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Online Reference Shaping with End-point Position Feedback for Large Acceleration Avoidance on Manipulator Control

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***Abstract*— A nonlinear reference shaping method for manipulators which are operated in living environments is proposed. It generates an intermediate reference position, and it is combined with a control based on the virtual spring-damper hypothesis proposed by Arimoto et al. The initial acceleration is moderated by an intermediate reference position inserted between the original target and the current position of the manipulator's endpoint and by a second-order-lag filter. The endpoint position is fed back to the proposed controller to prevent from excessive trailing force and large acceleration. As the result, human-like smooth reaching motions and pliant behaviors against external forces are achieved. The validity of the proposed method is shown through computer simulations on a planar 4-DOF manipulator.**

I. Introduction

In this study, we propose a control method on short and medium-range reaching motions of manipulators which moderates the initial acceleration of the manipulators and realizes human-like smooth endpoint speed profiles. The motions of the manipulator become pliant against external forces applied to the manipulator, and accurate reaching motions without large accelerations are realized when the external force is removed.

On the control of the manipulators which are operated in living environments, unlike industrial applications, it should be considered how to deal with unexpected external forces, cooperate with a human or humans and generate human-friendly motions. To realize pliant motions against the external force, the motions should be generated based on the feedback control without explicitly including time notion, different from the traditional method which generates target trajectories from given desired hand position and target arrival time. In human's unconstrained reaching motions, it is well known that the paths of the hand are roughly straight and the hand speed profiles are bell-shaped[1]. In considering the manipulator operation in human living environments, it is strongly desired to realize human-like smooth reaching motions with such endpoint speed profiles.

For these problems, Arimoto et al.[2] have proposed the control method for a redundant manipulator based upon the *virtual spring-damper hypothesis*, in which a control signal plays the role of a parallel pair of mechanical damper and spring that draws its endpoint to the target position so as to realize reaching motions without explicitly including time notion. This control method can generate reaching motions without planning trajectories, and solve the ill-posedness of inverse kinematics by introducing joint damping factors. However, this method cannot generate human-like smooth motions because the acceleration is theoretically maximized at the start of the motion. To realize bell-shaped endpoint speed profiles on this virtual spring-damper hypothesis, Sekimoto et al.[3] have proposed the *time-variable stiffness*, in which a spring stiffness is changed by using the gamma distribution as a function of time. Unfortunately, this method explicitly includes time notion so that it is difficult to realize the pliant motions in the existence of the external forces.

A nonlinear reference shaping method is proposed in this study to generate human-like smooth reaching motions without planning trajectories and explicitly including time notion. An intermediate reference position is generated and inputted to the virtual spring-damper system as the equilibrium point of the system so as to moderate the acceleration of the manipulator and realize bell-shaped endpoint speed profiles. It also makes the motion pliant against external forces by feeding the current endpoint position of the manipulator back to the reference shaping controller. The manipulator can generate the appropriate reaching motion without causing a large acceleration after the removal of the force.

This paper presents the related work in section II. The proposed reference shaping method with a current endpoint position feedback is described in section III, and computer simulations which are performed to illustrate the validity of the proposed method are presented in section IV. Finally, some concluding remarks are drawn in section V.

II. Related Works

An abundance of research has been accomplished to measure and analyze the human's reaching motions.

Abend et al.[1] investigated that the paths of the hand are roughly straight and the hand speed profiles are bell-shaped in human's unconstrained reaching motions on horizontal plane. Unconstrained human reaching trajectories on vertical plane were explored by Atkeson and Hollerbach[4], and they found that the hand paths were sometimes curved and the hand speed profiles were always bell-shaped despite the change of subjects, reaching ranges and payloads. Based on these findings, some researchers formulated the mathematical models of the human's reaching motions such as minimum hand jerk model[5], minimum joint torque-change model[6]

