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Design of Open-Closed-Loop Iterative Learning Control With Variable Stiffness for Multiple Flexible Manipulator Robot Systems

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ABSTRACT An open-closed-loop iterative learning method for multiple flexible manipulator systems with repeatable motion tasks was proposed to achieve the consensus tracking of a specified desired reference trajectory. The open-closed-loop iterative learning control scheme was used to reduce the effects of model error and disturbances, as the boundedness of both the tracking error and the control input can be simultaneously guaranteed. In addition, when combined with a novel rotational joint with a continuously adjustable stiffness, the open-closed-loop iterative learning method enhances the adaptability to meet the strict requirements of the next generation of robots with the physical human–robot interaction and highly dynamic motion. The convergence conditions of the approach were obtained by the theoretical analysis. The simulation results show that this control algorithm has a good tracking accuracy and a fast convergence rate when used in the high-precision trajectory control for robots.

INDEX TERMS Multiple flexible robot, open-closed-loop, iterative learning control, stiffness adjustment.

I. INTRODUCTION

Multiple flexible manipulator systems [1], [2] are superior to rigid manipulator systems [3]–[6] in terms of reduced inertia, power consumption, payload to weight ratio and manipulation speed. Flexible connections composed of mechanical springs [7]–[9] will vibrate inevitably during motion, which makes the accurate motion control of multiple flexible manipulator systems more difficult. Hence, the control design problem of multiple flexible manipulator systems has attracted considerable attention and interest in recent years. Many researchers [10], [11] have followed different approaches to control multiple flexible robot arms, which is a significant and challenging problem. Because of the flexible nature and distributed characteristics of multiple flexible manipulator systems, the dynamics are highly nonlinear and complex. Problems arise owing to non-minimum phase characteristics, vibrations due to system flexibility and precise positioning requirements. Li [12] proposed a system with a Lagrange modality assumption for the effective modelling and dynamic calculation of flexible manipulators. Eflychios [13] used the Lagrange formula and Hamilton principle to study flexible arms in depth. Ulrich *et al.* [14] built an accurate nonlinear flexible joint model and applied the design method of singular perturbation theory to flexible joint arms.

Iterative learning control (ILC) [15]–[18] can be used for implementing repetitive control, which can predict the future information of complex robotics systems by using the system input and output of previous trials. Many ILC-based control schemes for flexible manipulators have been reported in the literature [19]–[21]. Wang [22] considered the joint flexibility of the robot and designed an iterative learning controller. By means of the iterative learning method, Qu [23] obtained the boundary control conditions of a flexible manipulator system. Liu and Liu [24] proposed a new ILC law based on a prescribed performance bound to track the desired trajectory and suppress the vibration of the elastic deflection of a flexible manipulator. Gunnarsson *et al.* [25] used an estimate of the flexible arm angle by ILC and found that the controller is robust and has good control effects. The combination of ILC with the open-closed-loop control law [26]–[28] has been reported in the literature [29]–[31]. Over a wide range of operating conditions, open-closed-loop ILC controllers are robust, simple in structure and easy to implement.

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For multiple flexible manipulators, closed-loop and open-loop control techniques are used for position control and vibration suppression, respectively. However, the performance of fixed stiffness coefficient joint controllers [32]–[34] is limited in real-time operations of robot motion control. This paper thus proposes a variable stiffness coefficient flexible joint to achieve both rigid-body and flexible motion control in flexible manipulator systems. The system can constantly change the elastic stiffness and show different forces to the outside. At the same time, the joint can absorb, store or release energy to improve the energy efficiency and reduce the vibrations of an object in contact with the robot manipulator.

In this study, it is the first time that a collaboration of multiple flexible manipulator with a variable stiffness coefficient performing a repetitive task is considered. This paper presents investigations into the development of an open-closed-loop ILC scheme using a continuously adjustable stiffness for the optimization of the end-point vibration suppression and output tracking of a multiple flexible manipulator system.

This paper is organized as follows. In Section II, a dynamic model of multiple flexible manipulator system is presented. In Section III, a novel design of variable stiffness in the articular spring is proposed. The control is designed and the convergence analysis is provided in Section V. In Section VI, a comparative study of the simulation is presented to verify the effectiveness and robustness of the control strategy. Finally, conclusions are drawn in Section VII.

