Abstract

This paper studies the effects of three methods of kinematic redundancy resolution on teleoperation performance with a redundant slave robot in telemanipulation. First, we derive three kinematic redundancy control modes expressing different trade-offs between kinetic energy, joint usage, and joint-limit avoiding. To validate our algorithms, we perform simulations, autonomous robot tests, and teleoperation experiments. The trade-off between kinetic energy and joint-limit index is clearly shown in the autonomous test. For teleoperation, four tasks and seven indices are defined. A three-degrees-of-freedom (DOF), pen-based master and a 5-DOF, mini-direct-drive robot are used with position-to-position control in Cartesian space. Tasks are x-, y-, and z-positioning and contact-force control giving 2-DOF kinematic redundancy in the slave robot. Overall, the inertia-weighted pseudo-inverse, proposed by Whitney in 1969, shows best performance, while the least-square mode (using no inertial information) shows the worst performance.

1. Introduction

Since Goertz's practice in the 1940s (Goertz and Bevilaqua 1952), there have been many applications of teleoperation, such as space, undersea, and nuclear-plant remote manipulation. Recently, teleoperation application has expanded into microsurgery, microassembly, and inspection. Teleoperation enables a human to manipulate an object that belongs to the remote world or the microworld. A typical teleoperation system is composed of five subsystems: human operator, master handle or robot, communication, slave robot, and unstructured task environment. Consequently, many research results on the control and design of autonomous robots can be used for the master or slave robot in teleoperation.

Kinematically redundant robots have been an active research topic since the late 1970s. An increased number of joints compared to the main task dimensions gives a robot extra capacity to do subtasks or optimizations. Relatively little research has been performed on the use of kinematically redundant robots in teleoperation, and simulation results are predominant.

This paper is about the performance of a teleoperation system with kinematic redundancy in the slave robot. We describe three control methods and evaluate them on an experimental mini-teleoperation system. The master robot is a previously developed, pen-based, 3-degrees-of-freedom (DOF), serial/parallel mechanism (Buttolo and Hannaford 1995). The slave robot is a 5-DOF mini direct-drive robot also developed in our lab (Hannaford et al. 1996). If the teleoperation task is confined to x-, y-, z-positioning and contact, the slave can be thought of as having 2-DOF kinematic redundancy. The question we study in this paper is, Can the redundant DOF of the slave manipulator be used to improve or optimize the quality of the kinesthetic force feedback provided to the operator?

Our control system is a version of the force-reflective controller used as far back as the 1940s (Goertz and Bevilaqua 1952; Goertz and Thompson 1954), in which torque commands to master and slave are based on position error between master and slave in joint space. Since our master and slave manipulators are not kinematically correspondent, we compute this error in Cartesian space before computing the corrective feedback.

It is well known that in this kind of control, the operator feels forces proportional to the inertial forces in the slave, and this was confirmed in our initial informal experiments.
on the system. With a redundant slave manipulator, it may be possible to reduce or minimize this sensation.

The following section contains a review of relevant literature in the areas of redundant manipulator control and direct-drive robots.

1.1. Redundant Manipulator Control

The slave manipulator in teleoperation is a working robot performing the physical task. When the slave manipulator has kinematic redundancy, the global teleoperation system might be able to benefit from the extra capabilities of obstacle avoidance, singularity avoidance, and dexterity optimization, among others.

A robotic manipulator can be called redundant if it has more joint-space freedoms than the Cartesian task space in which it is working. This kind of robot can do one or more extra subtasks or optimize joint-space motion with a given criterion while performing the main task. Since the late 1970s, lots of research interest has been given to exploiting redundant manipulators for joint-limit avoidance (Liegeois 1977; Klein and Chirico 1987; Chan and Dubey 1995), singularity avoidance (Yoshikawa 1984; Sciacco and Siciliano 1987), obstacle avoidance (Glass et al. 1995; Klein 1985), dexterity optimization (Yoshikawa 1984; Williams 1994), torque optimization (Suh and Hollerbach 1987), global optimization (Kazerounian and Wang 1988; Nakamura 1991), etc.

Whitney (1969) used the redundant motion to minimize the kinetic energy of the manipulator at each instant of time. Vukobratovic (Vukobratovic and Kircanski 1984) developed an inverse solution involving the dynamic model of a hydraulic manipulator and its actuators for minimizing the energy consumption in the sampling-time interval. Optimization of the joint rates and kinetic energy over an entire trajectory was done by Kazerounian and Wang (1988). A similar problem was solved by Nakamura and Hanafusa using Pontryagin’s maximum principle (Nakamura 1991). Since 1988, global optimization along the whole path has been an active topic, but this work is mostly simulation oriented. In the teleoperation case, only local optimization is possible, since the slave manipulator is controlled by the human operator (HO) on-line and the full trajectory is thus unknown to the system in advance.

We can find several articles on teleoperation with kinematic redundancy, such as a telerobot task-execution system with a 7-DOF remote robot (Backes et al. 1994), and real-time collision avoidance using the damped least-square method (Glass et al. 1995). However, these studies mainly address system architecture and collision avoidance in the remote robot, not teleoperation performance or the quality of force feedback.

As telemanipulation systems become more advanced, we expect that redundant manipulators will be used more frequently as remote slave manipulators. Thus it is worthwhile to study the possible uses of kinematic redundancy for performance optimization.