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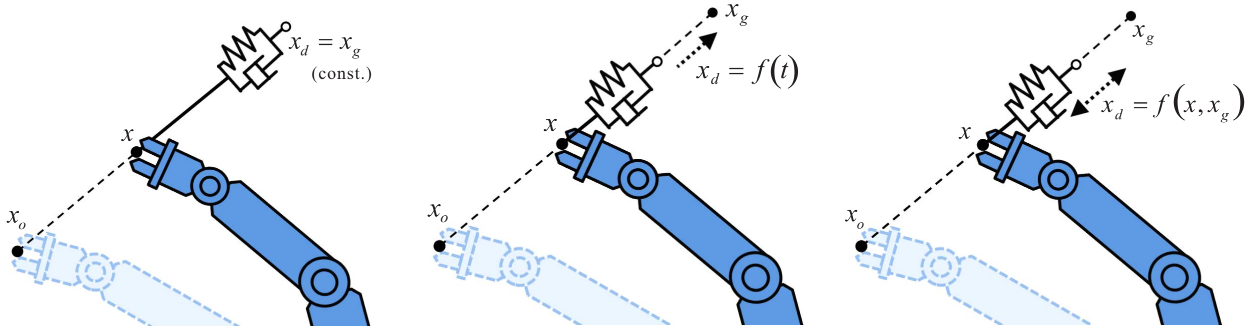


(a) Conventional Virtual Spring-Damper (b) Trajectory Tracking with Impedance (c) Proposed Online Reference Shaping

Fig. 1. Overview of Virtual Spring-Damper, Trajectory Tracking with Impedance & Online Reference Shaping

and so on. Svinin et al.[7] proposed the modified minimum hand jerk model in which the boundary conditions were reformulated using the concept of natural boundary conditions. Based on these mathematical models, human-like reaching motions could be obtained by planning the hand trajectories. However, these control methods need the target arrival time. The explicit inclusion of time-depending terms in motion control is not suitable for manipulators operating in living environments in which a lot of uncertainties such as external forces caused by collisions with obstacles and cooperations with humans are included. These external forces induce the manipulator's endpoint constraints, and unexpected motions with large acceleration might be generated when the constraints are removed.

To avoid such possible hazardous motions, the reaching motions should be generated not based on trajectory-planning but feedback control methods such as *virtual spring-damper hypothesis*[2], [3]. Tsuji et al.[8] proposed a trajectory generation method based on an artificial potential field approach combining a time scale transformation and a *time base generator* (TBG), which generates a time-series with a bell-shaped velocity profile. Although this method can generate human-like reaching trajectories and bell-shaped hand speed profiles for nonholonomic-constrained manipulators, the TBG explicitly includes the time notion.

There are some control methods for preventing large accelerations and position/velocity overshoots under the existence of external forces. With traditional trajectory-planning methods, the manipulator could generate pliant motions against temporal external forces by having compliance characteristic on its endpoint. This method cannot be implemented when the force is applied over an extended period of time, and the convergence performance to target endpoint position will be significantly decreased because of its compliancy. Gerelli and Bianco[9] proposed an online trajectory scaling filter to consider torque and torque-derivative bounds for manipulator control. However, some preliminal trajectory planning processes are required with this method.

To realize both the appropriate position control during normal operations and recovering from large positional errors without overshoots and vibrations, Kikuuwe et al.[10] extended a PID control approach to the *proxy-based sliding mode control* (PSMC), which is a modified version of a sliding mode control. PSMC was modified by Kikuuwe et al.[11], so that it can deal with an arbitrary magnitude limit on the velocity. For service robot applications, Broquère et al.[12] proposed the soft motion trajectory planner which can set the limitations in jerks, accelerations and velocities of the manipulator based on three elementary motions. These methods need to divide the state space which contributes to increased complications in controller design and we also might encounter the frame problems.

The proposed method can generate human-like smooth reaching motions without generating trajectories and including time notion explicitly, and it can realize the pliant motions against external forces without deteriorating the convergence performance to the desired endpoint position. Moreover, there is no need for dividing the state space to prevent large accelerations.