II. DYNAMIC MODEL OF A MULTIPLE FLEXIBLE MANIPULATOR SYSTEM

A multiple flexible manipulator system is composed of m manipulators holding a solid body in free operating space. The dynamic equation of the m manipulators is given by

$$M(q)\ddot{q} + H(q,\dot{q}) + G(q) + K_\Delta q = U + d \tag{1}$$

where $q_j \in R^n$ is the vector of the joint coordinates, $\dot{q}_j \in R^n$ is the velocity vector, $\ddot{q}_j \in R^n$ is the acceleration vector, $M_j(q_j) \in R^{n\times n}$ is the inertia matrix of the manipulator, $H_j(q_j, \dot{q}_j) \in R^{n\times n}$ is the matrix of the Coriolis and centripetal torques, $G_j(q_j) \in R^n$ is the gravitational vector, $K_{\Delta j} \in R^n$ is the variable stiffness elastic matrix of the articular spring, $U_j \in R^n$ is the input vector, which can improve the dynamic control accuracy of the mechanical hand control, and $d_j \in R^n$ is the unknown external disturbance, i.e. The vector of forces exerted on the object by the end-effector of the j-th manipulator, $j = 1, 2, \ldots, m$, where $M(q) = \mathrm{diag}(M_1(q_1), M_2(q_2), \cdots, M_m(q_m))$;

$$\begin{aligned} K_\Delta &= \left(K_{\Delta 1}^{\mathrm{T}}, K_{\Delta 2}^{\mathrm{T}}, \cdots, K_{\Delta m}^{\mathrm{T}}\right)^{\mathrm{T}}; \\ H(q,\dot{q}) &= \mathrm{diag}\Big(H_1(q_1,\dot{q}_1)^{\mathrm{T}}, H_2(q_2,\dot{q}_2)^{\mathrm{T}}, \cdots, \\ &\qquad H_m(q_m,\dot{q}_m)^{\mathrm{T}}\Big)^{\mathrm{T}} \\ G(q) &= \left(G_1(q_1)^{\mathrm{T}}, G_2(q_2)^{\mathrm{T}}, \cdots, G_m(q_m)^{\mathrm{T}}\right); \\ U &= \left(U_1^{\mathrm{T}}, U_2^{\mathrm{T}}, \cdots, U_m^{\mathrm{T}}\right)^{\mathrm{T}}; d = \left(d_1^{\mathrm{T}}, d_2^{\mathrm{T}}, \cdots, d_m^{\mathrm{T}}\right)^{\mathrm{T}}. \end{aligned}$$

Considering the k-th iteration, the dynamic equation of the whole system can be expressed as

$$M\left(q^k\right)\ddot{q}^k + H\left(q^k, \dot{q}^k\right) + G\left(q^k\right) + K_\Delta q^k = U^k + d^k \tag{2}$$

where $k = 1, 2, \ldots$ represents the iterations.

Definition 1: The error of the flexible manipulator is

$$e^k(t) = q^d(t) - q^k(t) \tag{3}$$

where $q^d(t)$ is the given desired output trajectory.

Definition 2: It is important to introduce the Lambda norm. The Lambda norm for a function is defined as:

$$\|*\|_\lambda = \sup\left[e^{-\lambda t}\|*\|\right](* \in R^n) \tag{4}$$

where $\lambda > 0$. The λ-norm is defined to simplify the formula.

$$\begin{aligned} Let\ \|f(x)\|_{\tilde{m}} &= \max_x(\|f(x)\|), e^k = q^d - q^k, \\ \dot{e}^k &= \dot{q}^d - \dot{q}^k, \ddot{e}^k = \ddot{q}^d - q^k. \end{aligned}$$