1.2. Direct-Drive Minirobot and Pen-Based Systems

The five-axis minirobot (Fig. 1b) we used as a slave manipulator was developed as a preliminary prototype for the NASA Micro Telerobotics Experiment, MicroTrex (Hannaford et al. 1994). This planned joint experiment between the University of Washington, the Jet Propulsion Lab, and Boeing Defense and Space Company, will launch a small robot manipulator into low earth orbit and control it from the ground to perform an end-to-end test of ground-based remote control of space robots.

Direct-drive (DD) robots have several advantages for manipulation, including high precision and high speed (Asada and Kanade 1983; Hannaford et al. 1994, 1996). Since they don’t use force- or torque-transfer mechanisms such as gears or belts, they have little backlash and deadband. DD robots have higher bandwidth, so that more advanced control-law application is possible. They also provide the teleoperation systems with the ability to backdrive.

DD robots also have disadvantages, which were recognized in the late 1980s, including high heat dissipation under gravity loads. However, scaling analysis shows that in small DD robots such as ours this problem is reduced dramatically (Hannaford et al. 1996).

The pen-based force display is a direct-drive, serial/parallel manipulator (3-DOF, four actuators) for teleoperation or virtual environments built by P. Buttolo in 1994 (Fig. 1a) (Buttolo and Hannaford 1995). The mechanism consists of a planar linkage which is tilted up and down by a pair of rotary actuators. Three two-link arms are located with bases at 120-degree intervals around a circle. The distal points of each arm are merged at the center of the workspace plane. The device can be interfaced with the human operator either at the fingertip or at the tip of a freely held pen-like instrument. A parallel-link mechanism with closed kinematics has some advantages over the usual serial mechanism: it increases the structural strength and end-effector forcing ability. On the other hand, control is more complicated (Buttolo and Hannaford 1995).

Slave-side force information to be reflected to the human operator can either be measured by a force/torque sensor or estimated from position error. When using a force sensor, separation between sensor and actuator often causes difficulties in stability and control. In addition, when the manipulator is small, attaching a sensor is hard and wiring is also a problem. In this study force was estimated from position error, as was done by Goertz (Goertz and Bevilacqua 1952; Goertz and Thompson 1954) and others (Hwang and Hannaford 1994).

This paper describes the performance of a kinematically redundant teleoperation system in terms of several indices,
such as completion time and mean force, and the human operator's subjective rating. Three control modes for kinetic energy minimization and joint-limit avoidance are derived in Section 2. In Section 3, we show the performance of these three control modes in the single robot case by simulation and experiment. In Section 4, the teleoperation performance is studied by experiment.

2. Kinetic Energy Optimization and Joint-Limit Avoidance

The pseudo-inverse and the weighted pseudo-inverse are briefly reviewed here. We analyze manipulator velocity in joint space ($\dot{\theta}$) and end-effector Cartesian space ($\dot{x}$).

When the equation for incremental motion is given as

$$\dot{x} = J\dot{\theta},$$

where $\dot{x} \in R^m$, $\dot{\theta} \in R^n$, $m \leq n$ with either of the following constraints:

- nonweighted case: $\min \| \dot{x} - J\dot{\theta} \|$ and $\min \| \dot{\theta} \|
- weighted case: $\min \| \dot{x} - J\dot{\theta} \|$ and $\min \| \dot{\theta} \|^2_M = \dot{\theta}^T M \dot{\theta}$

The solution is:

$$\dot{\theta} = J_1^+ \dot{x} + (I - J_1^+ J)\dot{z}$$

where $J_1^+$ is a pseudo-inverse matrix of $J$ and $\dot{z}$ is an arbitrary vector ($n \times 1$), and $M$ is a matrix of weights that can be the manipulator inertia matrix.

The pseudo-inverse solution for the nonweighted case is

$$J_1^+ = J^+ = J^T (JJ^T)^{-1}$$

and in the weighted pseudo-inverse case,

$$J_1^+ = J_M^+ = M^{-1} J^T (JM^{-1} J^T)^{-1}.$$
Fig. 2. (a) The second norms of the errors \( \left( J^+_M - J^+_{k_p} \right)^2 \) (the pseudo-inverse for the Whitney solution) and \( J^+_{k_p} \) (the pseudo-inverse for intermediate solution of eq. (11)); (b) the condition number (see the text) with varying \( k_p \).

where \( B = I + 2k_p(I - J^+ J)M, B_1 = 2(I - J^+ J)M, \) and \( B \) should be nonsingular. From eq. (10) we can define a kind of inertia-weighted pseudo-inverse of \( J \) as

\[
J^+_k = (I + 2k_p(I - J^+ J)M)^{-1} J^+
\]  

(13)

The positive, scalar value \( k_p \) determines how strongly the null-space motion will be driven by the gradient of KE. We have not fully analyzed the relationship between \( J^+_k \) and \( J^+_M \). However, when \( k_p = 0 \), it is clear from eq. (13) that \( J^+_k = J^+ \), and the KE gradient is ignored. We will now explore what happens to \( J^+_k \) as \( k_p \) is increased. We notice that as \( k_p \) becomes large, \( J^+_k \) approached the inertia-weighted pseudo-inverse, \( J^+_M \) as shown in Figure 2a. In Figure 2, the second norm of the difference between \( J^+_M \) and \( J^+_k \) and the condition number of the matrix \( B \) in eq. (11) are plotted as a function of \( k_p \). If \( k_p \) is beyond a big number (\( > 10^{16} \) for the SUN workstation), the finite precision of the computer arithmetic degenerates the accuracy. Also, the condition number of \( B \) increases from 1 at \( k_p = 0 \) as \( k_p \) increases. We will assume that the solution eq. (11) is only usable if the condition number of the matrix \( B \) is less than \( 10^5 \).