III. Nonlinear Reference Shaping with End-point Position Feedback

Let us consider an m-joint manipulator and a task coordinate system of l dimensions. Applying the virtual spring-damper hypothesis to this manipulator, $\boldsymbol{F}_d \in \mathbb{R}^l$, the force generated based on the virtual spring-damper system is calculated according to the following equations:

$$\boldsymbol{F}_d = \boldsymbol{K}_p (\boldsymbol{x}_d - \boldsymbol{x}) + \boldsymbol{\xi}\dot{\boldsymbol{x}} \tag{1}$$

$$\tau = -\boldsymbol{C}\dot{\boldsymbol{\theta}} + \boldsymbol{J}^{\mathrm{T}}(\boldsymbol{\theta})\boldsymbol{F}_d \tag{2}$$

where $\boldsymbol{K}_p,\ \boldsymbol{\xi} \in \mathbb{R}^{l\times l}$ are the stiffness coefficient matrix and the damping coefficient matrix of the virtual spring-damper system, $\boldsymbol{x}, \dot{\boldsymbol{x}} \in \mathbb{R}^l$ are the position and velocity vectors of the manipulator's endpoint and $\boldsymbol{\theta},\ \dot{\boldsymbol{\theta}} \in \mathbb{R}^m$ are the joint angle and angular velocity vectors, respectively. $\boldsymbol{C} \in \mathbb{R}^{m\times m}$ is the joint damping coefficient matrix and $\boldsymbol{J}(\boldsymbol{\theta}) \in \mathbb{R}^{l\times m}$ is the Jacobian matrix with respect to $\boldsymbol{x}$. $\boldsymbol{x}_d \in \mathbb{R}^l$ is the reference position inputted to the virtual spring-damper system as its equilibrium point. In the method proposed by Arimoto et al., $\boldsymbol{x}_d$ conforms to $\boldsymbol{x}_g \in \mathbb{R}^l$, the desired hand position of the reaching motion.

In this study, neither kept constant nor planned as a function of time depicted in Fig. 1, $\boldsymbol{x}_d$ is shaped in real-time as a function of $\boldsymbol{x}_g$ and $\boldsymbol{x}$ according to the equation

