes a positive definite matrix. We note that if \( \hat{k}_e \) was

\[ \dot{\hat{k}}_e = -P \hat{k}_e \]  

(16)

then differentiating (15) along (16) leads to the following negative semidefinite function as

\[ \dot{V} = -2 \hat{k}_e^T P \hat{k}_e \]  

(17)

Now, according to (15) and (17), the underlying asymptotically stable conditions for the system (14) is derived, namely,

\[ \begin{cases} 
V = \hat{k}_e^T P \hat{k}_e > 0 \\
\dot{V} = 2 \hat{k}_e^T P \hat{k}_e \leq 0 
\end{cases} \]  

(18)

Thus, as the estimated value \( \hat{k}_e \) is adjusted on-line according to the adaptive law (16), we have \( f_e \rightarrow f_r \) as \( t \rightarrow \infty \).

A straightforward calculation reveals the complete indirect adaptive time-varying force tracking schemes given the reference force trajectory \( f_r = At^2 \) are shown as

\[ x_r(t) = \frac{2A}{k_e k_s} \left( \frac{k}{2} t^2 + bt + m \right) + x_e \]  

(19)

\[ \hat{k}_e(t) = \hat{k}_e(0) - \gamma \int_0^t \frac{\hat{f}_e - f_e}{x - x_e} d\tau \]  

(20)

\[ \hat{f}_e = \hat{k}_e(t)(x - x_e) \]  

(21)

where \( \gamma \) is the update rate.
Substituting (19-21) into (4) yields the desired input trajectory of the inner position controller

\[ x_d = \frac{k_p e + k_i \int_0^t e d\tau + k_d \dot{e} + k x_r(t)}{m s^2 + bs + k} \]  

(22)

where we still assume a perfect position controller which implies \( x \approx x_d \).

Furthermore, to ensure robustness in the presence of the unmodeled effects, a slight modification of the adaption law of (20) can be made using the \( \sigma \)-modification terms [8]. Thus, the improved adaptive law for \( \hat{k}_e \) is given by

\[ \hat{k}_e(t) = \hat{k}_e(0) - \gamma \int_0^t \frac{f_e - f_x}{x - x_e} d\tau - \sigma \int_0^t \hat{k}_e(t) d\tau \]  

(23)

where \( \sigma \) is small positive constant.

IV. SYSTEM MODELING AND TRAJECTORY TRACKING

The newly developed automatic cell injection system [13] is chosen as the experimental setup of our research for its advantage of obtaining a single joint manipulator, which means the transformations between the Cartesian space and the joint space can be removed, i.e., the forward kinematics and the inverse kinematics operations are removed.

In view of the target system model depicted as

\[ M(x)\ddot{x} + N(x, \dot{x}) \dot{x} = \tau - f_e \]  

(24)

Trajectory control of the manipulator is performed by a feedforward torque controller, which is given by

\[ \tau = M(x)\ddot{x}_d + N(x, \dot{x}) \dot{x}_d + f_e + K_p e + K_i \int_0^t e d\tau + K_d \dot{e} \]  

(25)

where \( K_p, K_i \) and \( K_d \) are suitably chosen gains of the PID controller, and \( e = x_d - x \) denotes position error of the inner position controller. The nonlinear feedforward terms, \( M(x)\ddot{x}_d + N(x, \dot{x}) \dot{x}_d \), are used to cancel the nonlinear effects of \( M(x)\ddot{x} \) and \( N(x, \dot{x}) \dot{x} \) in the robot’s dynamics and result in a nearly uncoupled linear manipulator system.

However, a shortcoming of feedforward control is the requirement of precise knowledge of the system dynamics, which is often a difficult work in practice. On the basis of large amount of simulations and the consideration of practical feasibility, we observe that a modification to the method introduced in (25) could achieve good performance in trajectory tracking, that is,

\[ \tau = K_p e + K_i \int_0^t e d\tau + K_d \dot{e} + f_e \]  

(26)

Clearly, this method is a nonlinear PID controller to which the external force \( f_e \) is added as a feedforward term while the first two terms in (25) are removed. Compared with the traditional PID controller and the PID plus feedforward controller, the nonlinear PID controller (26) does not necessitate an exact model of the manipulator system and simultaneously, the interaction force, \( f_e \), is also removed without causing external disturbance to the inner trajectory controller. Stability analysis of the nonlinear PID controller is omitted in this article, and relative theoretical analysis can turn to [19].

V. SIMULATION

To verify the effectiveness of the proposed control algorithm, simulations of force tracking performance are performed on a newly developed automatic cell injection setup [13]. It is assumed that the initial position to be \( x_0 = x_c = 0.05 \), and the adaptive law \( \gamma = 5 \), the reference force \( f_r = -36\dot{x}^2N \). Then, simulations about trajectory tracking, online estimation of \( k_e \), time-varying force tracking and parameters selection are conducted, respectively.

