Augmented Haptics of Manipulator Kinematic Condition

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ABSTRACT

This paper describes a study of whether haptic feedback can be used to represent information that is normally difficult to obtain via visual feedback in telerobotic system. Problems of manipulator kinematic condition such as singularity and joint limit have been well known for a long time. Kinematic condition of the manipulator is difficult to be recognized visually. Poor kinematic condition often causes trajectory error or other undesirable effects in the system. This problem is quite significant in telerobotics since a fully pre-planned path that completely excludes poor kinematic condition is usually not available.

In this paper, the haptic representation for singularity and joint limit condition is introduced. The proposed haptic feedback allows the operator to be able to identify poor kinematic condition of the slave manipulator, and naturally recommends the suitable solution to the problem in real-time. Teleoperation experiment was conducted in order to validate and evaluate the proposed theoretical framework.

Keywords: Haptics, Telerobotics, Singularities, Joint limit, Augmented Reality

1. INTRODUCTION

Haptic or 'kinesthetic' feedback was proposed as an additional input to the operator that can improve the performance of a teleoperated system. The word 'haptic' refers to the sense of touch, including sense of position, motion and force. According to Hannaford et al. [2], force reflection from a slave manipulator increases remote manipulation quality for many tasks. Haptic feedback can provide realistic quality of object manipulation in a remote site or even in a virtual environment. The haptic device, which is at the same time used as an input device, produces the feedback force replicating the force of interaction between the manipulator and the environment. Conventionally, the studies of haptic feedback in teleoperation focus on the use of haptic feedback in object manipulation and obstacle avoidance.

In teleoperation, The kinematic behavior of the manipulator has a major effect on performance. ‘Kinematic condition’ refers to the kinematic performance of the manipulator, which usually relates to joint configurations. At the kinematically poor configuration, the manipulator may lose its capability to perform a certain task. One of the well-known problems in robot control that relates to kinematic condition is the singularity problem. In Cartesian-based control, the Jacobian of the manipulator defines the relationship between joint velocity and end-effector velocity. The singularity problem comes from the configuration of the manipulator that causes the Jacobian matrix of the manipulator to loose rank. Some control algorithms fail at singularity because of high and unrealizable joint velocity that is calculated from a differential inverse kinematics equation. When the Jacobian matrix is singular or nearly singular, even the small end-effector velocity in Cartesian space could result in an exceptionally high requested joint velocity. When the requested joint velocity is too high, the actuator output suddenly becomes saturated and sometimes causes a large trajectory error. At singular configuration, the manipulator loses one or more degree of freedom which means there are directions along (or around) which it can not move or exert force (or torque). The singularity problem is more severe in the teleoperated system than in the autonomous system because in the teleoperated system, a fully pre-planned path that completely excludes all singular configurations is usually not available. In a teleoperated system, the operator should have the ability to control the manipulator freely without having to do off-line path planning for every motion. The problem is more severe in the teleoperated system that employs a dissimilar master and slave mechanism. In the situation where the slave manipulator is in a singular configuration and the master is not, the operator may not be aware of the slave singularity and may keep sending commands that can not be attained by the slave. This situation can cause an infeasible joint velocity in the slave, system instability, and damage. The other problem related to the kinematic condition is caused by hardware limitation of the mechanism or joint limit. The saturation in joint actuation can cause the undesirable effect in the same fashion as from the kinematic singularity.

Several methods have been suggested during the past two decades to deal with singularity problem. One solution is by implementing the singularity avoidance technique into a low-level robot control algorithm. The damped least-square inverse technique always produces the path solution that deviates from singularity. In fact, we may be able to reach the singularity if the manipulator motion lies completely in the feasible direction at singularity. By using the damped least-square technique we ignore the possibility that motion through singularity is allowed [9]. Though it is desirable to adjust the motion of the manipulator so that it lies in the feasible direction near singularity, it is very difficult to do so in the teleoperated system. First, poor kinematic condition such as singularity is quite difficult to be recognized by visual observation. Many teleoperation systems provide an image of the slave manipulator to the operator in real-time during the operation. However, the image of the manipulator does not explicitly display the kinematic condition of the manipulator. Second, in the situation that the operator has to command a slave manipulator in a constrained motion through singularity, the feasible direction, which is derived from the velocity space of the Jacobian, needs to be precisely acquired. Visual feedback is clearly insufficient to provide all necessary information that allows the operator to deal with singularity problem in real-time.

In order to allow the operator to deal with the kinematic condition problem interactively, an additional information feedback other than visual feedback is required. Salganicoff et al. [7] implemented the slave singularity detection mechanism into the head-controlled assistive telerobot. With this system, the audio signal and the increasing back-drive forces are sent back to the master so that the singularity problem can be notified during the operation. However, the proposed singularity detection algorithm clearly does not incorporate all the necessary feedback information that allows the operator to respond to the problem appropriately.

To deal with the problem of poor kinematic condition, the additional feedback should provide the proximal information from the singular configuration as well as the directional information of the velocity space of the manipulator Jacobian. Haptic feedback seems to be the suitable solution for this problem. The haptic feedback, which is presented in the form of a force vector, naturally implies the directional information. Moreover, a haptic interface provides bi-directional flow of information in which the operator receives feedback information and sends out command input simultaneously. Therefore, haptic feedback allows the operator to interactively respond to the problem as it occurs.