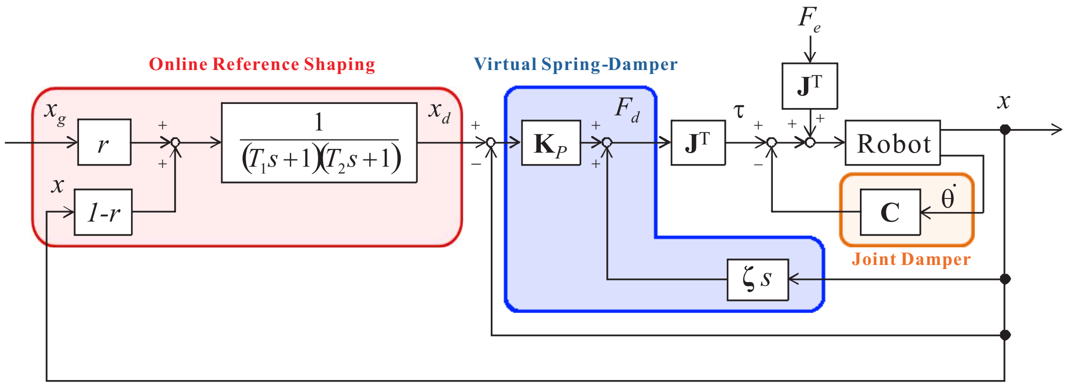


Fig. 2. Block Diagram of Proposed Online Reference Shaping Controller

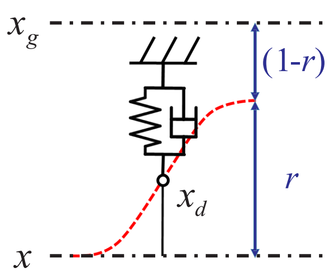
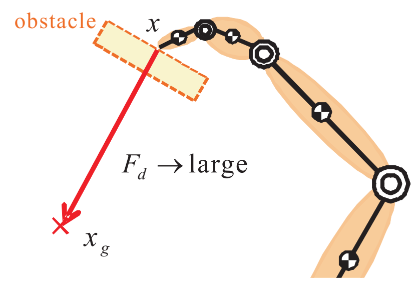
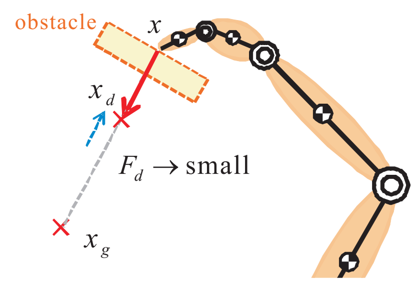


Fig. 3. Relationship among $\boldsymbol{x}$, $\boldsymbol{x}_g$, $\boldsymbol{x}_d$ and r in the Proposed Reference Shaping Method



(a) Without $\boldsymbol{x}_d$ Shaping



(b) With Online Shaping of $\boldsymbol{x}_d$

Fig. 4. Large Acceleration Avoidance with Online Reference Shaping

below;

$$\boldsymbol{x}_d = \frac{1}{(T_1 s + 1)(T_2 s + 1)} \left\{ r\boldsymbol{x}_g + (1 - r)\,\boldsymbol{x} \right\} \tag{3}$$

where T_1 and T_2 are positive constants and r is a constant which satisfies the following conditions.

$$0 < r \leq 1 \tag{4}$$

For convenience of description, the Laplace transform of $\boldsymbol{x}$, $\boldsymbol{x}_g$ and $\boldsymbol{x}_d$ are used in (3). The block diagram of the proposed controller including this online reference shaping is shown in Fig. 2. The initial value of $\boldsymbol{x}_d$ shall be conformed to the initial value of $\boldsymbol{x}$.

As we can see in Fig. 3, $\boldsymbol{x}_d$ moves gradually toward the internally dividing point between $\boldsymbol{x}_g$ and $\boldsymbol{x}$ in the proportion of r : $(1 - r)$ with a second order lag filter by using (3). By assigning $\boldsymbol{x}_d$ to the virtual spring-damper system as its equilibrium point, both the acceleration and the velocity of the manipulator are equal to 0 at the start of the reaching motion. Comparing to a first order lag filter, the manipulator's initial acceleration and velocity are more moderated with the second order lag filter, while the response time is about the same.

When the manipulator's motion is constrained by an obstacle as illustrated in Fig. 4, an excessive pushing force might be applied to the obstacle and large acceleration might be generated after removing the external force caused by this obstacle. This problem, typical in the virtual spring-damper hypothesis, is not resolved by applying the time-variable stiffness, especially for the case that the force is applied over a long time period.

However, in the proposed reference shaping controller, the current position of the manipulator's hand $\boldsymbol{x}$ is fed back to the controller to generate $\boldsymbol{x}_d$. Hence, the generated $\boldsymbol{x}_d$ is not located far from $\boldsymbol{x}$, so that excessive pushing forces and large accelerations can be avoided[1]. Even if an external force is applied over the long term, this controller is not affected by its time period, resuming an appropriate reaching motion after the removal of the external force.

With a back-drivable manipulator, $\boldsymbol{x}$ can be moved by the external force indicated as $\boldsymbol{F}_e \in \mathbb{R}^l$ in Fig. 2. In this case, the change of $\boldsymbol{x}$ will be reflected in shaping of $\boldsymbol{x}_d$, so that

[1] In the present paper, we focus on the short and medium-range reaching motions of manipulators so that the distance between $\boldsymbol{x}$ and $\boldsymbol{x}_g$ is not so widely separated.

