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MULTI-POINT IMPEDANCE CONTROL FOR REDUNDANT MANIPULATORS

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ABSTRACT

The method called *Multi-Point Impedance Control* (MPIC) for redundant manipulators is proposed in the present paper. The MPIC can regulate not only the end-effector impedance, but also the impedance of several points on the manipulator's links, and this method has taken the dynamic effects into account. By using the concept of the virtual arms and the virtual end-points, the dynamics of the virtual end-points are derived, and then the joint torque which is able to control the impedance of multiple points is calculated. It is shown that controlling the multipoint impedance is useful for certain environments where some obstacles impose restrictions on the task space of the manipulator.

1. INTRODUCTION

Most assembly operations and manufacturing tasks require mechanical interactions with the environment or with the object being manipulated. When the robot is applied to perform this kind of task, the robot must develop a compliant motion where the interaction force along the constrained direction must be accommodated rather than resisted. One of the most effective control method has been suggested for development of compliant motion is the impedance control proposed by Hogan [1].

Impedance control is an approach to robot control in which the controlled variables are not position or force, but rather, the dynamic relation between position and force. The inputs of an impedance controller include the stiffness, viscosity, and inertia parameters. These parameters describe the robot's desired force response in reaction to deviations from a desired trajectory, which is also an input to the controller. This control method has many desirable attributes such as the ability to come into contact with hard surface without losing stability and the ability to specify directly the behavior of the mechanical interaction with the environment. The effectiveness and the robustness of the impedance control method have been discussed and demonstrated in detail elsewhere by several researchers. For example, a method to realize the impedance control without the calculation of the inverse Jacobian matrix or without using the force sensor were proposed by Hogan [2] and Tachi et al.[3], respectively. The robustness of the impedance control method was discussed in detail by Kazerooni et al.[4]. On the other hand, in order to maintain performance quality as well as motion stability in the presence of parameter uncertainties and measurement noise, the adaptive impedance control was proposed by W. S. Lu and Q. H. Meng [5]. All of them, however, didn't positively utilize kinematic redundancy of robotic manipulators.

A robotic manipulator is called kinematically redundant , if it possesses more degrees of freedom than the ones being necessary for performing a specified task. Redundancy in the manipulator structure yields increased dexterity and versatility for performing a task due to the infinite number of joint motions which result in the same end-effector motion. Up to the present, there are small numbers of researches have been proposed to utilize the redundancy in terms of the impedance control. For example, Tanie et al.[6] and Teranishi and Yoshikawa [7] proposed independent impedance control of robot manipulator utilizing kinematic redundancy which are an extension of *Direct Compliance Control* (DCC) to dynamical case. Peng and Adachi [8], Newman and Dohring [9] proposed a control scheme for impedance control of redundant manipulators which combines Hogan's conventional impedance control with configuration control of redundant manipulator introduced by Seraji [10]. All of the researches, however, consider to regulate only the end-effector's impedance of the manipulator.

In the previous works, Tsuji et al.[11,12] proposed a method called *Multi-Point Compliance Control* (MPCC) which is able to regulate the compliance of several points on the manipulator's links as well as the end-effector compliance utilizing kinematic redundancy. The same method was also developed for dual-arm robots by Jazidie et al.[13]. Unfortunately, this method hasn't taken the dynamic effects into accounts. The present paper argues that kinematic redundancy of robotic manipulators should be positively utilized in terms of impedance control; and proposes a new impedance control method for redundant manipulators. The method able to regulate not only the end-effector impedance but also the impedance of several points on the manipulator's links.

First of all, we define all points in the manipulator's links which we want to regulate their impedance as virtual end-points. By using the concept of the virtual arms corresponding to the virtual end-points, the dynamics for those point are derived, and then, multi-point impedance control scheme is formulated. Finally, it is shown that the controlling the virtual end-point impedance is useful for certain environments where some obstacles impose restrictions on the task space of the manipulator.

2. VIRTUAL ARM AND ITS KINEMATICS

We consider a redundant manipulator having m joints shown in **Fig.1(a)** which is hereafter referred as an actual arm. Since the manipulator performing a task which requires a compliant motion of the end-effector (referred as an actual end-point) is close to some obstacles (**Fig.1(b)**), the manipulator may collide with them due to unexpected disturbance forces. Then, as shown in **Fig.1(c)**, we define the virtual arm as an arm which has its end-effector (referred as a virtual end-point) located on a joint or a link of the actual arm at the closest point to the obstacle. Using the virtual arms, the interaction between the manipulator and its environment can be considered within the framework of the impedance control. For example, to avoid a collision with the obstacles due to disturbance forces, the impedance of the virtual end-points should be as stiff as possible in the direction of the obstacles. Here, $(n\text{-}1)$ virtual arms are generally considered, and the actual arm is regarded as the n-th virtual arm.