To further study this type of control, we simulated a task in which the manipulator tip traced a horizontal circle 1 cm in diameter. The circle tracing was performed using three pseudo-inverse methods for solving the problem:

\[
\dot{x} = J^+_k \dot{\theta}.
\]  

(14)

These were

\[
J^+_M, \quad J^+_k \text{ where } k_p = 10^3 \sim 10^5
\]

The five-axis minirobot inertia matrix, \( M \) was derived (Hannaford et al. 1994), and the constant diagonal form was used. The robot is somewhat unusual in that its limited joint-motion range justifies this approximation (Hannaford et al. 1994). The resulting KE as a function of time during one revolution is shown in Figure 3.

2.2. Joint-Limit Avoidance

When we applied the kinetic energy optimization schemes of Section 2.1 to our slave manipulator, we found that the Whitney mode tries to use the lightest joints, J4 and J5, maximally to minimize the kinetic energy. The endpoint-positioning task was contained well within the dexterous workspace. However, the KE optimization generated null-space motion, which made joints 4 and 5 easily reach their limits. To solve this problem, we added a joint-limit avoidance (Liegeois 1977; Klein and Chirco 1987; Chan and Dubey 1995) criterion to the redundancy control. We determined that the gradient projection method was appropriate for joint-limit avoidance, because there is no kinematic singularity inside the workspace of our manipulator, and the gradient is easy to compute. The resulting trajectories with and without joint-limit avoidance are shown in Figures 4 and 5.
2.2.1. Homogeneous Solution for Joint-Limit Avoidance

It turns out (Liegeois 1977) that if we write eq. (5) as

$$
\dot{\theta} = G_1 \dot{x} - (I - G_2 J) x,
$$

then $G_1$ and $G_2$ need not be the same pseudo-inverse matrices of $J$.

We use this idea for the two subtasks: kinetic optimization and joint-limit avoidance, i.e., $G_1$ can be $J^+$, $J_+^+$, or $J_M^+$ in Section 2.1; $G_2$ is the pseudo-inverse $J^+$; and $x$ is the gradient descent of the cost function for joint-limit avoidance. Here, we used a typical cost function for joint-limit avoidance (Liegeois 1977; Klein and Chirco 1987), namely

$$
H_2(\theta) = \sum_{i=1}^{n} \left( \frac{c_i}{a_i^2} \right) (\theta_i - \theta_{ih})^2,
$$

where

$$
\theta_{ih} = \text{home position vector in joint space},
$$

$$
a_i = \left( \frac{1}{2} \right) |\theta_{i,max} - \theta_{i,min}|,
$$

$$
c_i = \text{weight for each normalized joint displacement from home position}.
$$

For the optimization of both instantaneous kinetic energy and joint-limit avoidance, we compose the joint-velocity solution as

$$
\dot{\theta} = \dot{\theta}_p + \dot{\theta}_H
$$

$$
= G_1 \dot{x} - \alpha(I - J^+ J) \nabla H_2.
$$

In eq. (17), the inertia-weighted particular solution, $\dot{\theta}_p$, is decided by the optimization of $H_1$, and the homogeneous solution, $\dot{\theta}_H$, is decided by the optimization of $H_2$.

2.2.2. Weighting Factors for Joint-Limit Avoidance

One of the two gains to be decided is $\alpha$ in eq. (18). This gain decides the null-space solution size in eq. (18), which is the relative amount of joint-limit avoidance. If $\alpha$ is too big, the null-space solution dominates the total joint-space solution, and the motion for joint-limit avoidance will be overly active. In addition to this, the kinetic energy level difference between the three inertia-weighting modes will fade. The other gain, $c_i$, which is the weighting factor in eq. (16), strongly affects the robot joint motion for joint-limit avoidance. To decide the weighting factor for each joint, we tested many combinations starting from the vector with all elements of one. Then we did the circle drawing ($R = 5 \sim 12$ mm) by simulation and experiment. We applied three criteria during the tests. One was whether joint 4 or 5 touched a limit. The second was...
the stability of the motion; some weighting vectors showed oscillation at some regions of the circle. The third was the tracking error in the Cartesian space. If some joints have lag owing to friction, gravity, heavy dynamics, or low gains, high tracking error in the Cartesian space and poor performance of the subtask will result. After many rounds of trial and error, we chose the following values for the later experiments:

\[
[c_3] = [1 \ 4 \ 600 \ 8.5 \ 2750] \\
\alpha = 0.003
\]

However, there can be many other combinations to meet the three criteria.

3. Single Robot Performance Comparison

To verify the basic algorithms, we made a comparison using the slave robot alone. We used the three different pseudo-inverses of \( J \), with the same null-space solution for joint-limit avoidance. The five-axis minirobot was used in this simulation and experiment.