Assumption 1: For the governing equation for the multiple flexible manipulator system (1) if $M(q)$, $H(q,\dot{q})$, and $G(q)$ satisfy the Lipschitz condition,

$$\begin{aligned} \left\|M^{-1}(x) - M^{-1}(y)\right\| &\le m\|x-y\|, x,y \in S \\ \|H(x,\dot{x}) - H(y,\dot{y})\| &\le h_1\|x-y\| + h_2\|\dot{x}-\dot{y}\|, x,y \in S \\ \|K_\Delta x - K_\Delta y\| &\le \tilde{k}_\Delta\|x-y\|, x,y \in S \\ \|G(x) - G(y)\| &\le g\|x-y\|, x,y \in S \\ \|d(x) - d(y)\| &\le w\|x-y\|, x,y \in S \end{aligned} \tag{5}$$

where S is the possible state domain space of the manipulator, $m, h_1, h_2, \tilde{k}_\Delta, g, w$ are finite positive numbers.

Assumption 2: For input U^{k+1}, U^k, the system state satisfies

$$\begin{aligned} \left\|q^{k+1} - q^k\right\| &\le \int_0^t a\left\|U^{k+1} - U^k\right\| \mathrm{d}f \\ \left\|\dot{q}^{k+1} - \dot{q}^k\right\| &\le \int_0^t b\left\|U^{k+1} - U^k\right\| \mathrm{d}f \end{aligned} \tag{6}$$

where $a > 0$, $b > 0$ are finite positive numbers.

III. THE DESIGN OF VARIABLE STIFFNESS IN THE ARTICULAR SPRING

Let k^Δ be the spring stiffness, L be the original length of the spring, and l be the pretensioning length of the spring at equilibrium. The rotational stiffness of the system K_Δ is

$$K_\Delta = \frac{k^\Delta l}{l+L} \tag{7}$$

If l is large, the rotational stiffness of the joint becomes large; if l is small, the rotational stiffness becomes small. The elastic stiffness of the joint is regulated by changing the effective working length of the elastic element. Meanwhile, the joint stiffness presents nonlinear characteristics. As the joint spring can deform with in only a limited range, K_Δ can

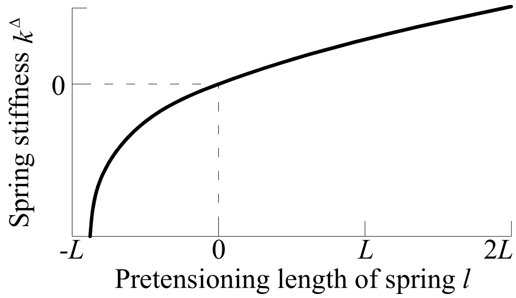

FIGURE 1. Stiffness characteristics for variable stiffness in the articular spring.

be adjusted within only a limited range, and the limit is determined by the maximum compressible amount and maximum tensile amount. The efficiency of the robot in different motion states can be enhanced and the adaptability of the robot can be improved by adjusting the stiffness of the flexible arm joints.

IV. DESIGNED CONTROLLER AND CONVERGENCE ANALYSIS

The open-closed-loop ILC law of the multiple flexible manipulator is

$$U^{k+1}(t) = U^k(t) + M\left(q^{k+1}\right)\ddot{e}^{k+1} + M\left(q^k\right)\ddot{e}^k + K_D\dot{e}^{k+1} + K_D\dot{e}^k + K_P e^{k+1} + K_P e^k \tag{8}$$

where K_D, K_P are control gain matrices.

Theorem: The sufficient convergence conditions of the ILC algorithm are

$$\left\|\frac{I - MM^{-1}\left(q^k\right)}{I + MM^{-1}\left(q^k\right)}\right\| \le d < 1 \tag{9}$$

Then, we can reasonably choose a group control parameter to reach the conclusion of this theorem: $\lim_{k\to\infty}\left\|e^k\right\| \to 0$and $\lim_{k\to\infty}\left\|q^d(t) - q^k(t)\right\| \to 0.$

Proof: From (2), we obtain

$$\ddot{q}^{k+1} = M^{-1}\left(q^{k+1}\right)\left[-H\left(q^{k+1}, \dot{q}^{k+1}\right) - G\left(q^{k+1}\right) - K_\Delta q^{k+1} + U^{k+1} + d^{k+1}\right] \tag{10}$$

$$\ddot{q}^k = M^{-1}\left(q^k\right)\left[-H\left(q^k, \dot{q}^k\right) - G\left(q^k\right) - K_\Delta q^k + U^k + d^k\right] \tag{11}$$