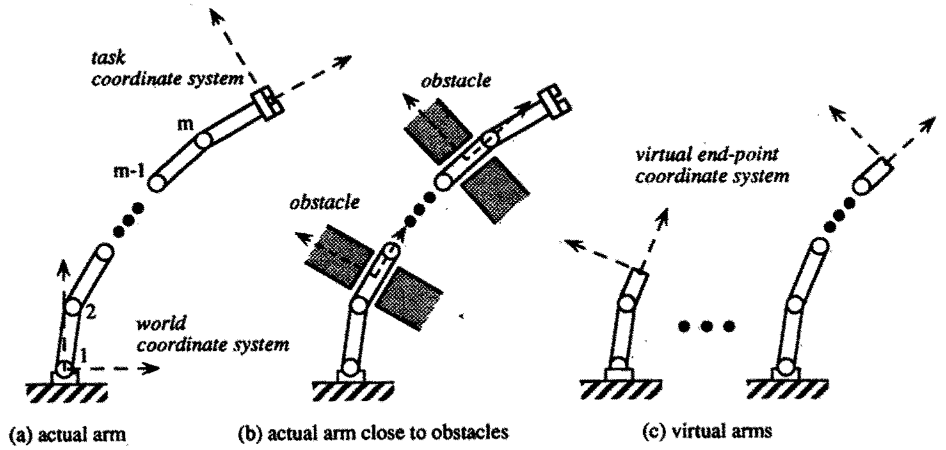


Fig. 1 Actual arm and virtual arms

Let the virtual end-point position vector of the i-th virtual arm in the i-th virtual end-point coordinate system be denoted as $X_{vi} \in R^l$ where l is the dimension of the task coordinate system, and the joint angle vector of the actual arm be denoted as $\theta \in R^m$. Let also the corresponding force vector be denoted as $F_{vi} \in R^l$ and $\tau \in R^m$, respectively. For redundant manipulators, m is larger than l. The instantaneous forward kinematics of the i-th virtual arm is given by

$$\dot{X}_{vi} = J_{vi}\, \dot{\theta} \ , \tag{1}$$

$$\tau = J_{vi}^T F_{vi} \ , \tag{2}$$

where $J_{vi} \in R^{l \times m}$ is the Jacobian matrix associated with the i-th virtual-arm. Concatenating eqs. (1) and (2) for all virtual arms, we can obtain the instantaneous kinematics which relates all of the virtual end-point velocities and the joint velocities as given by

$$\dot{X} = J\, \dot{\theta} \ , \tag{3}$$

$$\tau = J^T F \ . \tag{4}$$

Here, $\dot{X} = [\dot{X}_{v1}^T\ \dot{X}_{v2}^T \cdots \dot{X}_{vn}^T]^T \in R^{nl}$ and $F = [F_{v1}^T\ F_{v2}^T \cdots F_{vn}^T]^T \in R^{nl}$ are the concatenated end-point velocities vector and the concatenated external forces vector exerted to the virtual end-points, respectively. $J = [J_{v1}^T\ J_{v2}^T \cdots J_{vn}^T]^T \in R^{nl \times m}$ is the concatenated Jacobian matrix. Note that $\dot{X}_{vn}$, F_{vn}, J_{vn} are corresponding to the actual end-point.

It was pointed out by Tsuji et al.[14] that there are three cases can be categorized in order to design the control system using the virtual arms: (a) redundant and non-singular case, (b) over-constrained case, and (c) singular case. The method presented here will be addressed to the redundant and non-singular case, that is, for the case where the concatenated Jacobian matrix, J, is of full row rank. In this case, m is still larger than or equal to nl.