3.1. Three Schemes for Comparison

Scheme 1 uses \( J_M^+ \), Whitney's inertia-weighted pseudo-inverse, for \( H_l \) optimization. Including the joint-limit avoidance gives

\[
\hat{\theta} = J_M^+ \hat{x} - \alpha (I - J^+ J) \nabla H_2 ,
\]

where \( J_M^+ = M^{-1} J^T (J M^{-1} J^T)^{-1} \).

Scheme 2 uses \( J_{kp}^+ \) for \( H_l \) optimization, with \( kp = 40,000 \):

\[
\hat{\theta} = J_{kp}^+ \hat{x} - \alpha (I - J^+ J) \nabla H_2 ,
\]

where \( J_{kp}^+ = (I + 2kp(I - J^+ J)M)^{-1} J^+ \).

Scheme 3 uses the least-squares solution pseudo-inverse of \( J \). In this case, kinetic energy information is not used:

\[
\hat{\theta} = J^+ \hat{x} - \alpha (I - J^+ J) \nabla H_2 .
\]

3.2. Simulation and Experiment

We chose circle drawing (\( R = 5 \) mm) in the horizontal plane as a single robot task. This circle is relatively small, but so is the robot. The diameter of 1 cm represents about 40% of the total x-axis (i.e., joint 1) travel of the robot.

3.2.1. The Simulation

Figure 6 is the block diagram of the simulation. We ignored the robot dynamics and its control in the simulation. In this simulation, the angle of the desired Cartesian point was increased in each time increment by 360°/1030, which is a similar increment size to that used in the experiment. This rate corresponds to 0.2π rad/sec.

The circle-drawing trajectories followed by the joints using the three control modes are shown in Figure 7. Figures 8 and 9 show the kinetic energy level and joint-limit index as the robot followed the circular trajectory in the simulation. The averaged kinetic energy level difference was about 1% between the three modes, with scheme 1 (Whitney) lowest. This small difference results from the small task size and because the joint-limit avoidance solution term is dominant. The mean joint-limit indices of the three modes were 0.48, 0.46, and 0.41.

3.2.2. The Experiment

The system block diagram for the circle-drawing experiment is the same as for the teleoperation case, except that the slave robot uses a computed circular trajectory instead of receiving one from the master (Fig. 14). The joint trajectories for the three modes when the slave robot traced the circle are shown in Figure 10. Figure 11 shows the measured KE of the slave in the three modes. Spikes are apparent in the kinetic energy owing to sensor noise amplified by the velocity estimator and squared. The averaged levels of KE were 8.79 \times 10^{-8}, 10.1 \times 10^{-8}, and 16.8 \times 10^{-8}J for the Whitney, intermediate, and least-squares modes, respectively. Figure 12 shows the joint-limit index curves for the three modes. Mean values were 0.65, 0.63, and 0.37. Except for joint 5, there were differences among the three modes. The implemented path of the slave end effector is shown in Figure 13.
some tracking error and lagging in the x-direction and in the second and fourth quadrants owing to slow dynamics of the first linear joint. The repetitive accuracy is good, as shown in Figure 13. Overall, the intermediate mode shows the smallest Cartesian space tracking error.

3.3. Discussion of the Single Robot Case

The curves of the KE level and joint-limit (JL) index are similar in the simulation and the experiment. However, the difference between the three modes was larger in the experiment. One reason is that the simulation didn’t include the robot dynamics. If we compare the mean of the instantaneous KE between simulation and experiment, there is a big difference. For example, the least-squares (LS) mode has
Fig. 12. The joint-limit index curves of an $R = 5$-mm circle drawing by three modes: (a) Whitney; (b) intermediate; (c) least squares. Experiment.

$1.3 \times 10^{-6} J$ in simulation and only $1.0 \times 10^{-7} J$ in the experiment. In the experiment, the heavy, first linear joint moved only 5% as much as in the simulation. Further analysis of the KE showed that the first joint KE was 90% of the total KE in the simulation.

The reduced motion of joint 1 occurred because the nullspace part of our solution is achieved only by local control without global joint-configuration control, while the first joint has heavy dynamics.

The Whitney mode showed the lowest KE level and highest JL index curve. If we calculate the JL index for each joint separately from Figure 10, the joint JL indices are $0.004$ (joint 1), and $0.02$, $0.01$, $0.29$, and $0.32$ (joints 2–5, respectively). These indices are normalized without weighting; hence, joints 4 and 5 generate most of the total JL index. In the case of joint 4 motion, the LS mode showed little use of this joint, while the Whitney mode used it a lot. This made a big difference in the JL index curve.

A trade-off between KE level and JL index is shown by simulation and experiment. The trade-off degree depends on the weighting vector for JL avoidance, joint-range normalization, and $\alpha$ in eq. (18). We cannot simply say that the higher JL index curve is undesirable. If a robot actively uses the lighter joints without touching the joint limits during the task performance, this may be good in terms of KE and dexterity.

