Haptic Teleoperation of Robotic Manipulator

Wusheng Chou[1] and Jing Xiao[2]

[1] Robotics Institute Beijing University of Aeronautics & Astronautics
[2] Dept. of Computer Science University of North Carolina at Charlotte

Abstract. In teleoperated robotic systems, a user controls a robotic manipulator via an input device. Generally the position and velocity commands generated by the user in free space can be arbitrary in the workspace of the input device. However, due to the mechanical limitation and workspace constraints of a manipulator, the manipulator cannot always exactly follow the input command and often runs into a stop. This paper proposes a haptic teleoperation method to enable a user to control a manipulator conveniently and without violating constraints of the manipulator. The configuration constraints and mechanical limits, such as singularities and joint limits, are converted into a constraining force. It is then fed back to the user via a haptic device to restrict the motion of the user's hand so that the manipulator can be operated smoothly without being interrupted by constraint violation. Experimental results demonstrate the feasibility of the proposed method.

1 Introduction

A teleoperated robotic system consists of a device (master) that a user holds and a robotic tool (slave) on the other site, and the bilateral control method is often used in such a system [1]. Most of the literature in the field of teleoperation assumes that an input position/velocity command from a user is always reasonable and the slave manipulator has the ability of replicating the input command. In fact, because the slave manipulator has a finite workspace due to its mechanical limitations, not all input commands can be followed by the slave manipulator.

In addition, even during the motion of an actuated manipulator within its workspace, the manipulator may run into singularity configurations. For instance, in the course of teleopreation, the exact path is not known a priori and hence singularity-free paths cannot be preprogrammed, and as a result the robot manipulator can easily run into a small neighborhood of a singularity configuration. In this case, the manipulability of the robot is compromised, and the user usually has no instructive information on how to back away from such a configuration.

While much work focuses on designing control architectures and algorithms to guarantee the stability and transparency of teleoperation with/without time delay in virtual or real world applications [2], or focuses on the physically accurate force feedback of the interaction between the robot and environment [3], little literature has addressed the issue of restricting the input command of a user during teleoperation. Some assistive virtual force generated by "virtual pipe" or "virtual fixtures" [4,5] are fed back to guide a user's hand motion to improve the efficiency of teleoperation in

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free space. However, they are not concerned with the configuration constraints and mechanical limits and do not restrict the motion of the user hand from violating such constraints. Recently, there is work [6] to reflect the topological constraints of an unactuated virtual serial linkage through haptic forces on a user when the user manipulates any link of the virtual linkage, and a haptic device controller is designed to penalize a user's departure from the configuration manifold of the virtual linkage. The directions of topological constraints are not very accurate for the sake of real time computation, and the impedance controller alone cannot restrict the user's motion according to the virtual topology.

This paper considers teleoperating a real robot manipulator by a user holding and moving a virtual replica via a haptic device. We present how to produce a (virtual) constraining force to provide the user the perception of a singular configuration or a joint limit and prevent the user's hand motion from violating these constraints. Obstacle avoidance and compliant motion constraints can also be easily incorporated into such a constraining force. The combined effect provides the user information for selecting appropriate motion directions for the manipulator to follow.

The rest of this paper is organized as follows. Constraints on the motion of an articulated manipulator are analysed in Section 2. Haptic rendering of these constraints via a constraining force is described in Section 3. In Section 4, we present the implementation of the proposed method, and in Section 5, the preliminary results are given. Section 6 concludes the paper.

2 Constraints of an Articulated Manipulator

A manipulator's motion is limited by its workspace determined by the mechanical structure of the manipulator and the travel limits of its joints. If a joint moves to its limit, then it will reach a stop.

Besides joint limits, a manipulator is constrained by singular configurations. If the end-effector of the manipulator cannot be rotated about a certain axis or translated along a certain direction, even though none of the joints of the manipulator has reached its limit, then the manipulator is in a singularity or singular configuration.

In addition to joint limits and singular configurations, a manipulator's motion is also constrained by obstacles in its workspace. A manipulator needs to either avoid an obstacle or move compliantly along an obstacle surface.

3 Haptic Rendering of Configuration Constraints

Our idea is to feedback a constraining force to the user's hand via the haptic device as it leads the motion of a manipulator when the measure of singularity or joint limit is below a threshold or when the manipulator is near an obstacle in order to prevent violations of their constraints on the manipulator.