In this paper, we propose that the haptic feedback of kinematic condition should be augmented to the standard feedback that the operator receives from the slave manipulator such as vision or force from interaction with the environment. The augmented haptics does not directly provide the realistic quality of an interaction with the environment, but instead provides additional guidance to assist the operator when the slave approaches a poor kinematic condition. The main purpose of this paper is to verify that the augmented haptics can convey a useful information to the operator, and can improve the performance of the teleoperation. In the first section, we will explain the theory of the problem. Then, the mathematical framework of the singularity force feedback and the joint limit force feedback will be presented. The teleoperation experiment will be discussed in the last section.

2. THEORY

In teleoperation, Cartesian-based control has the advantage of being more compatible with the operator input in Cartesian space. Unfortunately, the joint velocity that is calculated from the relation between the joint velocity and the end-effector velocity (eq. 1) can be very sensitive to the singularities.

$$\dot{q} = J^{-1}\dot{x} \tag{1}$$

A singularity is the condition where the Jacobian matrix (*J*) in eq.1 becomes singular. Near singularities, many control algorithms fail because the high and unrealizable joint velocity is calculated from eq.1. When the Jacobian matrix is singular or nearly singular, even a small desired end-effector velocity can result in a very high joint velocity.

Among various approaches, the damped least-square inverse method seems to be most widely adopted technique in teleoperated system [6]. The damped least-square inverse minimizes the error of the joint velocities solution and magnitude of joint velocities.

$$\left\| J\dot{q} - \dot{x} \right\|^2 + \lambda^2 \left\| \dot{q} \right\|^2 \tag{2}$$

The joint velocities are given as the solution of the normal equation

$$(J^T J + \lambda^2 I)\dot{q} = J^T \dot{x} \tag{3}$$

$$\dot{q} = J^{*}\dot{x} \tag{4}$$

where $J^{*} = (J^{T}J + \lambda^{2}I)^{-1}J^{T} = J^{T}(JJ^{T} + \lambda^{2}I)^{-1}$, J^{*} is the damped least-square inverse Jacobian. The damping factor λ is a scalar representing the relationship between joint velocity and velocity error (eq.3). The larger the value of λ, the more position error occurs between the requested and the actual end-effector velocity. However, λ has to be sufficiently large to be able to maintain the feasible joint velocity.

Even though the damped least-square inverse approach may eliminate the numeric problem at singularities, it may cause an error in Cartesian trajectory. The new trajectory generated by this approach always deviates from the original path near singularity. The singularity is never reached using this method, and some portions of the workspace are always excluded. From the concept of manipulability [10], motion near and at singularity can be achieved as long as the command velocity stays within the manipulability ellipsoid i.e. the singularity can be reached if no manipulator motion lies in the null space of the Jacobian. In order to stay on the path at singularity, the velocity command has to be restricted to be within the velocity space (i.e. any component in the null space of the Jacobian has to be zero.) The singularity avoidance algorithm such as the damped least-square inverse seems to simply ignore this fact.

In order to obtain a good compromise between the operational speed and the trajectory error, the operator should be able to interactively adjust the direction and the magnitude of the command velocity to stay within with the velocity space near singularity. The operator needs to get information about the kinematic condition fast enough to be able to respond appropriately. The proximal information, which indicates the distance from the singularity, can be obtained from the reciprocal of the condition number of the Jacobian defined by $C_j = (\sigma_{max}/\sigma_{min})^{-1}$. The directional information, derived from the velocity space of the Jacobian, should also be communicated to the operator. The null space and the velocity space can be obtained by applying a singular value decomposition to the Jacobian matrix. With recently available low-cost computing power, singular value decomposition (SVD) can now be computed in real-time. This provides significant information for new operator feedback approaches. Knowing all the necessary information, the operator should be able to make an appropriate adjustment to the command input near singularity, either to move into the feasible direction or to slow down if necessary.

Joint limits are associated with the physical limitation of the joint actuators including joint position, velocity and torque. Due to these limitations, the desired trajectory may not be attained and the trajectory error is created. The solution to this problem generally utilizes the redundancy of the manipulator. In teleoperation, Hwang [3] suggested the inertia weighted pseudo-inverse solution. The solution to the joint limit problem is added to the algorithm by utilizing the null space of the main task. When the slave manipulator encounters joint limit, an image of the manipulator alone may not be sufficient to make the operator understand what actually happens at the slave. In this case, the haptic feedback allows the operator to experience the limitation of the mechanism physically, which may lead him/her to feel as if he/she controls the robot from inside the mechanism.

3. MATHEMATICAL FRAMEWORK

3.1 Singularity force feedback

The purpose of the singularity force feedback is to inform the operator about the poor kinematic condition near or at singularity and to guide the operator so that he/she can react appropriately when approaching the singularity [4]. When the slave manipulator approaches the singular configuration, the appropriate response is to change the command direction if it is possible, to slow down as it gets close to singularity and to correct back to the original path as soon as possible.