A. Trajectory tracking

First, a series of simulations are implemented to verify the effectiveness of the proposed position algorithm. Three control methods: PID, PID plus feedforward compensation and the proposed nonlinear PID controller are carried out, respectively, to show their effects in trajectory tracking. Before simulation, we choose the parameters of the impedance controller to be: \( m = 10, b = 40, k = 40 \), which represents a critically damped (\( \zeta = 1 \)) second-order manipulator-environment system.

Figure 2 illustrates the different performance of the three controllers: a traditional PID controller without any feedback terms depicts the worst performance and the position error is
almost proportional to the desired trajectory. As to the PID plus feedforward compensation controller, proposed in (25), executes a better performance compared with the traditional PID algorithm, and we can see from Figure 2 that the position error is largely reduced, however, its defect is also evident in that the steady-state position error is unable to converge to zero. As expected, the proposed nonlinear position controller in (26) presents strong capability in position tracking and its relative position tracking error converges to zero within a short time, about less than 0.5 second. Thus, the proposed nonlinear PID controller exhibits good performance in position tracking, not only lies in its robustness to external force when compared with the traditional PID controller, but also in its computationally attractive feature as compared to the PID plus feedforward compensation algorithm.

B. Online identification of \(k_e\) and \(f_e\)

Figure 3 illustrates the online identification of the environment stiffness \(k_e\), and large amount of simulation tests show that a small value of the update rate \(\gamma\), will lead to a slow identification of the parameter \(k_e\), and eventually a slow and bad response of cell injection force tracking. Through a serious of tests, we initially specify \(\gamma = 5\) and have the following identification figure which depicts a quick identification response so that an acceptable force tracking error can be achieved.

On the basis of the estimated values of \(k_e\) and equation (13), the online estimated value of the actual sensed injection force \(f_e\), is given in Figure 4. Corresponding to the identification of \(k_e\) in Figure 3, the estimated value \(f_e\) is able to track the actual injection force \(f_e\) within about 1 sec, just as the time of perfect identification of \(k_e\) shown in Figure 3.

Consequently, the proposed adaptive law works well in identifying the time-varying environment stiffness, and correspondingly, exhibits good performance in approaching the real contact force \(k_e\) and the eventually, the desired injection force \(f_r\).

C. Time-varying force tracking

In this section, force control towards the twice continuously differential function and comparisons of force control performance between different target impedance controllers are presented.

The parameters of the impedance parameters are specified as \(m = 1, b = 600, k = 5000\) and the reference force is set to be \(f_r = 36t\). The two improved models of the target impedance function, model (5) presented in [4] and the model (6) proposed in this paper, are implemented to track the reference ramp force signal, as shown in Figure 5 and Figure 6. Clearly, it can be seen from the force control performance that the impedance model (5) is capable to track the reference ramp force, which is depicted by the actual force 2 in Figure 5, while sustained oscillation is also observed when model (5) is applied and undesired oscillations can be also found in force tracking error, which are respectively drawn by the actual force 1 and force error 1 in Figure 5 and Figure 6. A similar or even worse force-tracking phenomenon, which means an unstable system induced from large hunting, can also be viewed in Figure 7 and Figure 8, where the reference force is defined as \(f_r(t) = -36t^2\) and the impedance parameters are \(m = 20, b = 20, k = 40\).

It is obviously pictured by the actual force in Figure 7 that the impedance model (5) without differential part exhibits poor force-tracking performance: the increasingly enhanced oscillations as time goes by. While once a differential part is added into the force error regulator as proposed in this article, excellent performance in time-varying force-tracking is obtained, as shown by the dashed line in the Figures 7 and
8. Results in Figures 5-8 announce such a phenomenon that the proposed target impedance model in this paper performs much better performance in time-varying force tracking. This is expected results for which only the proportional and integral roles are insufficient when confronted with a system that contains inertia or delay elements, and thus, in order to remove the oscillations, the differentiation element of a traditional PID controller is naturally introduced as an indispensable part to produce a stabilized control system.

VI. CONCLUSIONS

In order to meet the time-varying injection force, an improved position-based impedance controller is systematically discussed and proposed. A nonlinear PID controller that can accurately and rapidly position the end-effector is developed, which lays a foundation for the time-varying force regulating in impedance control. An adaptive impedance algorithm coping with the uncertain environment stiffness is proposed and the relative stability analysis is also provided. Finally, simulations are performed to verify the effectiveness of the proposed methods both in position tracking and force control.

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