4. Teleoperation Performance Study

4.1. Teleoperation Experiments

We performed additional experiments to study the effects of the three kinetic energy control schemes on teleoperation performance. The same three control modes used in the single robot study were used here. Master and slave control and communication occurred at a 300-Hz rate, owing to the computation time required for the pseudo-inverse. In this teleoperation control, no force sensors were used. Instead, the master reaction force to the human operator was based on the Cartesian position error between the master and the slave. The slave interaction force with an object was estimated using the relationship, $F = (J^T)^{-1} \tau$. The torque, $\tau$, was computed from the measured current of each joint. The master used PD control for the force reflection (Buttolo and Hannaford 1995). For the slave dynamics control, we used the PD plus computed torque method. The integral gain was disabled, because when it was used, the LS mode showed unnecessary self-motion.

4.1.1. Performance Indices and Tasks

4.1.1.1. Performance Indices

Seven performance indices were used, depending on the task, to evaluate teleoperation performance under the three modes. The indices were: averaged kinetic energy level, joint-limit index, completion time, master reaction force to the human operator, slave-reaction force from the environment, variance of slave force, and variance of position error in the slave. The performance indices are defined as follows.

Averaged kinetic energy of the slave robot:

$$P_{KE} = \frac{\sum_{k=1}^{N} \frac{1}{2} \left( \frac{\theta_{sk} - \theta_{sk-1}}{\Delta t} \right)^T}{N} \times M_s \left( \frac{\theta_{sk} - \theta_{sk-1}}{\Delta t} \right) / [t_f N],$$

where $N$ is the recording rate (/100 sec), and $t_f$ is the completion time (sec).

Joint-limit index of the slave robot:

$$P_{JL} = \frac{\sum_{k=1}^{N} \sum_{i=1}^{5} \left| \frac{\theta_{ski} - \theta_{skh}}{a_i} \right|}{[t_f N]}.$$

Completion time of a task:

$$P_{CT} = \int_0^{t_f} dt.$$

Master reaction force to human operator:

$$P_{f_m} = \left( \sum_{k=1}^{N} |f_{mk}| \right) / (t_f N).$$

Slave reaction force from the task object:

$$P_{f_s} = \left( \sum_{k=1}^{N} |f_{sk}| \right) / (t_f N).$$
Fig. 13. Measured Cartesian path of two turns in single robot circle test using three modes: (a) Whitney (mode 1); (b) intermediate (mode 2); (c) least squares (mode 3). Experiment.

Fig. 14. Teleoperation control block diagram: master (3-DOF, pen-based system) and slave (5-DOF minirobot). Position-to-position control in Cartesian space for teleoperation. Three different differential inverse kinematics modules are used in the slave robot.

Variance of the applied force by the slave robot:

\[
P_{f_s} = \frac{1}{t_f N} \sum_{k=1}^{t_f N} (\bar{f}_s - f_s(k))^2, \quad \bar{f}_s = \frac{1}{t_f N} \sum_{k=1}^{t_f N} f_s(k).
\]  

Variance of the position error by the slave robot:

\[
P_{p_{ep}} = \frac{1}{t_f N} \sum_{k=1}^{t_f N} (e_{p}(k) - \bar{e}_{p})^2, \quad \bar{e}_{p} = \frac{1}{t_f N} \sum_{k=1}^{t_f N} e_{p}(k).
\]

Note that better performance is indicated by lower values of all of these performance measures.

4.1.1.2. Task Definition

Three tasks were defined for evaluation of teleoperation system performance:

Two-point tapping. This task was to make alternate tapping contacts between the end-effector tip and two 2-mm-diameter circles arranged 10-mm apart on a diagonal line in the x-y plane (Fig. 15a). The task was paced by a metronome. Two speeds were used: slow tapping (subtask 1a) with 56 taps/min, and fast tapping (subtask 1b) with 108 taps/min; 20 s of tapping were recorded for each trial. Performance indices used for this subtask included \( P_{KE} \) the average kinetic energy level (slave), \( P_{JL} \) the joint-
Corner tracing. This subtask was to perform a constrained motion following a raised edge in an aluminum test fixture (Fig. 15b; thick-lined edge). The length of each side was 14 mm, and the edge depth was 1.0 mm. Data were recorded from five repetitions of the task. $P_{KE}$, $P_{JL}$, $P_{CT}$ (completion time), $P_{Fe}$ (variance of slave force), and $P_{v_{tip}}$ (variance of the slave tip position) were chosen as performance indices for this task.

Nut pushing. The third subtask was to move a 4.6-mm nut by pushing it along an L-shaped channel (Fig. 15c). The channel width was 5.2 mm. Data were recorded from five repetitions of the task. $P_{KE}$, $P_{JL}$, $P_{CT}$, and $P_{Fe}$ (slave contact force) were the performance indices.

Six test operators performed the teleoperation experiment. The order of execution of the three control modes and the subtask order in each mode were randomized. The performance indices were computed from each subtask, and each test operator answered a questionnaire after the experiment. Test operators used the questionnaire to characterize any disturbance forces they felt into categories of inertia force, bias force, and noise. Each force was rated between 1 (light feel or low noise level) and 7 (heavy feel or high noise level).

4.2. Teleoperation Results

4.2.1. Experimental Data Sets

In this section, we describe the data obtained during teleoperation with the three tasks and three control modes. For each subtask we first show a typical recording of position and force data from a single repetition, and then plot averages over all six test operators and repetitions.