The singularity force feedback should resist the commanded motion that lies in the null space of the Jacobian. The magnitude of the force feedback should depend on the proximity from singularity so that the operator can feel more resisting force as the slave manipulator moves closer to the singular configuration. The magnitude of the force feedback also depends on the magnitude and the direction of the velocity command. If the magnitude of the velocity command that lies in the null space of the Jacobian is large, the operator should feel more resisting force and has to make a larger deviation to avoid singularity. The singularity force feedback naturally guides the operator to command the manipulator into the feasible direction, described by the velocity space of the Jacobian.

The proposed singularity force feedback is required to have these properties:

- The singularity force feedback only exists within the neighborhood of singularity

- The magnitude of the singularity force feedback depends on the proximity from the singularity
- The magnitude of the singularity force feedback depends on the magnitude of the velocity command
- The singularity force feedback virtually guides the manipulator to move into the feasible direction defined by the manipulator Jacobian

Even though a singular configuration is described by the joint configuration of the manipulator. The positional singularity can be visualized in Cartesian space as the surface defined by the relation

$$C_j(J(inv\_kin(x)) = 0 \qquad (5)$$

where *Cj(J)* is the condition number^{-1} of the Jacobian matrix, *inv_kin( )* is the nonlinear mapping from joint space to Cartesian space *q = inv_kin(x)* and *x* is the position of the end-effector in Cartesian space.

The neighborhood of singularity is defined where the Cj of the Jacobian is below the specified minimum value, Cj_{min} that the feasible joint velocity can still be maintained. The boundary of the neighborhood of singularity can be described in Cartesian space by eq.6 in the same way as the surface of singularity in eq.5

$$Cj(J(inv\_kin(x)) - Cj_{\min} = 0 \qquad (6)$$

The first property states that the singularity force feedback can only exist within the neighborhood of singularity. Eq (6) can be used as a condition for activating the singularity force feedback (i.e. the singularity force feedback only occurs when $Cj(J(inv\_kin(x)) < Cj_{min.}$) From the second and third property, the singularity force feedback can be described as the combination of spring and damper force. The spring force component depends upon the proximity from the singularity and the damper force component depends upon the velocity command.

According to the last property, the force should contain directional information that guides the operator into the feasible direction. The appropriate direction of force feedback near singularity can be derived from the damped least-square inverse Jacobian. The damped least-square inverse Jacobian is used so that the force feedback could be gradually increased as the manipulator moves closer to a singular configuration until it reaches maximum value in the direction that lies on the null space of the Jacobian at singularity. The damped-null subspace of the Jacobian can be derived from the damped least-square inverse Jacobian as follows

$$J^* = V\Sigma^* U^T \qquad (7)$$

where the singular value decomposition of the Jacobian is described by $J = U\Sigma V^T$ and

$$\Sigma^* = \begin{bmatrix} \frac{\sigma_1}{\sigma_1^2 + \lambda^2} & 0 & \cdots \\ 0 & \ddots & 0 \\ \cdots & 0 & \frac{\sigma_m}{\sigma_m^2 + \lambda^2} \end{bmatrix}.$$

$$JJ^* = U \begin{bmatrix} 1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \frac{\sigma_m^2}{\sigma_m^2 + \lambda^2} \end{bmatrix} U^T \qquad (8)$$

$$I - JJ^* = \frac{\lambda^2}{\sigma_m^2 + \lambda^2} u_m u_m^T \qquad (9)$$

σ_m is the minimum singular value of the m-dimensional Jacobian that is rank-deficient by one. u_m is the *m*-th column vector of U that corresponds to the damped-null subspace of the Jacobian. $I - JJ^*$ represents the mapping to the damped null subspace of the Jacobian.

To create the virtual boundary of the neighborhood of singularity, the spring force calculation is derived from the rendering technique used for rendering the surface of a solid model with an implicit representation [5][8]. The implicit representation of a solid model defines the surface enclosing solid objects where the point-set inside the surface is entirely separate from the outside space. When the probe point is contacting with solid objects, the responsive force is a force that prevents a probe point from penetrating into the surface. The gradient of the implicit surface equation is proportional to the surface normal vector pointing outward direction. The responsive force always occurs in the direction of the surface normal vector. In our case, the rendered surface is not the surface of a solid model, but the surface boundary of neighborhood of singularity. Although the surface boundary of neighborhood of singularity is described by an implicit representation (eq.6), the singularity surface is different from the surface of a regular solid model in many aspects.

The algorithm for calculating the spring force component in the singularity force feedback can be described as follows.

I. The first collision

The collision is established when the end-effector is inside the surface boundary of the neighborhood of singularity for the first time, which means at time k, $cnd\_no^{-1}(J(q(k)) < cnd\_no^{-1}_{min}$ and at time $k\text{-}1$, $cnd\_no^{-1}(J(q(k)) > cnd\_no^{-1}_{min}$. The surface contact point is defined as the midpoint between $P(k)$ and $P(k\text{-}1)$ in figure 1. Although the actual surface contact point may not be at the midpoint, the error is considered to be negligible at 1 kHz servo loop rate.