Multiplying both sides of M and inserting $e^k = q^d - q^k, \dot{e}^k = \dot{q}^d - \dot{q}^k, \ddot{e}^k = \ddot{q}^d - q^k$ yields

$$\begin{aligned}
&\left[M\ddot{e}^{k+1} + K_D\dot{e}^{k+1} + K_P e^{k+1}\right] \\
&= \left[M\ddot{e}^k + K_D\dot{e}^k + K_P e^k\right] - K_D\left(\dot{q}^{k+1} - \dot{q}^k\right) \\
&\quad - K_P\left(q^{k+1} - q^k\right) - MM^{-1}\left(q^k\right)\left[U^{k+1} - U^k\right] \\
&\quad + M\left[M^{-1}\left(q^k\right) - M^{-1}\left(q^{k+1}\right)\right]\left[-H\left(q^{k+1}, \dot{q}^{k+1}\right)\right. \\
&\quad \left. - G\left(q^{k+1}\right) - K_\Delta q^{k+1} + U^{k+1} + d^{k+1}\right] \\
&\quad + MM^{-1}\left(q^k\right)\left[H\left(q^{k+1}, \dot{q}^{k+1}\right) + G\left(q^{k+1}\right) + K_\Delta q^{k+1}\right. \\
&\quad \left. + d^{k+1} - H\left(q^k, \dot{q}^k\right) - G\left(q^k\right) - K_\Delta q^k - d^k\right]
\end{aligned} \tag{12}$$

Inserting (8) into (11) gives

$$\begin{aligned}
&\left[I + MM^{-1}\left(q^k\right)\right]\left[M\ddot{e}^{k+1} + K_D\dot{e}^{k+1} + K_P e^{k+1}\right] \\
&= \left[I - MM^{-1}\left(q^k\right)\right]\left[M\ddot{e}^k + K_D\dot{e}^k + K_P e^k\right] \\
&\quad - K_D\left(\dot{q}^{k+1} - \dot{q}^k\right) - K_P\left(q^{k+1} - q^k\right) \\
&\quad + M\left[M^{-1}\left(q^k\right) - M^{-1}\left(q^{k+1}\right)\right]\left[-H\left(q^{k+1}, \dot{q}^{k+1}\right)\right. \\
&\quad \left. - G\left(q^{k+1}\right) - K_\Delta q^{k+1} + U^{k+1} + d^{k+1}\right] \\
&\quad + MM^{-1}\left(q^k\right)\left[H\left(q^{k+1}, \dot{q}^{k+1}\right) + G\left(q^{k+1}\right) + K_\Delta q^{k+1}\right. \\
&\quad \left. + d^{k+1} - H\left(q^k, \dot{q}^k\right) - G\left(q^k\right) - K_\Delta q^k - d^k\right]
\end{aligned} \tag{13}$$

After taking the norm of both sides of (12), **Assumption 1** yields

$$\begin{aligned}
&\left\|M\ddot{e}^{k+1} + K_D\dot{e}^{k+1} + K_P e^{k+1}\right\| \\
&\quad \le \left\|\frac{I - MM^{-1}\left(q^k\right)}{I + MM^{-1}\left(q^k\right)}\right\|\left[M\ddot{e}^k + K_D\dot{e}^k + K_P e^k\right] \\
&\qquad + \rho 1\left\|q^{k+1} - q^k\right\| + \rho 2\left\|\dot{q}^{k+1} - \dot{q}^k\right\| \\
&\quad \le \left\|\frac{I - MM^{-1}\left(q^k\right)}{I + MM^{-1}\left(q^k\right)}\right\|\left[M\ddot{e}^k + K_D\dot{e}^k + K_P e^k\right] \\
&\qquad + \rho\int_0^t\left\|U^{k+1} - U^k\right\| dt
\end{aligned} \tag{14}$$