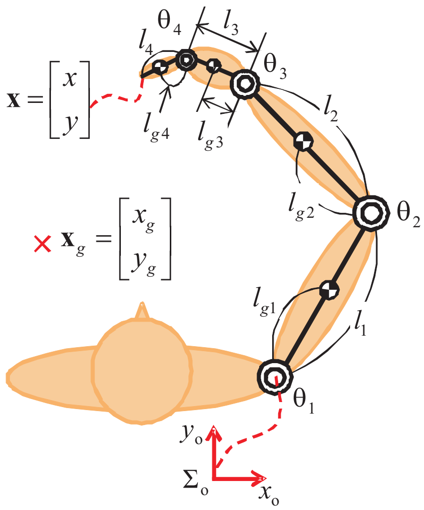


Fig. 5. Simulation Setup

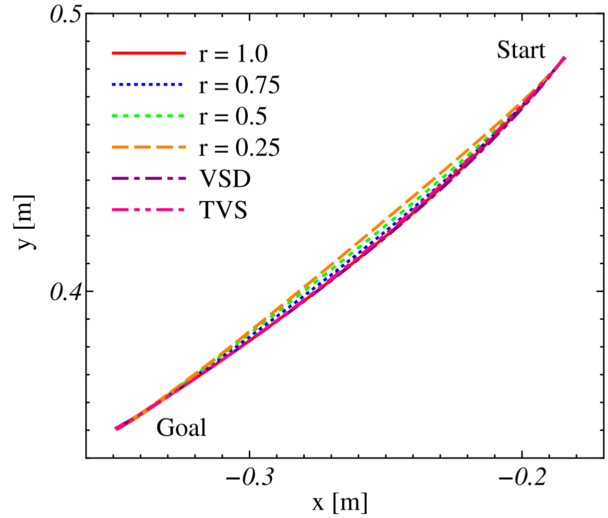


Fig. 6. Endpoint Path of Normal Reaching Motion

the manipulator's endpoint can smoothly follow this external force, as shown in the latter section.

IV. Simulations

In this section, the proposed reference shaping method is implemented in a planar 4-DOF manipulator shown in Fig. 5, and computer simulations are performed to show its validity. Through these computer simulations, we confirm whether the human-like smooth hand velocity profile is realized and the excessive pushing force and large acceleration can be avoided with the proposed method. For purpose of comparison, the traditional virtual spring-damper hypothesis (VSD) and the time-variant stiffness (TVS) are also simulated.

The torque for each joint of the manipulator, denoted by τ, is calculated by (2) from $\boldsymbol{F}_d$ in the VSD, TVS and the proposed method. Although τ is supposed to be realized completely in these simulations, these method can be implemented to actual robots with a torque controller by inputting τ as the torque command. Furthermore, $\boldsymbol{F}_d$ is completely unaffected by sensor noise even in actual implementation because it is the virtual force calculated by (2).

The physical parameters of the manipulator are summarized in Table I. For the online reference shaping controller, $T_1 = T_2 = 0.05$ and $r = 0.25, 0.5, 0.75, 1.0$ are used, while $\boldsymbol{K}_p = diag\{10.0, 10.0\}$, $\boldsymbol{\xi}_1 = diag\{4.7, 4.7\}$ and $\boldsymbol{C} = diag\{0.378, 0.242, 0.058, 0.014\}$ are selected for the VSD system (cf. [2]). Instead of $\boldsymbol{K}_p$, the following $\boldsymbol{K}_p'(t)$ is used in the case of TVS method:

$$\boldsymbol{K}_p'(t) = \boldsymbol{K}_p \left\{1 - \left(1 + \alpha t + \frac{\alpha^2}{2} t^2\right) e^{-\alpha t}\right\} \quad (5)$$

where the sampling time is 1.0 $[ms]$ and the constant parameter α is 8.0. In all the simulations, we select $\boldsymbol{\theta}_o = [70.0\ 50.0\ 30.0\ 80.0]^{\mathrm{T}}$ $[deg]$ as the initial joint angle, and the desired endpoint position is located at $\boldsymbol{x}_g = [-0.35\ 0.35]^{\mathrm{T}}$ $[m]$.