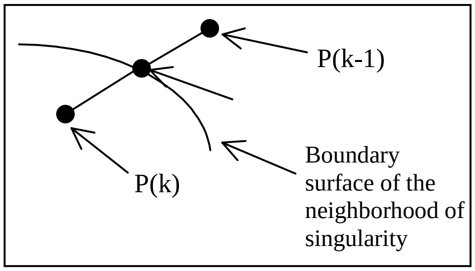


Figure 1. The contact point on the boundary surface of the neighborhood of singularity that is defined as a midpoint between end-effector position (P) at time k and k-1

After the interaction point is established, the vector from $P(k)$ to $Po(k)$ is mapped to the damped null subspace of the manipulator Jacobian in the direction opposite to the command velocity. The spring force is calculated from

$$f_{spring} = K(I - JJ^{*})(P_o(k) - P(k)) \qquad (10)$$

,where $I - JJ^{*}$ is the mapping to the damped null subspace of the Jacobian (eq.9) and K is a constant that defines stiffness. Since the mapping into the damped null subspace does not necessary indicate the outward direction from the surface, the direction of force has to be adjusted so that it is always opposite to the velocity command after the first collision.

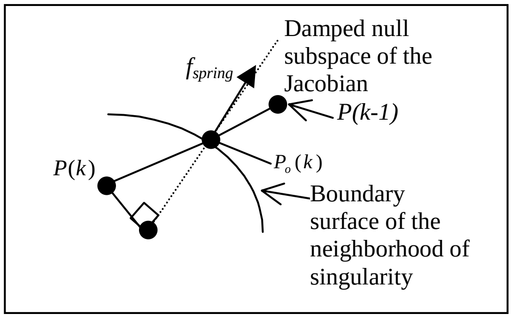


Figure 2. The spring force lies in the damped null subspace of the Jacobian and points outward from the boundary surface of singularity

The damper force is calculated from the mapping of the command velocity onto the damped null subspace of the Jacobian. The direction of the damper force should also in the opposite direction from the velocity command.

$$f_{damper} = B(I - JJ^{*})v_c \qquad (11)$$

,where $I - JJ^{*}$ is the mapping to the damped null subspace of the Jacobian (eq.9) and B is the damping coefficient
The singularity force feedback is the combination of the spring force (eq.10) and the damper force (eq.11).

$$f_{total} = f_{spring} + f_{damper} \qquad (12)$$

II. After the collision

After the collision occurs, if $P(k)$ is still inside the surface (i.e. $cnd\_no^{-1}(J(q(k)) < cnd\_no^{-1}_{min})$, the new interaction point $Po(k)$ will be defined from the mapping of the vector $P(k\text{-}1)$ to $P(k)$ onto the subspace that orthogonal to the damped null subspace ,which is in fact the velocity space of the Jacobian (figure 3). The velocity space of the m-dimensional Jacobian is defined as $u_{1..m-n}u^T_{1..m-n}$, when *u* is the column vector of U in eq.8 and the Jacobian is rank deficient by n.

$$P_o(k) = P_o(k-1) + u_{1..m-n}u^T_{1..m-n}(P(k) - P(k-1)) \qquad (13)$$

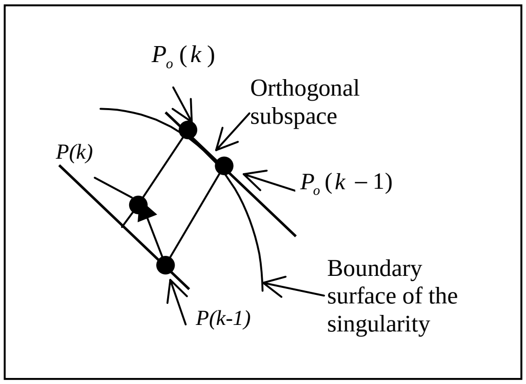


Figure 3. The new interaction point Po(k) is defined by mapping the vector P(k-1)P(k) to the orthogonal subspace.

The spring and damper force is calculated in the same way as in the case of the first collision (eq. 10,11,12). Note that the direction of the total force should be adjusted so that it agrees with the direction of the previous force vector in order to keep the uniformity in force direction.

4. TELEOPERATION EXPERIMENT

4.1 Experimental setup

The singularity force feedback and joint limit force feedaback algorithm is implemented on the haptic interface system at Biorobotics Laboratory University of Washington using Excalibur as the master manipulator, the 3 degree-of-freedom haptic linear haptic display device. The operator can input the positional command in Cartesian space by moving the handgrip that connects to light linkage elements. The 3-dimensional force feedback is generated from motors mounted on the base of the mechanism. The Excalibur uses steel cable transmission that enables high forces and high rigidity in the three-axis translation motions. The workspace of the device is 300x300x200 mm3 with the maximum force of 100 N and the position resolution of 0.008 mm [1]. The singularity force feedback and joint limit force feedback algorithm is implemented on a 266 MHz Pentium II processor PC that controlled the Excalibur in real-time with the fixed update rate of 1 KHz.

The slave manipulator is a software simulation of the PUMA 560. The graphical interface software is implemented in C using OpenGL library on the Pentium-II PC running Windows NT. PUMA 560 has 6 DOF, but in this experiment we study the first 3DOF (positional DOF). The first 3DOF of PUMA 560 has 2 types of positional singularity: the ‘elbow’ singularity (joint 3 is fully extend or folded up completely) and the ‘alignment’ singularity (the end-effector is as close to the axis of joint 1 as possible). The surface that describes the both types of singularity in Cartesian space can be visualized as in fig.4.