3. MULTI-POINT IMPEDANCE CONTROL

Now, let's assume that an external force, F, is exerted on the virtual end-points of the redundant manipulator. The dynamic equation of the manipulator can be represented in the general form

$$M(\theta)\, \ddot{\theta} + h(q, \dot{\theta}) = \tau + J^T F \ , \tag{5}$$

where $M(\theta) \in R^{m \times m}$ is the non-singular inertia matrix, $h(\theta, \dot{\theta}) \in R^m$ is the nonlinear term representing the torque vector due to centrifugal, coriolis, gravity and friction forces. In the present paper, we propose the target impedance for all virtual end-points as the following

$$M d\ddot{X} + B d\dot{X} + K dX = F \ , \tag{6}$$

where the matrices $M = diag.\ [M_{v1}\ M_{v2} \dots M_{vn}] \in R^{nl \times nl}$, $B = diag.\ [B_{v1}\ B_{v2} \dots B_{vn}] \in R^{nl \times nl}$, and $K = diag.\ [K_{v1}\ K_{v2} \dots K_{vn}] \in R^{nl \times nl}$, are, respectively, the concatenated of inertia, viscosity and stiffness of virtual end-points, and $diag.\ [\cdot]$ denotes a diagonal matrix. Here, $M_{vn} \in R^{l \times l}$, $B_{vn} \in R^{l \times l}$, and $K_{vn} \in R^{l \times l}$, are corresponding to the actual end-point impedance parameters, and $dX = X - X^d \in R^{nl}$ is the concatenated deviation vector of virtual end-points position from the desired trajectory, $X^d \in R^{nl}$.

To implement the multi-point impedance control method, the following control law is used

$$\tau = \tau_{mp} + \tau_{comp} \ , \tag{7}$$

where $\tau_{mp} \in R^m$ is the joint torque vector needed to produce the desired multi-point impedance of all virtual end-points and $\tau_{comp} \in R^m$ is the joint torque vector for the nonlinear decoupling as given by

$$\tau = \widetilde{h}(\theta, \dot{\theta}) \cdot \tag{8}$$

It is assumed that $\widetilde{h} = h$. So, after the nonlinear decoupling, the manipulator dynamics becomes

$$M(\theta)\,\ddot{\theta} = \tau_{mp} + J^T F \cdot \tag{9}$$

The inertia matrix of the manipulator, $M(\theta)$, is a symmetric, positive definite matrix. Therefore, this matrix is always invertible. Using the relationship: $\tau_{mp} = J^T F_{mp}$, we can rewrite (9) in the form

$$\ddot{\theta} = M^{-1}(\theta)\, J^T [F_{mp} + F]\, , \tag{10}$$

where $F_{mp} \in R^{nl}$ is the concatenated force vector exerted by the manipulator to the external system at the virtual end-points. On the other hand, by differentiation we can obtain from (3) the following equation

$$\ddot{X} = J\,\ddot{\theta} + \dot{J}\,\dot{\theta} \cdot \tag{11}$$

Also, from (6) we have

$$\ddot{X} = \ddot{X}^d - M^{-1}\,(\,KdX + Bd\dot{X} + F\,) \cdot \tag{12}$$

Finally, it can be readily shown that the joint torque needed to produce the desired multi-point impedance, τ_{mp}, can be computed without the calculation of the inverse Jacobian matrix as the following

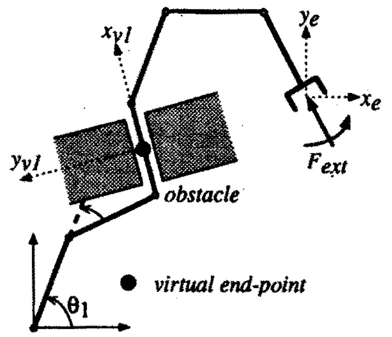
$$\tau_{mp} = J^T\,[\,W^{-1}\,\{\,\ddot{X}^d - M^{-1}\,(\,KdX + Bd\dot{X}\,)\} + (\,W^{-1}M^{-1} - I_{nl}\,)\,F - W^{-1}\dot{J}\,\dot{\theta}\,]\, , \tag{13}$$

where $I_{nl} \in R^{nl}$ is an $nl \times nl$ unit matrix and $W = JM^{-1}(\theta)J^T \in R^{nl \times nl}$ is the mobility tensor which the inverse is the actual inertia matrix of the manipulator in the virtual end-point spaces. It should be noted that for redundant case, the matrix W is always invertible, since it is always a full rank matrix. Using the control law given in eqs. (7), (8) and (13) we can regulate, at the same time, the actual end-point impedance and the impedance of multiple points on the manipulator's links simultaneously.

4. SIMULATION EXPERIMENTS

The manipulator and the task considered in the computer simulations are the same as the ones in Tsuji et al.[11]. That is, the MPIC is applied to the collision avoidance problem using a six-joint planar manipulator (l=3) as shown in **Fig.2.** The link parameters of the manipulator are shown in Table 1.