The total constraining force can be represented as

$$\mathbf{F}_c = \mathbf{F}_s + \mathbf{F}_j + \mathbf{F}_o \tag{1}$$

Where $\mathbf{F}_s$ is the constraining force caused by a singularity, $\mathbf{F}_j$ is the constraining force caused by joint limits, and $\mathbf{F}_o$ is the constraining force caused by interaction with an obstacle.

Each of these forces is calculated by a spring model as detailed below.

3.1 Constraining Force Caused by Singularities

A manipulator M with n joints is shown in Fig. 1.

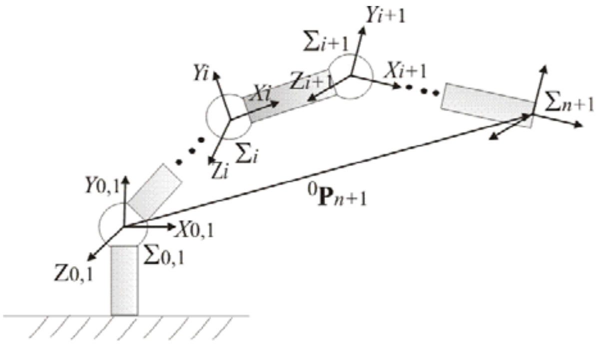

Fig. 1. Link Frames

The Jacobian matrix of M can be expressed as

$$\mathbf{J} = \begin{bmatrix} \mathbf{J}_{l1} \, \mathbf{J}_{l2} & \cdots & \mathbf{J}_{ln} \\ \mathbf{J}_{\omega 1} \, \mathbf{J}_{\omega 2} & \cdots & \mathbf{J}_{\omega n} \end{bmatrix} \tag{2}$$

Where $\mathbf{J}_{li}$ and $\mathbf{J}_{\omega i}$ (i=1,2,…,n) denote the linear and angular velocities of the end-effector of M contributed by the ith joint, respectively.

When the manipulator M is at a singular configuration, either the non-zero components of the first row or the non-zero components of the second row of equation (3) are coplanar or two of them are collinear[7]. The singular direction $\mathbf{d}s$ along which the manipulator cannot be moved satisfies the following equations:

$$\mathbf{d}s \cdot \mathbf{J}_{li}(\boldsymbol{\theta}_s) = 0, \ (i=1,2,\ldots,n) \tag{3}$$

or

$$\mathbf{d}s \cdot \mathbf{J}_{\omega i}(\boldsymbol{\theta}_s) = 0, (i=1,2,\ldots,n) \tag{4}$$

where $\boldsymbol{\theta}_s = (\theta_{1s}, \theta_{2s}, \ldots, \theta_{ns})$ denotes a singularity of M.

Thus the singular direction of M when it is at a singular configuration can be obtained:

$$\mathbf{d}_{sl} = \frac{\mathbf{J}_{li} \times \mathbf{J}_{lj}}{\left\| \mathbf{J}_{li} \times \mathbf{J}_{lj} \right\|} \tag{5}$$

Or

$$\mathbf{d}_{s\omega} = \frac{\mathbf{J}_{\omega i} \times \mathbf{J}_{\omega j}}{\left\| \mathbf{J}_{\omega i} \times \mathbf{J}_{\omega j} \right\|} \tag{6}$$

Where $\mathbf{J}_{li}$ and $\mathbf{J}_{lj}$ are non-zero components of $\mathbf{J}$ and are not collinear. $\mathbf{J}_{\omega i}$ and $\mathbf{J}_{\omega i}$ are also non-zero components of $\mathbf{J}$ and are not collinear.

Let ${}^{n+1}\mathbf{P}_e$ denotes the error between the position of the hand proxy in the virtual environment and the position of the end-effector when it is virtually held by the user through the haptic device. Let ${}^{n+1}\Omega_e$ (which can be expressed as the product of a nominal vector and a certain angle) denotes the orientation increment commands of $\sum n+1$ with respect to the last time step. Using a spring model, we can compute the constraining force $\mathbf{f}_{sl}$ and moment $\mathbf{m}_{s\omega}$ at a singular configuration acting on the origin of $\sum n+1$ respectively. We have

$$\mathbf{F}_s = [\mathbf{f}_{sl} \quad \mathbf{m}_{s\omega}]^T \tag{7}$$

$$\mathbf{f}_{sl} = k_{sl}({}^{n+1}\mathbf{P}_e \cdot \mathbf{d}_{sl}) \tag{8}$$

$$\mathbf{m}_{s\omega} = k_{s\omega}({}^{n+1}\Omega_e \cdot \mathbf{d}_{s\omega}) \tag{9}$$

Where k_{sl} and $k_{s\omega}$ are the stiffness coefficients.