where $\rho = \rho 1 * a + \rho 2 * b$, $\rho 2 = \frac{\|K_D\| + h_2\left\|MM^{-1}\left(q^k\right)\right\|_{\tilde{m}}}{\left\|I + MM^{-1}\left(q^k\right)\right\|}$,

$$\begin{aligned}
\rho 1 &= \frac{\|K_P\| + \left\|MM^{-1}\left(q^k\right)\right\|_{\tilde{m}}\left(h_1 + g + w + \tilde{k}_\Delta\right)}{\left\|I + MM^{-1}\left(q^k\right)\right\|} \\
&\quad + \frac{m\|M\|_{\tilde{m}}\left(\|H\|_{\tilde{m}} + \|G\|_{\tilde{m}} + \|K_\Delta\|_{\tilde{m}} + \left\|U^{k+1}\right\|_{\tilde{m}} + \left\|d^{k+1}\right\|_{\tilde{m}}\right)}{\left\|I + MM^{-1}\left(q^k\right)\right\|}
\end{aligned}$$

We define $\|f(x)\|_{\tilde{m}} = \max_x(\|f(x)\|)$. Multiplying both sides of (13) by $e^{-\lambda t}$ to compute the λ-norm gives

$$\begin{aligned}
&\exp(-\lambda t)\left\|M\ddot{e}^{k+1} + K_D\dot{e}^{k+1} + K_P e^{k+1}\right\| \\
&\le \exp(-\lambda t)\left\|\frac{I - MM^{-1}\left(q^k\right)}{I + MM^{-1}\left(q^k\right)}\right\|\left[M\ddot{e}^k + K_D\dot{e}^k + K_P e^k\right] \\
&\quad + \rho\int_0^t \exp(-\lambda(t - f))\left\|M\ddot{e}^k + K_D\dot{e}^k + K_P e^k\right\| \\
&\quad * \exp(-\lambda f)\, df
\end{aligned} \tag{15}$$

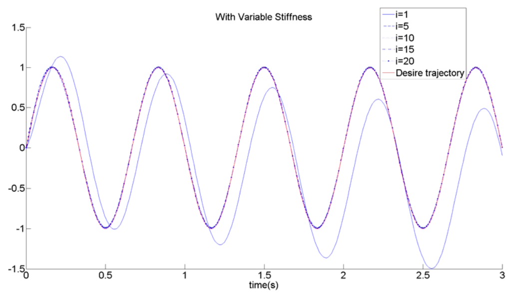

FIGURE 2. Trajectory tracking of the first joint in the iterative operation process.

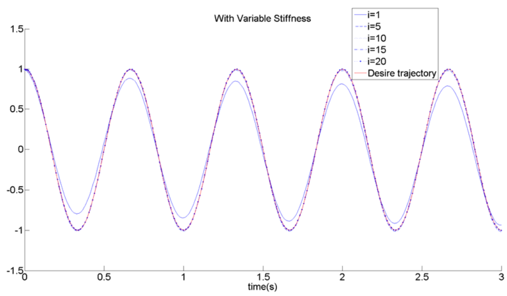

FIGURE 3. Trajectory tracking of the second joint in the iterative operation process.

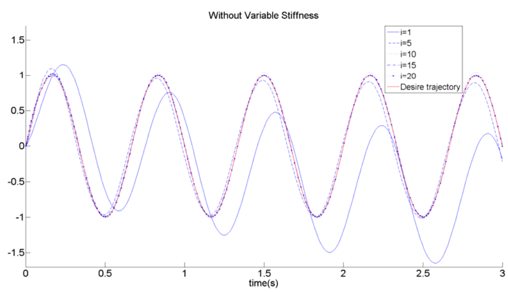

FIGURE 4. Trajectory tracking of the first joint in the iterative operation process.