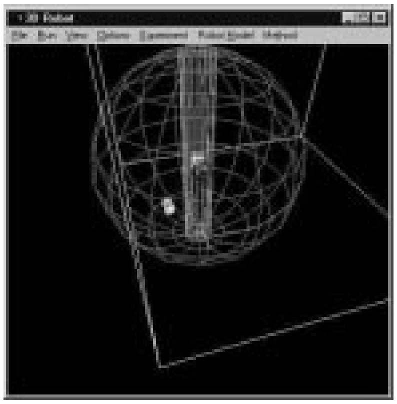
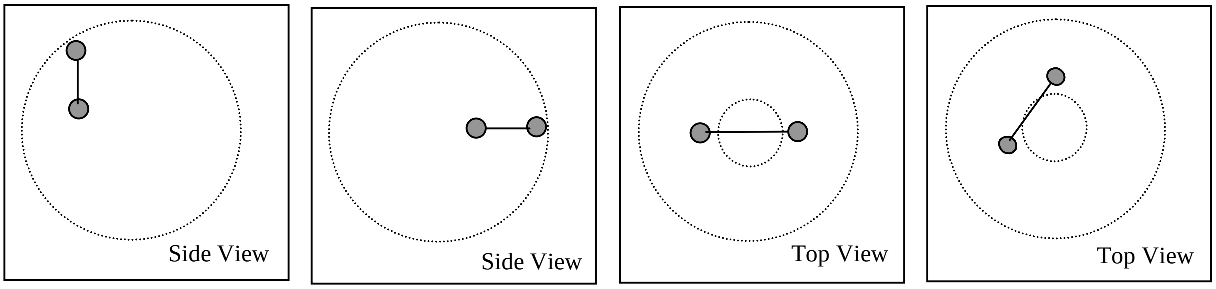


Figure 4. The surface that describes positional singularity in Cartesian space for PUMA 560

The goal of the operator in each of the experimental tasks was to command the end-effector motion using the Excalibur from an initial point to a target point inside the workspace of the manipulator. The graphic simulation of the manipulator was displayed while the operator was performing the operation.The manipulator display window consisted of a scaled wire-frame rendition of the PUMA-560 manipulator in the 3D perspective view. The viewpoint was fixed to avoid an unnecessary variability in the experiment. The initial point and the target point were displayed as a green sphere and an orange cylinder. The initial and the target point would change color to white when they were touched by the end-effector. The operator was required to position the end-effector at the initial point, then move to the target point with the shortest amount of time possible. The operator was suggested to command the end-effector in a straight line from the initial point to the target point in order to minimize the completion time and the trajectory deviation unless it is necessary to deviate otherwise. The operator started the task by positioning the end-effector at the initial point and terminated it by bringing the end-effector to the target point. The test tasks were selected such that a straight line from the initial point to the target point was susceptible to be in the neighborhood of singularity (as shown in figure 5). The target point for all the tasks was indeed reachable, thus the operators were encouraged to complete the task regardless of its difficulty.



(a) Task 1 (b) Task 2 (c) Task 3 (d) Task 4

Figure 5. (a) Task 1: The target point is near the elbow singularity (b) Task 2: The target point is near the elbow singularity
(c) Task 3: The straight line from the initial point to the target point passes through the elbow and the alignment singularity
(d) Task 4: The straight line from the initial point to the target point slightly passes through the alignment singularity

Four methods of kinematic information feedback were presented to the operator in the experiment
method A: No kinematic information feedback is given.
method B: Visual and auditory feedback that indicate the kinematic information of the slave manipulator is given
method C: Singularity force feedback is given
method D: Multimodal kinematic information feedback(visual, auditory and force) is given