Figs. 6, 7 and 8 show the results of the simulations to investigate whether the human-like smooth endpoint velocity profile is realized with the proposed method. In these simulations, no external force is applied to the manipulator during the reaching motion. The endpoint paths of the manipulator are plotted in Fig. 6, Fig. 7 shows the tangential hand velocity profiles and Fig. 8 is a close-up of Fig. 7 indicating the initial velocity profiles.

From Fig. 6, it can be seen that the endpoint paths of the manipulator are roughly straight with all methods, similar to the paths of the hand in human's reaching motions. However, the initial hand accelerations are very large, resulting in the rapid increase of the endpoint velocities with the VSD method as plotted in Figs. 7 and 8. With the TVS and the proposed method, on the other hand, the initial endpoint accelerations are equal to 0 and the endpoint velocities are changed smoothly. In the case of the proposed method, these initial endpoint acceleration and velocity profiles are achieved thanks to the second-order lag filter. It can also be seen that the maximum velocity is reduced by decreasing the value of r, meanwhile the time to reach the desired position is increased.

Next, two types of computer simulations are performed to evaluate the proposed method capability to avoid excessive pushing forces and large accelerations.

Figs. 9 and 10 show the results of the simulations in which the position of the hand is constrained from 0.0 to 3.0$[s]$. The tangential hand velocity profiles are plotted in Fig. 9, and the point when the constraint is removed around 2.93$[s]$ in Fig. 9 is close up in Fig 10. From Figs. 9 and 10, it can be seen that the velocities are rapidly changed with the VSD, TVS method and $r = 1.0$; the case which $\boldsymbol{x}$ is not fed back to the reference shaping controller. By decreasing the value of r and feeding $\boldsymbol{x}$ back to the reference shaping controller, the velocity change becomes tempered and the maximum velocity becomes reduced with the proposed method.

Fig. 11 illustrates varying $\boldsymbol{F}_d$, the force needed to constrain the endpoint position and the absolute maximum values of

TABLE I
PARAMETER LISTS OF 4-DOF MANIPULATOR

	Link 1	Link 2	Link 3	Link 4
Link Length l $[m]$	0.280	0.280	0.095	0.090
Position of CoM l_g $[m]$	0.140	0.140	0.0475	0.045
Link Mass m $[kg]$	1.4070	1.0780	0.2423	0.2552
Moment of Inertia I $[kgm^2]$	9.758×10^{-3}	7.370×10^{-3}	2.004×10^{-4}	1.780×10^{-5}