Then, (15) implies

$$\left\|M\ddot{e}^{k+1}+K_D\dot{e}^{k+1}+K_Pe^{k+1}\right\|_\lambda \le \left[\left\|\frac{I-MM^{-1}\left(q^k\right)}{I+MM^{-1}\left(q^k\right)}\right\|+\frac{\rho}{\lambda}\left(1-\exp\left(-\lambda t\right)\right)\right] * \left\|M\ddot{e}^{k}+K_D\dot{e}^{k}+K_Pe^{k}\right\|_\lambda \quad (16)$$

When the conditions $\left\|I–MM^{-1}\left(q^k\right)/I+MM^{-1}\left(q^k\right)\right\| < 1$ is satisfied, we can find a sufficiently large positive number λ, and we obtain $\left[\left\|I-MM^{-1}\left(q^k\right)/I+MM^{-1}\left(q^k\right)\right\|+ \rho/\lambda\left(1-\exp\left(-\lambda t\right)\right)\right] < 1$. Then, we have $\lim_{k\to\infty}\left\|M\ddot{e}^k +K_D\dot{e}^k+K_Pe^k\right\|_\lambda \to 0$. Therefore, we can choose a reasonable group control parameter to reach the conclusions of this theorem: $\lim_{k\to\infty}\left\|e^k\right\| \to 0$ and $\lim_{k\to\infty}\left\|q^d\left(t\right)-q^k\left(t\right)\right\| \to 0$.

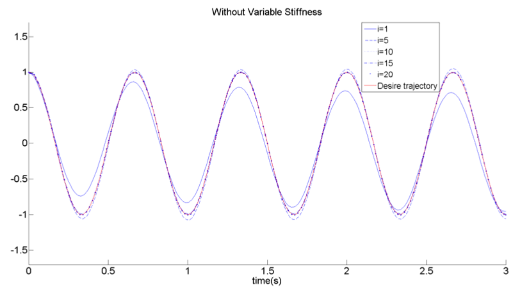

FIGURE 5. Trajectory tracking of the second joint in the iterative operation process.

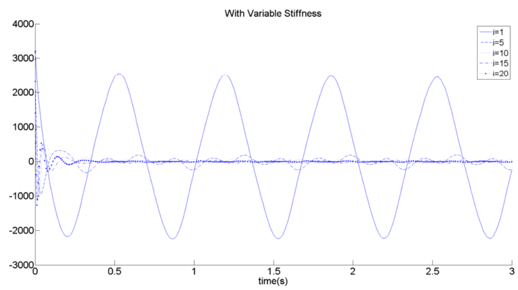

FIGURE 6. Control input trajectories of the first joint with variable stiffness by ILC.

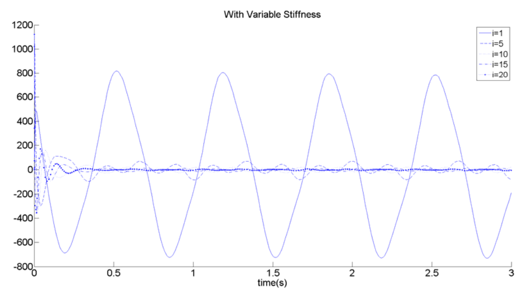

FIGURE 7. Control input trajectories of the second joint with variable stiffness by ILC.

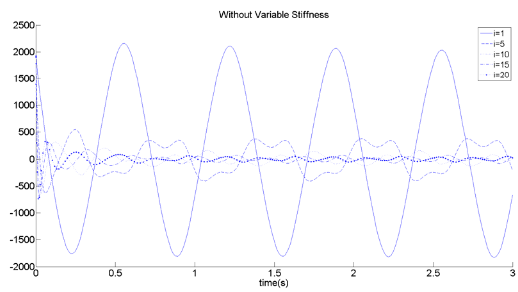

FIGURE 8. Control input trajectories of the first joint without variable stiffness by ILC.

V. SIMULATION

For illustration purposes, the proposed control algorithm (8) is applied to the coordinated manipulation of two planar flexible robot manipulators holding a common object. Each mechanical arm of the multiple flexible manipu-

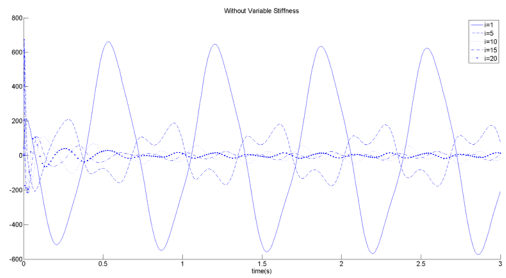

FIGURE 9. Control input trajectories of the second joint without variable stiffness by ILC.