3.2 Constraining Force Caused by Joint Limits

If the ith joint is close to its limit, then the constraining force $\mathbf{f}_{jl}$ and moment $\mathbf{m}_{j\omega}$ caused by the limit of this joint can be calculated as:

$$\mathbf{F}_j = [\mathbf{f}_{jl} \quad \mathbf{m}_{j\omega}]^T \tag{10}$$

$$\mathbf{f}_{jl} = \sum_{i=1}^{n} k_i k_{jl} \left| \theta_i - \theta_{i\lim} \right| \mathbf{d}_{jl} \tag{11}$$

$$\mathbf{m}_{j\omega} = \sum_{i=1}^{n} k_i k_{j\omega} \left| \theta_i - \theta_{i\lim} \right| \mathbf{d}_{j\omega} \tag{12}$$

Where k_{jl} and $k_{j\omega}$ are the stiffness coefficients, k_i =1 if the ith joints reaches its limit, otherwise k_i =0. $\mathbf{d}_{jl}$ and $\mathbf{d}_{j\omega}$ denote the directions of the constraining force and moment acting on the origin of $\sum n+1$ respectively as derived below.

Let ${}^{j}\mathbf{p}_i$ denote the position vector from the origin of $\sum j$, O_j, to the origin of $\sum i$, O_i, expressed in $\sum j$. For a revolute joint i, suppose that link i is driven by the ith joint. If ${}^{i}\mathbf{p}_{n+1}$ is zero, then $\mathbf{f}_{jl}=0$, and $\mathbf{d}_{j\omega}$ aligns with the joint i axis. If ${}^{i}\mathbf{p}_{n+1}$ is not zero, then $\mathbf{m}_{j\omega}=0$, and $\mathbf{d}_{jl}$ is the cross product of ${}^{i}\mathbf{p}_{n+1}$ and the Z axis Z_i of $\sum i$.

$$\mathbf{d}_{jl} = \frac{Z_i \times {}^{i}\mathbf{P}_{n+1}}{\left\| Z_i \times {}^{i}\mathbf{P}_{n+1} \right\|} \tag{13}$$

For a prismatic joint i, $\mathbf{m}_{j\omega}$ is equal to zero, and $\mathbf{d}_{jl}$ aligns with the joint i axis.

3.3 Constraining Force Caused by Obstacles

When a manipulator is close to an obstacle so that the minimum distance $\mathbf{d}_0$ between the robot and the obstacle is less than a pre-defined threshold ε, the constraining force $\mathbf{F}_o$ can be calculated as:

$$\mathbf{F}_o = k_f(\varepsilon - d_o)\mathbf{d}_f \tag{14}$$

Where k_f is the stiffness coefficient, and $\mathbf{d}_f$ is a unit vector along the direction of $\mathbf{d}_0$.

4 Implementation

We have implemented the proposed method in C++ and OpenGL in a virtual environment connected to a PHANToM desktop device. The virtual environment includes a virtual planar manipulator with 3 revolute joints. The length of each link is 7 units. A user can virtually hold and move the end-effector of the manipulator via the haptic device. As the user moves the manipulator, the constraining force is calculated in real-time and fed back to the user by haptic rendering to constrain the user's motion.

Since the real-time requirement on graphic display and haptic rendering are different (20~30Hz for the former and 300~1000Hz for the latter), graphic rendering and the haptic rendering loops are decoupled and communicated via the virtual environment. By doing so, the haptic rendering loop can achieve 1000 Hz update rate to guarantee the stability and fidelity of the force feedback.

A user input command is given in the Cartesian space, and the manipulator should reproduce the input command in its joint space. If the manipulator is not close to a singularity, the pseudo-inverse technique [8] is adopted to calculate the joint velocity.

5 Experimental Results

In the following experiments, the ranges of the three joints of the planar manipulator are (-11π/12, 11π/12), (-π/6, π/6) and (-11π/12, 11π/12), respectively.