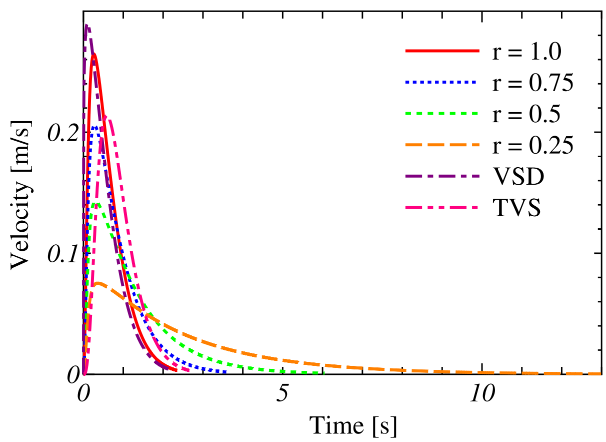


Fig. 7. Tangential Endpoint Velocity Profile of Normal Reaching Motion

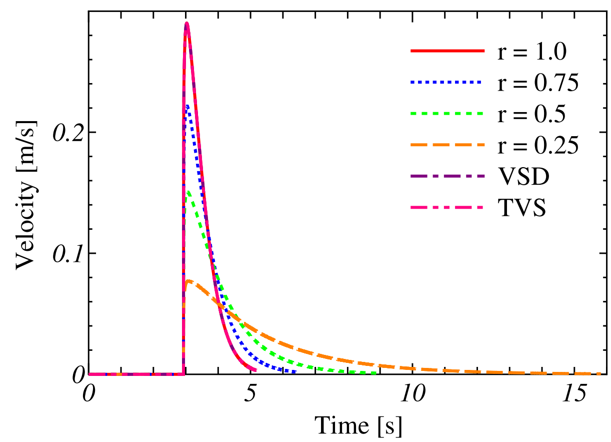


Fig. 9. Endpoint Velocity Profile with Hand Position Temporarily Constrained

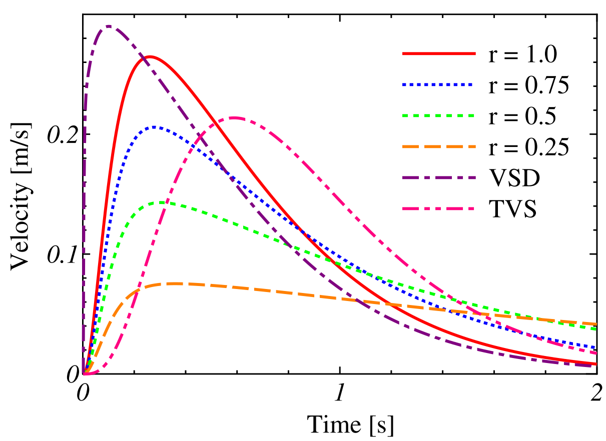


Fig. 8. Close-up of Endpoint Velocity Profile of Normal Reaching Motion

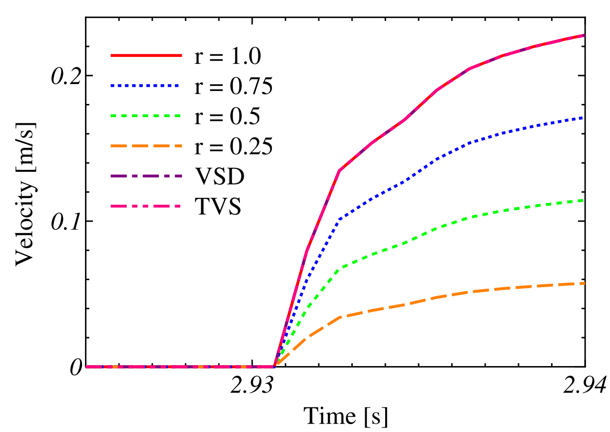


Fig. 10. Close-up of Endpoint Velocity Profile with Hand Position Temporarily Constrained

$\boldsymbol{F}_d$ are indicated in Table II. If the manipulator's motion is constrained by a collision with an obstacle or a human, $\boldsymbol{F}_d$ is applied to it as the pushing force. From Figs. 11 and Table II, it is shown that the pushing forces can be maximized with the VSD, TVS method and $r = 1.0$ while the endpoint position is constrained. On the contrary, the maximum value of pushing force can be reduced by using the proposed method with the feedback of $\boldsymbol{x}$.

The simulations in which the external force $\boldsymbol{F}_e$ is applied during the reaching motion are also performed. In this simulation, $\boldsymbol{F}_e = [1.0\ 1.0]^T$ $[N]$ is applied to the hand for 2.0 $[s]$ The manipulator's endpoint paths are plotted in Fig. 12. $\boldsymbol{F}_e$ is applied when the endpoint comes to the point indicated by a dotted line in Fig. 12. It can be seen from this plot that the manipulator continues the reaching motion against the applied force with the VSD, TVS method and $r = 1.0$. On the other hand, the manipulator can generate the pliant motion to follow the external force with the proposed reference shaping method with the feedback of $\boldsymbol{x}$. The manipulator can also realize the appropriate reaching motion to the desired endpoint position after the removal of the external force. The pliability for the external force is enhanced as the value of r decreases.