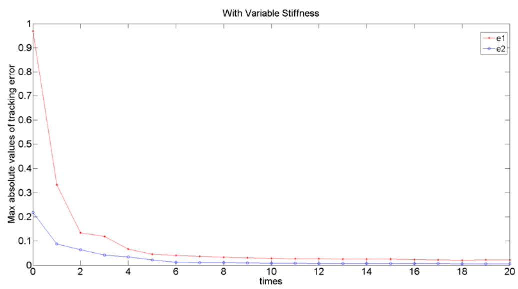

FIGURE 10. Maximum absolute tracking error with variable stiffness in each iteration.

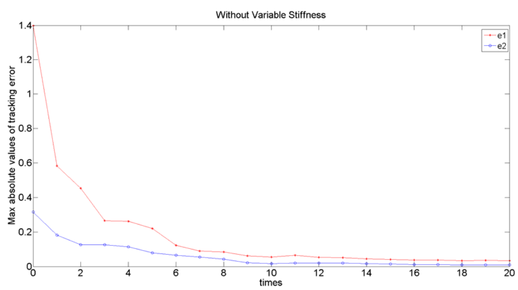

FIGURE 11. Maximum absolute tracking error without variable stiffness in each iteration.

lator system has the same dynamic characteristics. The desired reference trajectory of each mechanical arm is $q(t) = \left[\sin 3\pi t \ \cos 3\pi t\right]^{\mathrm{T}}$, and the initial state is $x(0) = \left[0\ 3\ 1\ 0\right]^{\mathrm{T}}$. The lengths of the manipulator links are $l_1 = l_2 = 1\mathrm{m}$, $m_1 = 10$, $m_2 = 5$, $K_D = \mathrm{diag}(250, 250)$, $K_P = \mathrm{diag}(50, 50)$, $L = 0.05\mathrm{m}$ and $k^{\Delta} = \mathrm{dig}\,[9.15]\ \mathrm{N \cdot m/rad}$. The interference of the j-th mechanical arm is $d_j(t) = \left[0.3 \sin t \ \ 0.1\left(1\text{-}e^{-t}\right)\right]^{\mathrm{T}}$.

Notably, the proposed ILC controller with variable stiffness is capable of reducing the system vibration while achieving better manipulator tracking performance. An improvement in the performance of ILC with variable stiffness compared to ILC without variable stiffness is observed in Figs. 2–5. The reference trajectory and actual trajectory of the proposed ILC controller with variable stiffness after 20 iterations are shown in Fig. 2 and Fig. 3, which show that the tracking error is extremely small. Furthermore, the proposed controller is robust to disturbances. Figs. 6–9 present the two control inputs of the two joints. The control input trajectories of the proposed controller are smoother than those using the other traditional control algorithm. In Fig. 10 and Fig. 11, the tracking error of the multiple flexible manipulator system with ILC continues decreasing as the number of iterations increases. The proposed controller has a high convergence speed compared with the traditional controller, as the error norm drops rapidly to 0.03 in 6 iterations, which drastically reduces the tracking lag. As demonstrated in the simulation diagrams, an observably better response is obtained with the proposed ILC controller with variable stiffness.

VI. CONCLUSION

An open-closed-loop ILC algorithm is developed to achieve the trajectory tracking of an end-effector directly for the consensus problem of multiple flexible manipulator systems in which a variable-stiffness actuator is used. A dynamic mathematical model of a multiple flexible manipulator robot is derived from the Lipschitz conditions and Lagrange equations. The simulation results demonstrate that the proposed method is effective for obtaining exact output tracking for a multiple-flexible manipulator system. This approach is expected to perform equivalently well for other flexible manipulator systems. The experiments on the control method presented in this paper are currently being conducted.

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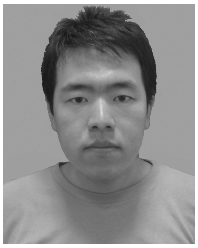

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