When some joint reaches one of its limits (as shown in Fig. 2, joint 1 reaches $11\pi/12$ after time step 10), the constraining force is shown as Fig. 3. The trajectories of the user's hand and the manipulator's are shown in Fig. 4. The arrow in Fig. 4 indicates the motion directions, and the shadow area represents the unreachable region when joint 1 reaches its limit under certain joint configuration A (2.848, -0.9718, -2.229) (in radian), as the user's hand is mechanically restricted by the feedback force. Note that the input motion command is a velocity. Thus, there is an offset between the positions of the user hand and the manipulator end-effector.

In Fig.5, the initial configuration is (1.491, -1.018, -1.247). Joint 2 and joint 3 are zero, and the manipulator is singular between time step 16 and time step 38, as well as the interval of time step 58 and time step 99. Under these situations, the constraining force is shown as in Fig. 5. When the manipulator is not singular, there is no constraining force. Fig. 6 gives the trajectories of the user hand and the manipulator end-effector. The motion of the user is restricted by the manipulator's singular configurations.

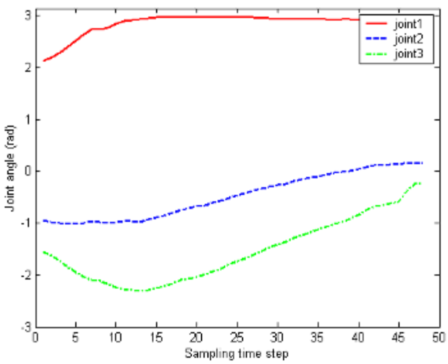

Fig. 2. Joint trajectories When Joint 1 Reaches a Limit

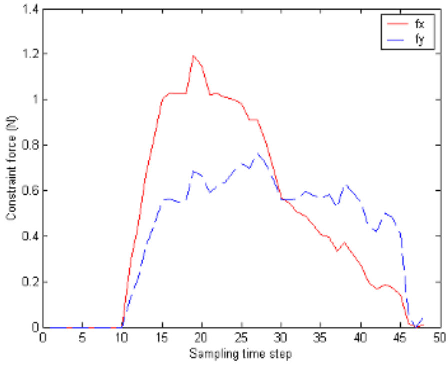

Fig. 3. Constraining Force From Joint 1's Limit

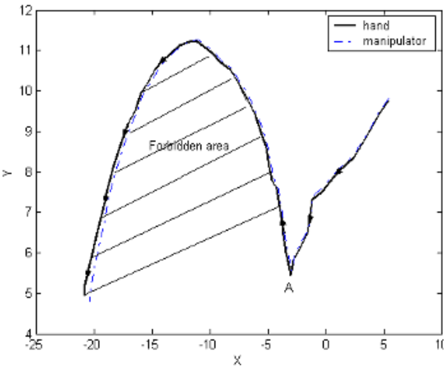

Fig. 4. Trajectories of the Hand and the End-effector When Joint 1 Reaches Limit

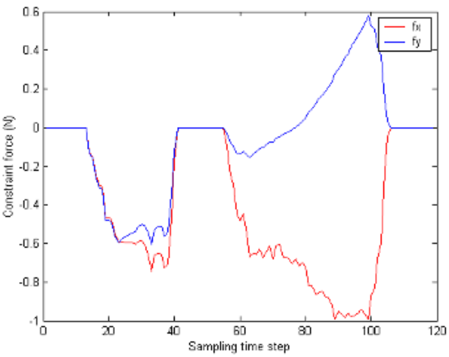

Fig. 5. Constraining Force at a Singularity

Fig. 7 and Fig. 8 present interaction force and the hand trajectory respectively, when the third link of the manipulator interacts with an obstacle located at (10,10). The initial configuration of the manipulator is (2.973151, -0.693032, -2.003396). From time step 42, the third link interacts with the obstacle. The constraining force restricts the user hand motion, and the third link slides along the obstacle surface.