4.2.1.1. Slow Two-Point Tapping

Figure 16 shows typical position and force recordings in the slow two-point tapping task in the Whitney mode. The upper four subplots are master and slave Cartesian-position trajectories in the x-, y-, and z-directions, as well as their projections into the xy-plane. The projected Cartesian trajectories look quite crowded, because 20 loops are overlapped. In the x- and z-directions, larger amplitude curves are the master position. The tracking errors are visible at the turning points. The z-direction tracking error is rather big, because of the heavy master inertia in the z-direction and the large inertia and gravity term of the third joint in the slave. The lower four subplots are master and slave Cartesian-force trajectories in the x-, y-, and z-directions and the Cartesian-force projection into the xy-plane. In the x- and y-force trajectories, the spiky curve with larger amplitude is the master force. The y-direction slave force shows much smaller magnitude than the master. The x-direction slave force shows much larger magnitude than the master. The z-direction force shown in Figure 17 has the bias level in Figure 16 removed. The slave forces $F_{xy}$ and $F_{xyz}$ increased by 47% and 13% from mode 1 to mode 3.

4.2.1.2. Fast Two-Point Tapping

Figure 18 shows typical data from the fast two-point tapping task with the intermediate control mode. The number of repetitions almost doubled compared with the slow-tapping case. Figure 19 shows the performance evaluation for the fast two-point tapping. The average KE was almost four times greater than with slow tapping, but as with the slow tap-
Fig. 16. Typical position and force of master and slave in slow two-point tapping task with Whitney control mode. Upper row: master and slave Cartesian space position trajectories in x-, y-, and z-directions (left three plots), and their projection into the xy-plane (right plot). Lower row: master and slave Cartesian space force trajectories in x-, y-, and z-directions (left three plots), and their projection into the xy-plane (right plot).

ping, the KE level of the slave robot increased by 153% from mode 1 (Whitney mode) to mode 3 (LS mode). The variance also increased from the Whitney mode to the LS mode. The joint-limit index was unchanged from slow tapping, and increased by 56% across the modes, also a similar increase to slow tapping. The force levels were almost the same between fast and slow tapping. The master reaction force to the human operator in the xy-plane slightly decreased from mode 1 to mode 3. If we look at the force components, the x-direction force is unchanged and the y-direction force decreased by 50% from mode 1 to mode 3. The z-direction force is two times larger than the xy-plane force. The slave forces, $F_{xxy}$ and $F_{xxyz}$, increased by 88% and 20%, respectively.

4.2.1.3. Corner Tracing

Figure 20 shows typical data from the corner-tracing task. The position-tracking errors have increased owing to contact with the environment. Figure 21 shows the performance evaluation for the corner-tracing task. The KE level of the slave robot increased by 133% from the Whitney mode ($4.3 \times 10^{-6}$ J) to the LS mode ($10 \times 10^{-6}$ J). The joint-limit index increased by 30%. The completion time was unchanged. Regarding the force application in the slave manipulator, there were little or no differences in the x- and z-directions over the three modes; however, the LS mode showed large variance in the y-direction.

Although this was a constrained-motion task, it was easy to lose the constraint by popping over the 1-mm high edge. Recovery was easy as well, and this event did not suspend the task. Thus, position error can be viewed as a measure of the ability of the operator to stay within the constraint. The Whitney mode had more error in the x-direction (following the y-axis in Fig. 15b) and has less error in the y-direction (following the x-axis) than the LS mode. The Whitney mode had 20% less position-error variance in the z-direction than the LS mode.

4.2.1.4. Nut Pushing

Figure 22 shows typical data from the nut-pushing task. The position-tracking error was greatly reduced compared with the corner-tracing task. This means that only small forces were needed in this task. Figure 23 shows the performance evaluation result for the nut-pushing task. The KE level of the slave robot increased by 230% from the Whitney mode ($2.03 \times 10^{-6}$ J) to the LS mode ($6.69 \times 10^{-6}$ J). The joint-limit index increased by 40%. The completion time was unchanged. In the master, the Whitney mode showed a 17% lower force level than the LS mode, while the x-, y-, and
Fig. 17. Overall performance indices of the slow two-point tapping experiment: average kinetic energy, joint-limit index, master reaction force ($F_{xy}$ and $x$-, $y$-, and $z$-components). Asterisk represents mean value; line shows +/- 1 standard deviation interval.

Fig. 18. Recorded position and force of master and slave in fast two-point tapping. Upper row: master and slave Cartesian space position trajectories in the $x$-, $y$-, and $z$-directions (left three plots), and their projection into the $xy$-plane (right plot). Lower row: master and slave Cartesian space force trajectories in the $x$-, $y$-, and $z$-directions (left three plots), and their projection into the $xy$-plane(rightmost plot).
Fig. 19. Overall performance indices of fast two-point tapping experiment: average kinetic energy, joint-limit index, master reaction force ($F_{xy}$ and x-, y-, and z-components). Asterisk represents mean value; line shows +/- 1 standard deviation interval.