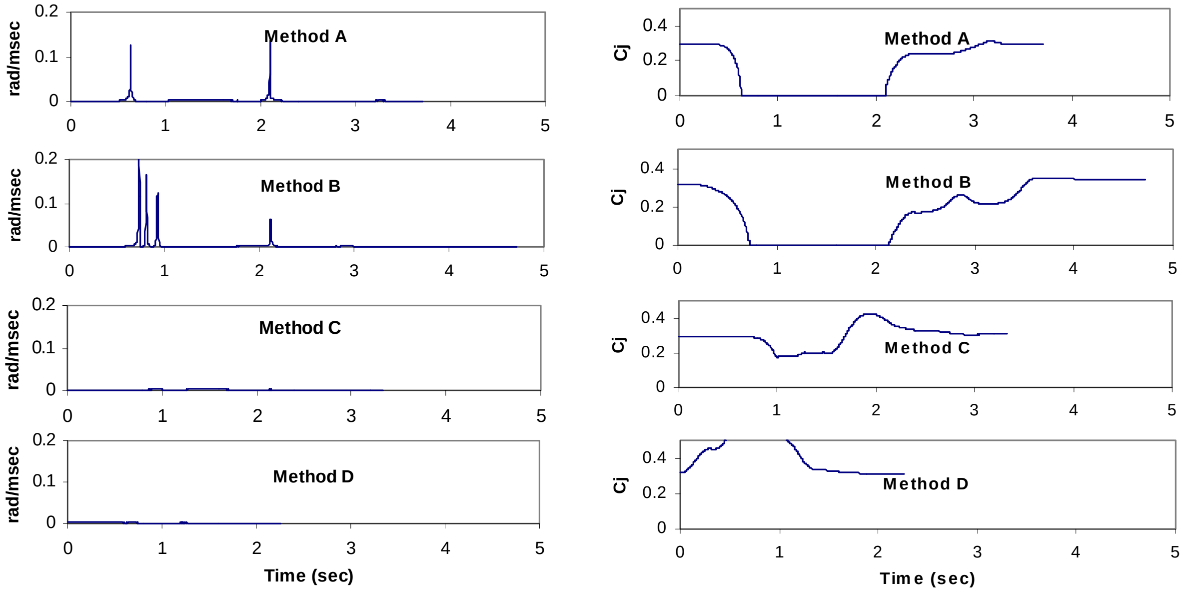
In method B and D, the visual feedback was given as a small icon on the lower-left corner of the manipulator window that showed the kinematic condition of the manipulator. The icon changed as the manipulator approached the undesirable configuration indicated by the Cj that is lower than the specified threshold (0.01). The operator may respond by changing the commanded direction or slowing down the operation. The auditory feedback would provide a *'beep'* sound whenever the robot approached the undesirable configuration. In method C and D, the singularity force feedback was generated from the algorithm presented in the previous section when the manipulator approached the neighborhood of singularity.

12 students from the college of engineering volunteered to be the operator in the teleoperation experiment. Each operator attended the standard training session where the objective and the procedure of the experiment were explained. All operators were trained by performing a point-to-point operation repetitively until they achieved a desired level of performance. The operator was considered to be satisfactorily trained after the successful completion of at least 10 successive tasks with the converging performance measure comprised of the completion time and the trajectory deviation.
After the operators were satisfactorily trained, they were presented the test tasks. The test tasks appeared essentially identical to the training tasks. Each operator was required to perform four sets of point-to-point motion tasks with four different information feedback methods (totally 16 task-method pairs). To minimize any carry-over and learning effects over different task-method pair, the order of task-method was determined using a Graeco-Latin-square. The operator was required to perform 5 repetitions for every task-method pair.

The teleoperation performance was evaluated upon 4 performance measures:

- Minimum Cj
- Maximum joint velocity
- Percentage of time that the Cj is below the threshold value
- Percentage of time that the joint velocity is higher than the maximum allowable joint velocity

4.2 Results and Analysis



(a) (b)

Figure 6. (a) Joint velocity (rms) vs. time when the operator performed task 3 in one repetition. (b) Cj of the Jacobian vs. time when the operator performed for task 3 in one repetition.

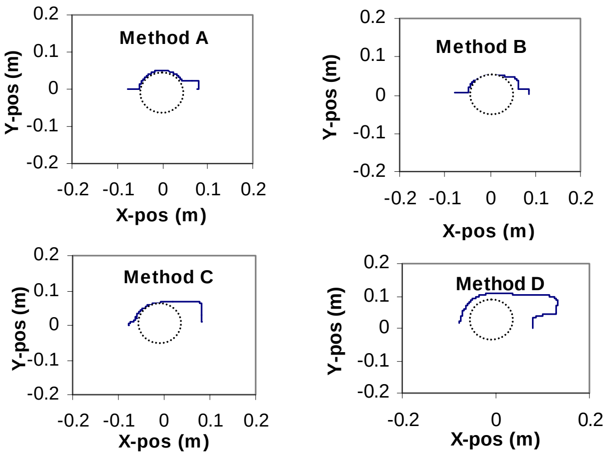
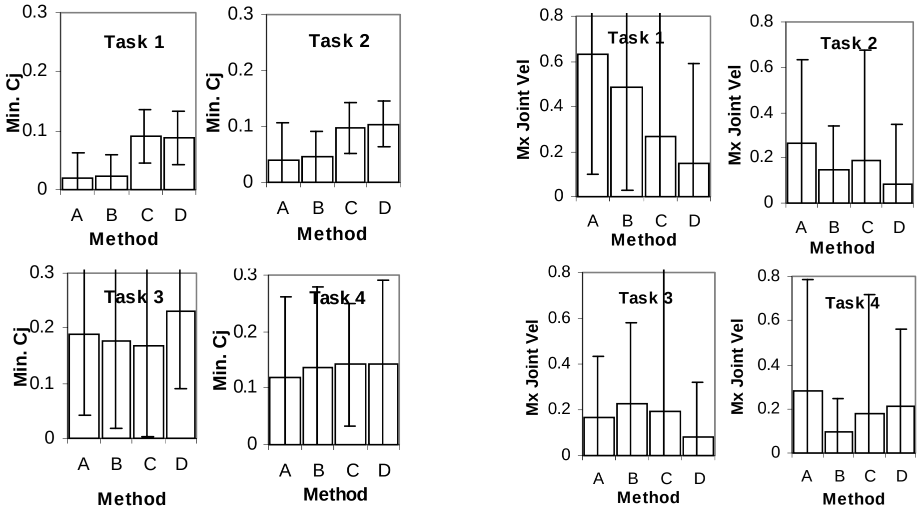


Figure 7. Top-view plot of the slave trajectory (solid line) when the operator performed task 3 in one repetition. The dash line represents the inner workspace singularity.