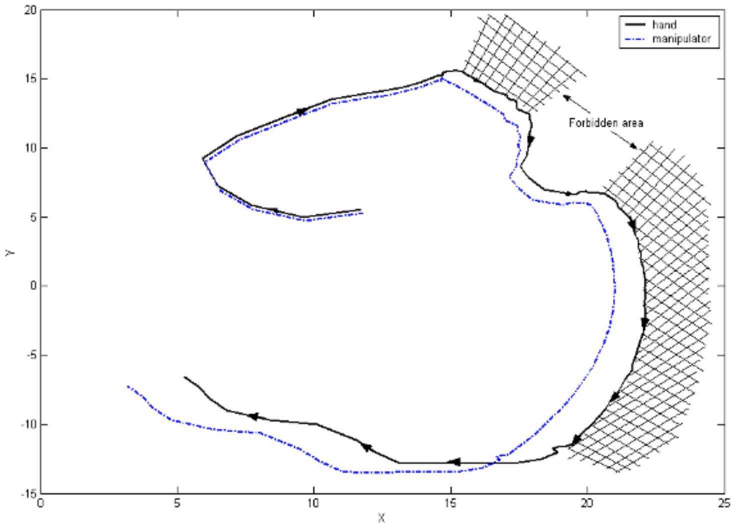

Fig. 6. Trajectories of Hand and the End-effector at a Singularity

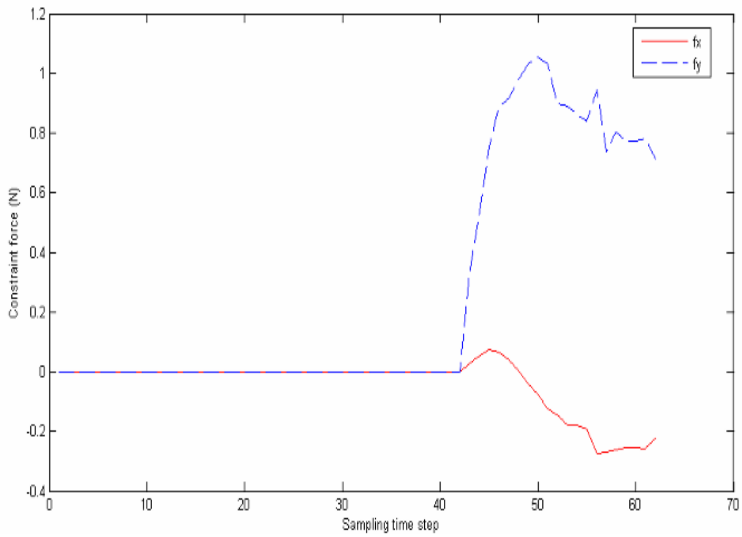

Fig. 7. Constraining Force Caused by Contact

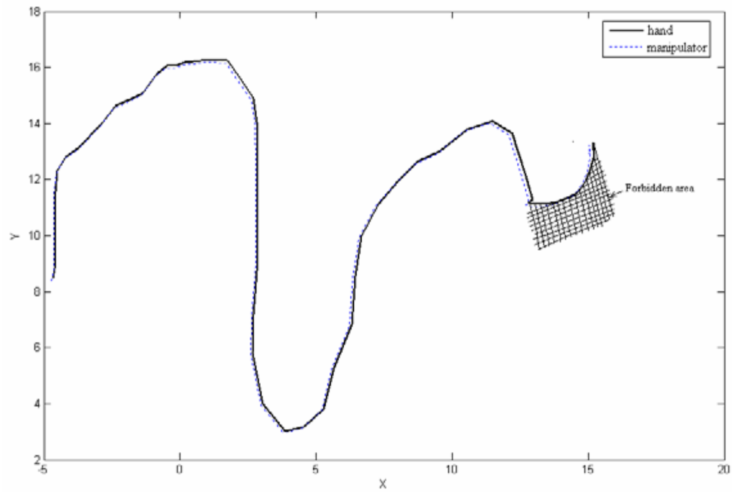

Fig. 8. Trajectories of the Hand and the End-effector with an Obstacle

6 Conclusions

This paper proposes a method to convert configuration constraints on an articulated manipulator into haptic force feedback to a user's hand moving the manipulator via a haptic device. The haptic force can restrict the motion of the user's hand and give the user perception of the configuration status and mechanical characteristics of a manipulator during the course of teleoperation. It can also be helpful to the user in devising an optimal path for the manipulator to perform certain tasks without violating the constraints on the manipulator. The proposed method could also be used for computer aided design of an articulated manipulator to appreciate its workspace and its mobility and dexterity under different configurations, as well as the teaching of articulated manipulator in industrial application.

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