Fig. 20. Typical position and force of master and slave in corner-tracing task. Upper row: master and slave Cartesian position trajectories in the x-, y-, and z-directions (left three plots), and their projection into the xy-plane (right plot). Lower row: master and slave Cartesian force trajectories in the x-, y-, and z-directions (left three plots), and their projection into the xy-plane (right plot).
z-force components are changed by 12%, -41%, and 16%, respectively, from the Whitney mode to the LS mode. In the case of the slave reaction force from the object, the Whitney mode showed a 32% smaller force than the LS mode, while the x-, y-, and z-force components for the Whitney mode were smaller than the LS mode by 17%, 61%, and 35%, respectively.

4.2.2. Subjective Quality Ratings
Each test operator was asked to rate their subjective impressions of quality after performing each subtask. The collected data were classified by the control mode, then summed and averaged. The data were essentially random, without a consistent difference evident between the modes.

5. Discussion
5.1. Teleoperation Performance
5.1.1. Performance Indices
5.1.1.1. Kinetic Energy
The KE index showed a consistent trend over the four tasks. The Whitney mode showed the lowest KE level, while the LS mode showed the highest KE level. This trend agrees with the single robot circle-drawing experiment.

5.1.1.2. Joint-Limit Index
The JL index showed a similar trend with a smaller change between the three modes. This result was opposite to the single robot case. The difference between the single robot test and teleoperation was that integral gain was not used in the teleoperation case. This integral gain plays a big role in achieving accurate tracking of the null-space solution in the joint space. Without the integral gain, small joint-space motion doesn’t occur because of friction and gravity.

5.1.1.3. Master Reaction Force
In the nut-pushing task, the master reaction force increased by 25% from the Whitney mode to the LS mode. In the slow and fast two-point tapping, this force decreased about 10%. Overall, there was no clear trend.

5.1.1.4. Slave Contact Force
The slave force applied to the object increased by 20% and 50% from the Whitney mode to the LS mode in the fast two-point tapping task and the nut-pushing task, respectively.

Fig. 21. Overall performance indices of corner-tracing task: average kinetic energy, JL index, completion time (CT), master reaction force (Fx, y, and z-components), standard deviation of tracking force in slave. Asterisk represents mean value; line shows +/- 1 standard deviation interval.
5.1.1.5. Completion Time

Completion time (CT) was measured for the tasks that were not paced by the metronome. There was statistically little difference among the three modes, but the variance was large. We observed that the CT declined in the experiments performed later by each subject. This suggests that the learning effect was quite large. We randomized the order of the control modes and subtasks to control for this, but we may have obscured a small effect by doing this. In a future experiment, more training time should be used.

Apparently, the differences in inertia and other properties among the modes were not enough to make a measurable difference in the CT. The lightness of the master dynamics and the relatively slow, simple tasks may be some reasons for the small difference.

5.1.1.6. Variance of Slave Force

This data was measured during the corner-tracing task. Variance in force is a measure of the ability to control force during constrained motion. Higher variance means poor control. It is notable that we could do a constrained-motion task without using force sensing. The relationship $F = (J^T)^{-1} \tau$, and the low-friction, direct-drive robot made this possible. The Whitney mode showed more stable (low variance) forces in the x- and y-directions in the corner-tracing task.

5.1.1.7. Variance of Positioning

The results from the corner-tracing task showed that the best mode varied with the direction. The intermediate mode showed more variance in this contact motion.

5.1.2. Overall Performance

Table 1 summarizes the performance ratings from the four tasks. There was no mode showing superiority over all tasks and their performance indices. However, the Whitney mode (mode 1) excelled in 14 of 18 conditions. The intermediate mode (mode 2) showed medium performance overall, but it had the worst performance in five indices not related to the KE level. The least-squares mode (mode 3) showed the worst performance overall in 11 of 18 conditions. The LS mode had the best performance in the positioning accuracy of the corner-tracing task and in the completion time of the nut-pushing task.
Fig. 23. Overall performance indices of nut-pushing task: average kinetic energy, JL index, master reaction force ($F_{xy}$ and $x$-, $y$-, and $z$-components), slave force ($F_{xyz}$ and $x$-, $y$-, and $z$-components). Asterisk represents mean value; line shows $\pm 1$ standard deviation interval.

Table 1. The Three Modes Performance Rating

<table>
<thead>
<tr>
<th>Subtask 1:</th>
<th>mode 1 (Whitney)</th>
<th>mode 2 (Intermediate)</th>
<th>mode 3 (Least Squares)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-point slow tapping</td>
<td>KE level</td>
<td>●</td>
<td>△</td>
</tr>
<tr>
<td></td>
<td>JL index</td>
<td>●</td>
<td>△</td>
</tr>
<tr>
<td></td>
<td>$F_{mx}$</td>
<td>△</td>
<td>△</td>
</tr>
<tr>
<td></td>
<td>$F_{xy}$</td>
<td>●</td>
<td>△</td>
</tr>
<tr>
<td>Subtask 2:</td>
<td>KE level</td>
<td>●</td>
<td>△</td>
</tr>
<tr>
<td>Two-point fast tapping</td>
<td>JL index</td>
<td>●</td>
<td>△</td>
</tr>
<tr>
<td></td>
<td>$F_{mx}$</td>
<td>△</td>
<td>△</td>
</tr>
<tr>
<td></td>
<td>$F_{xy}$</td>
<td>●</td>
<td>△</td>
</tr>
<tr>
<td>Subtask 3:</td>
<td>KE level</td>
<td>●</td>
<td>△</td>
</tr>
<tr>
<td>Corner tracing</td>
<td>JL index</td>
<td>●</td>
<td>△</td>
</tr>
<tr>
<td></td>
<td>CT</td>
<td>●</td>
<td>△</td>
</tr>
<tr>
<td></td>
<td>Force variance (slave)</td>
<td>●</td>
<td>△</td>
</tr>
<tr>
<td></td>
<td>Position variance (slave)</td>
<td>□</td>
<td>△</td>
</tr>
<tr>
<td>Subtask 4:</td>
<td>KE level</td>
<td>●</td>
<td>△</td>
</tr>
<tr>
<td>Nut pushing</td>
<td>JL index</td>
<td>●</td>
<td>△</td>
</tr>
<tr>
<td></td>
<td>CT</td>
<td>△</td>
<td>□</td>
</tr>
<tr>
<td></td>
<td>$F_{m}$</td>
<td>●</td>
<td>△</td>
</tr>
<tr>
<td></td>
<td>$F_{s}$</td>
<td>●</td>
<td>□</td>
</tr>
</tbody>
</table>