The plots in figure 6 and 7 show the example of operator responses toward the different type of kinematic information feedback during task 3 operation in a single repetition. In figure 6 (a), the joint velocity in method A and B increases dramatically near time 1 and 2 second. The abrupt changes in joint velocity correspond to the decrement of the Cj as demonstrated in figure 6 (b). With the singularity force feedback in method C, the Cj maintains the minimum value close to 0.2 and the magnitude of joint velocity remains small. In method D, the trajectory plot in figure 7 shows that there is a large deviation from the straight lined trajectory before reaching the neighborhood of singularity. The result demonstrates the high Cj and the low joint velocity all along the trajectory (figure 6).

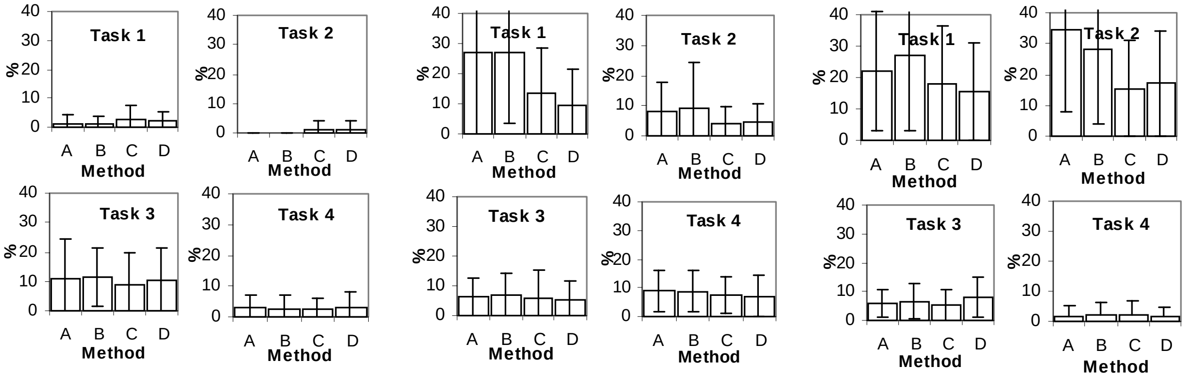


(a) (b)

Figure 8. (a) Mean of the minimum Cj for each task, Line(+-)1 standard deviation interval
(b) Mean of the maximum Joint velocity rms (10^3 rad/sec) for each task, Line(+-)1 standard deviation interval

The performance measures are summarized in figure 8, 9 and 10. The bar graph demonstrates the performance measures of four different methods for each task. The two-way analysis of variance (ANOVA) was used to analyze the data. The graph of the minimum Cj is shown in figure 8 (a). The high value of the minimum Cj indicates a good teleoperation performance. In task 1,2 and 3, the minimum Cj of method D is significantly higher than other method ($p < 0.05$). In task 1 and 2, with the singularity force feedback in method C and D, the minimum Cj is approximately 150 to 300 % higher than in method A and B. The effect of methods in task 4 is not significant ($p>0.05$). In figure 8 (b), the maximum joint velocity is demonstrated. In task 1 and 2, method D has the lowest maximum joint velocity while method A has the highest among all methods (with $p < 0.05$). The declining trend is shown in task 1, where the maximum joint velocity of method A>B>C>D. In task 3 and 4, there is no significant difference among methods. However, the maximum joint velocity is still very high for all the methods, considering that the desirable joint velocity should be no larger than 1 rad/sec.

The percentage of time that the joint velocity exceeds the specified value (1 rad/sec) for each task is shown in figure 9. For joint 1 velocity, the effect of methods is not significantly different in task 1,3 and 4. The percentage of time that joint 1 velocity exceeds 1 rad/sec is slightly higher (less than 2%) in method C and D than method A and B. For joint 2, the percentage of time that the joint velocity exceeds 1 rad/sec in method A and B is approximately 20% higher than in method C and D for task 1 and 5% higher for task 2 (with $p<0.05$). The difference in methods is not significant in task 3 and 4. For joint 3, the percentage of time that the joint velocity exceeds 1 rad/sec is also significantly higher in method A and B than method C and D for task 1 and 2 ($p<0.05$).



(a) (b) (c)

Figure 9. (a) Percentage of time that Joint 1 velocity exceeds 1 rad/sec. (b) Percentage of time that Joint 2 velocity exceeds 1 rad/sec. (c) Percentage of time that Joint 3 velocity exceeds 1 rad/sec.