The manipulator is needed to perform a task which requires its actual end-point to be soft in the direction of x_e axis, and to be stiff in the direction of y_e axis and its rotation, represented in the task coordinate system. The 3rd link of the manipulator lies between a couple of obstacles. Therefore, a virtual end-point is located on the middle point of the third link. The desired virtual end-point impedance parameters should be determined depending on the subtask which will be performed. In this simulation experiment, the subtask is to avoid any collision with the obstacle. The collision can be caused by the large motion of the third link in the direction of y_{v1} axis of the virtual end-point coordinate system, and the large rotation of the third link. So it is desired that the virtual end-point to be stiff in that direction and its rotation. On the other hand, since the motion in the



$\theta = [\,1.2, -0.8, 1.4, -0.6, -1.2, -1.0\,]^T$ (rad)

Fig.2 A six-joint planar manipulator close to obstacles (a non-singular case)

Table 1 Link parameters

	Link i (i=1, ..., 6)
length (m)	0.20
mass (kg)	1.57
center of mass (m)	0.10
moment of inertia (kgm^2)	10.00

direction of x_{vl} axis doesn't cause the collision with obstacle, the virtual end-point in this direction is set to be soft. The stiffness/softness in some directions can be specified by the stiffness matrices of the impedance parameter. In this paper, the concatenated stiffness matrix is set as K = *diag.* [200 (N/m), 1000 (N/m), 1000 (Nm/rad), 200 (N/m), 1000 (N/m), 1000 (Nm/rad)]. By using the MPIC we can also specify the dynamic characteristics of the multiple points through the proper selection of inertia and viscosity matrices. In the simulation, those matrices are set in the concatenated form as B = *diag.* [4 (N/(m/s)), 20 (N/(m/s)), 20 (Nm/(rad/s)), 4 (N/(m/s)), 20 (N/(m/s)), 20 (Nm/(rad/s))] and M = *diag.* [0.02 9 (kg), 0.1 (kg), 0.1 (kgm^2), 0.02 (kg), 0.1 (kg), 0.1 (kgm^2)].

Fig.3 shows stick pictures of the manipulator under the conventional impedance control, where the disturbance force exerted to the actual end-point, F_{ext} = [-20 (N), -20 (N), 20 (Nm)]^T in terms of the task coordinate system, where the desired impedance of the virtual end-point is not included in the control law. On the other hand, **Fig.4** shows a simulation result under the proposed method with the same condition as Fig.3.

The response of the actual end-point is the same between Fig.3 and Fig.4. In terms of the virtual end-point, however, the effectiveness of the proposed method appears clearly. It can be seen that the MPIC can be used as a configuration control of the manipulator through the regulation of the virtual end-point impedances. Since the motion planning can be performed in the virtual and actual task coordinate systems, it is effective to solve the collision avoidance problem.

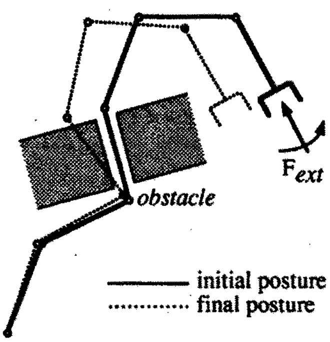


Fig. 3 Stick picture for disturbance force under the conventional impedance control

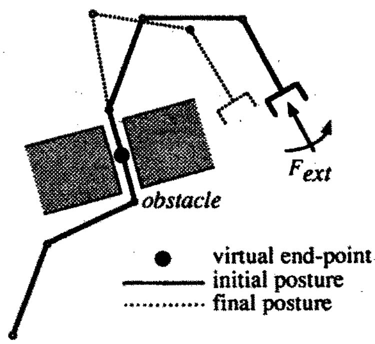


Fig. 4 Stick picture for disturbance force under the multi-point impedance control

5. CONCLUSION

We have proposed the multi-point impedance control method for redundant manipulators. It was shown that the method was able to regulate the impedance of several points on the manipulator's links as well as the actual end-point impedance by positively utilizing the kinematic redundancy. This feature has been demonstrated in the case of the collision avoidance problem. Only the redundant case, however, has been considered in the present paper. Therefore, the generality of the proposed method for all kinematic conditions of the manipulator including over-constrained and singular cases is recommended as a further research.

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