Performance rating indicators: best (●), middle (△), and worst (□).
5.1.3. Mode Comparisons

In this section, we discuss the advantages and disadvantages of the three modes.

5.1.3.1. Whitney Mode

This mode has the following advantages:

1. The master reaction force in free motion was reduced. This is evident in the nut-pushing task, which had the lowest level of slave contact force of any of the tasks. The Whitney mode achieved this reduction by using the kinematic redundancy to favor lighter joints, resulting in faster position tracking of the slave manipulator. This helps reduce human-operator fatigue during long-time operation.
2. The interaction force in the slave side can be reduced, as shown in the tapping and nut-pushing experiments. This makes the execution of teleoperation smooth, because the slave robot can avoid a big reaction force when the slave handles the task object.
3. The slave manipulator can be more dexterous when the task size is comparable to the lighter joint's (usually the distal joint's) link length. This is analogous to human hand motion for a small task. Conversely, if the task (or motion size) is large, it is more effective to use the longer arm.

The disadvantage of this mode is that the lighter joints are likely to reach the joint limits.

5.1.3.2. Intermediate Mode

In the intermediate mode, we can set $k_p$ to be large (Whitney mode) for a small-sized task and $k_p$ to be small (LS mode) for a large-sized task if we know the size of the current task. Thus, the intermediate mode can reflect the Whitney mode and the LS mode, but this mode shows less robustness in some categories, such as the master and slave forces in the nut-pushing task.

5.1.3.3. Least-Squares Mode

The LS mode advantages depend on the kinematic structure of the robot. It can be superior in specific cases, such as large motion. For instance, this mode showed higher end-effector tip stiffness with a more stable joint-space configuration (less null-space motion) while tracing the $y$-axis in the corner-tracing experiment. However, in addition to overall poor performance, this mode generated unnecessary self-motion when using integral gain. This may have been due to controller "windup," which was present in the control law used.

5.2. Subjective Performance Survey

The master reaction force level was below 10 grf (grams of force) in the four experimental tasks. Therefore, it was not easy for test operators to discern or rate the inertia force, bias force, and noise. Perhaps as a result of the low levels of force feedback, the subjective survey results were essentially random. Our research was initially prompted by a strong perception of inertial forces when the slave was used with only joints 1, 2, and 3 in early experiments. All three of the modes evaluated in this study were effective enough to substantially eliminate that perception.

5.3. Limitations

Our study has limitations that suggest a conservative approach to applying its results to other systems. Our manipulator was somewhat unusual, in that the motion of its four rotary joints was limited to about 40°. This meant that joint-limit avoidance strongly conflicted with KE minimization, and our results were somewhat dependent on the weight vector selected for the joint-limit index. However, regardless of the weights used, these two goals are likely to always be in conflict, even for manipulators with larger joint-motion ranges. Distal joints have low inertia, but also a relatively small effect on end-effector motion. Thus, as displacements are progressively commanded, they will be favored by KE minimization and preferentially used until they hit joint limits.

Second, our control system only implicitly controlled null-space motion, and so we cannot be sure to what extent the system actually achieved the kinematically computed null-space motion.

6. Conclusions

The experimental results showed that the kinetic energy level of the slave manipulator with kinematic redundancy affected teleoperation performance in many aspects. Overall, the Whitney mode showed the best performance among the three modes. However, the other modes may have advantages, depending on the task and task direction. In the literature so far, the Whitney mode has been recognized only as a solution for the redundant kinematics of autonomous manipulators.

In real practice, robustness against kinematic singularities or high joint velocities should be considered. We did not address these problems because our five-axis robot did not have any kinematic singularities inside its joint limits. We expect that singular kinematics could cause difficulties to our algorithms in regions where the Jacobian matrix drops in rank below the number of DOFs of the master. In this case, the damped least-squares method (Vukobratovic and Kircanski 1984) could be incorporated into our solution.
Also, global control schemes are necessary not only for the primary task (Cartesian space task), but also for the subtask (null-space motion), as suggested by Seraji (1989). By global control, we mean control incorporating a closed-loop position comparison between desired and actual positions. In our case we used the global control only for the main task. Hence, the null-space command tracking (KE optimization, joint-limit avoidance) may not have been accurate.

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References