From these simulation results, it is confirmed that human-

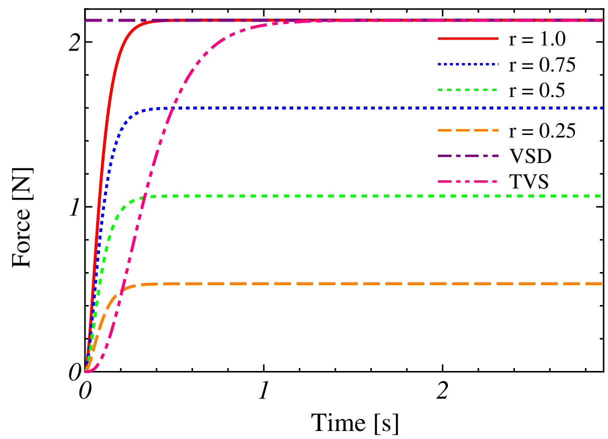


Fig. 11. $\boldsymbol{F}_d$ while Endpoint Position Temporarily Constrained

TABLE II
ABSOLUTE MAXIMUM OF $\boldsymbol{F}_d$ [N]

$r = 1.0$	$r = 0.75$	$r = 0.5$	$r = 0.25$	VSD	TVS
2.133	1.600	1.067	0.534	2.132	2.132

like smooth reaching motions are generated by implementing the proposed reference shaping controller. It is also verified that excessive pushing forces and large accelerations can be avoided and pliant motions can be generated to follow applied external force by feeding $\boldsymbol{x}$ back to the proposed controller. Then, the validity of the proposed method can be shown through these simulations.

V. Conclusion & Future Work

In this study, the nonlinear reference shaping controller for the manipulator control in living environments has been proposed. The acceleration of the manipulator can be moderated by using this controller, and human-like roughly straight

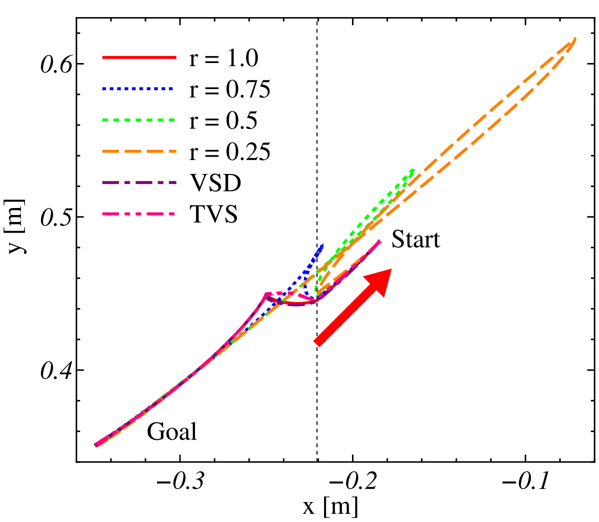


Fig. 12. Endpoint Trajectory with External Force

endpoint paths and bell-shaped endpoint velocity profiles are realized on short and medium-range reaching motions. Moreover, by feeding $\boldsymbol{x}$ back to the proposed controller, excessive pushing forces and large accelerations could be avoided. The motion pliability to follow applied external force could also be accomplished.

However, it might take a long time to reach the desired position when the value of r is small. Furthermore, the maximum velocity and the pushing force were not so moderated when the value of r is large. The value of r is kept constant throughout the reaching motion in the present paper. However, it should be changed based on the current endpoint position, the desired position and so on. It should also be designed depending on whether the external force is applied or not. In our future work, we have to investigate how to design the value of r during the reaching motion to generate more smooth, human-like motion.

Acknowledgment

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