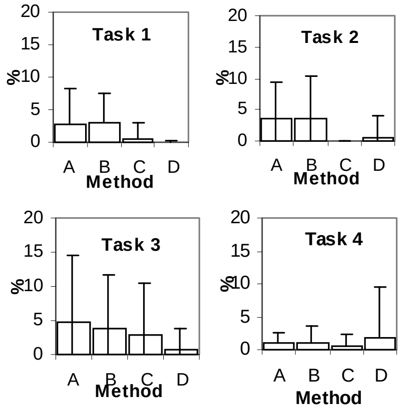


Figure 10. Percentage of time that the Cj is below 0.01

In figure 10, the bar graph shows the percentage of time that the Cj is below 0.01 for each task. In task 1,2 and 3, the percentage of time that the Cj is below 0.01 is significantly higher for method A and B than C and D. Method D has the lowest percentage of time in task 1 and 3, while method C has the lowest percentage of time in task 2. The effect of methods is not significant in task 4.

From the experimental result, the singularity force feedback (method C and D) seems to be able to improve the teleoperation performance considerably in task 1 and 2. In task 3, the singularity force feedback alone (method C) does not improve the teleoperation performance as much as when multimodal feedback is given (method D). In task 4, the effect of singularity force feedback is considered to be insignificant. However, the graph of the minimum Cj in figure 8 (a) shows that the minimum Cj for all methods is generally higher in task 3 and 4 than in task 1 and 2. By observing the trajectory deviation data in task 3, the operator tends to manage a large deviation from the straight-lined trajectory even before reaching singularity in the later trials after experiencing the problem from singularity in the first trial. In task 4, a straight line from the initial point to the target point only passed through the alignment singularity very slightly. Thus, even a small deviation from the trajectory can easily keep the operator from approaching the singularity.

5. CONCLUSIONS

The objective of this study is to demonstrate that the haptic feedback of kinematic condition can be augmented to the standard feedback such as visual feedback from the slave manipulator. When the slave manipulator reaches a poor kinematic configuration, haptic feedback can provide the additional guidance to the operator so that he/she could respond to the problem interactively. The haptic feedback of the two well-known kinematic condition problems, the singularity and the joint limit, are proposed. The singularity force feedback provides both proximal and directional information, necessary for dealing with singularity, to the operator in real-time.

The teleoperation experiment was performed to validate the effect of the kinematic information feedback in the teleoperated system. Three alternative methods of kinematic information feedback including visual and auditory feedback, singularity force feedback, and multimodal feedback, as well as a standard method with no kinematic information feedback were investigated in the experiment. The test tasks were defined so that they were susceptible to the singularities. For the tasks that were highly sensitive to singularities, the teleoperation performance as measured by kinematic conditioning of the slave manipulator was greatly improved in the methods that the singularity force feedback was given. With the multimodal feedback (visual, auditory and force), the teleoperation performance is generally better than other methods.

The result from the experiment shows that the haptic feedback, which represents kinematic information of singularity, can improve the teleoperation performance in the neighborhood of singularity. However, the result demonstrates a very high joint velocity (figure 8b) even when the singularity force feedback or the multimodal feedback is used. To reduce these high joint velocities, we may have to improve the proposed singularity force feedback by adjusting some parameters in the force feedback calculation or modifying the algorithm. We also plan to study the effect of joint limit force feedback in the teleoperated system and the effect of haptic feedback of kinematic condition in the situation where it is superimposed by other type of force feedback.

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REFERENCES

1. Adams R. and Hannaford B, “Excalibur, A three-axis force display,” ASME Winter Annual Meetings Haptics Symposium, Nashville, TN, Nov 1999.
2. Hannaford B.,Wood L.,McAffee A., and Zak H., “Performance evaluation of a six-axis generalized force-reflecting teleoperator,” IEEE Trans. On Systems, Man and Cybernetics, vol.21, No.3, pp.620-633, 1991.
3. Hwang D.Y., “Teleoperation Performance with a Kinematically Redundant Slave Robot,” Ph.D. Dissertation ,University of Washington, Department of Electrical Engineering, Dec 1995
4. Maneewarn T., and Hannaford B., “Haptic feedback of kinematic conditioning for telerobotic applications,” Proceedings of IROS 98, pp.1260-65, Canada, 1998.
5. Maneewarn T., Hannaford B., Storti D. and Ganter M., “Haptic rendering for internal content of an implicit object,” ASME Winter Annual Meetings Haptics Symposium, Nashville, TN, Nov 1999.
6. Nakamura Y., and Hanafusa H, “Inverse Kinematic Solutions with Singularity Robustness for Robot Manipulator Control,” ASME J.Dynam.Sys.Measurement and Control vol.108,pp.167-171,1986.
7. Salganicoff M., Rahman T., Mahoney R., Pino D.,Jayachandra V.,Kumar V., Chen S., and Harwin W., “Head controlled assistive telerobot with extended physiological proprioception capability,” Proceedings of SPIE, vol.2590, pp.108-119,1995.
8. Salisbury K., and Tar C., “Haptic rendering of surfaces defined by implicit functions,” Proc. ASME Dyn. Sys. and Control Div., DSC-Vol.61,pp.61-67,1997.
9. Smith D.,”Kinematic Do-ability for manipulator analysis”, MSEE Thesis, University of Washington, Department of Electrical Engineering, 1994.
10. Yoshikawa T., “Translational and rotational manipulability of robotic manipulators,” Proc. of the 1990 American Control Conference, San Diego, CA, pp.228-233, May 1990.