2008 IEEE International Conference on
Robotics and Automation
Pasadena, CA, USA, May 19-23, 2008

Singularity Avoidance by Inputting Angular Velocity to a Redundant Axis During Cooperative Control of a Teleoperated Dual-Arm Robot

Masanori Hayakawa, Keiko Hara, Daisuke Sato, *Member, IEEE*, Atsushi Konno, *Member, IEEE* and Masaru Uchiyama, *Member, IEEE*

Abstract— **This paper describes a procedure of avoiding singularity for a redundantly-driven, dual-arm, master-slave robotic system. In cooperative operation, the procedure starts with a periodic check if one of the dual arms is close to a singular configuration by examining the manipulability of the arm. If it is close to a singularity, then the system stops its cooperative operation and control scheme switches to redundancy control. Then the operator manipulates the joint until the arm moves away from the singular configuration by inputing angular velocity to a redundant axis. The fact that the operator can select a new arm configuration to avoid singular configuration in teleoperation is the contribution of this research. After moving away from the singular configuration, the system can resume cooperative operation. Because this manual operation applies to a redundant axis only (in the null space of the Jacobian matrix), it does not affect the current end-effector pose and force status. Experimental examples are provided to demonstrate the proposed method.**

I. INTRODUCTION

Nowadays, complete autonomous robots that can replace human are expected, especially under dangerous environments. However, it is difficult to develop such robots with the present robot technology. So the concept of robot teleoperation was built up.

The teleoperation is an idea that human operates robot. Until now, many people have researched teleoperation. In case of teleoperation in space, time delay is a serious problem. It makes difficult for the operator to teleoperate robots in space. Therefore, a model-based teleoperation system has been proposed to solve this problem and a predictive display using virtual reality techniques has also been introduced. In this system, the operator controls the robot and equipment in virtual environment. As a result, the operator is able to manipulate the robots easily even in time delay condition.

In general, dual-arm robot can do a variety of works better than single arm robot. And it is clear that dual-arm cooperation improves efficiency in some tasks, such as the transportation of massive objects, the assembly of components. This is why the need of a dual-arm robot is increasing.

Focusing attention on the cooperative control of a dual-arm robot, the operator pays attention to the end-effector or the object in the teleoperation. So the operator is unable to know the state of arm configuration at the time. Therefore, there is possibility that the operator leads either or both of the arms to the singular configuration. There are researches to solve the problem [1]–[4]. But most of the previous research works on the singular configuration have mainly focused on the control of a single-arm robot. And there are few research works on the singular configuration with the cooperative control of a dual-arm robot. If the end-effector moves as a result of solving configuration problem, the object captured by dual-arm or arms themselves may be broken. Therefore, it is desirable to apply the singularity avoidance method uses redundancy [5], [6]. So this research is based on Yoshikawa's work [1], [5]. Some of the findings about redundancy were assembled by Nenchev [7].

In this research, the singularity avoidance support system is developed on these backgrounds. This system has the following features: First of all, when a arm is close to singular configuration, this system makes arm stop moving and control scheme switches to redundancy control. Secondly, this system shows operator the possible arm configuration during singularity avoidance in advance. And the operator can select the arm configuration from them. Then, by inputing angular velocity to a redundant axis, new configuration is allowed, while preservin desired internal forces. Finally, this system makes arms move toward the selected arm configuration.

This system doesn't avoid singularities autonomously because robot is not more intelligent than human. There are researches to avoid obstacle by using redundancy [8]. But under the circumstances that the robot is surrounded by many obstacles, arms may be crashed if the arms avoid singularities autonomously. Then, there is an idea that the arms should avoid obstacles autonomously as well as avoiding singularities. However, even with the autonomous obstacle avoidance function, there is a possibility that the arms come back to the singular configuration resulting from the obstacle avoidance. In case of repeating such action, there is a possibility that the arms get into a deadlock. Furthermore, resulting from the singularity avoidance, the arm configuration may become unfit for the next movement. It is difficult for robot to select the optimal arm configuration autonomously unless they are more intelligent than human. So, a human should take charge of intelligent part, and use the robot as a tools to manipulate.

In this paper, the concept of the singularity avoidance support system is to develop a supporting function for human to manipulate robot easily.

This research was supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Scientific Research (A), 16206024.

The authors are with the Department of Aerospace Engineering, Tohoku University, Aoba-yama 6-6-01, Sendai 980-8579, Japan (e-mail: {hayakawa, hara, konno, uchiyama}@space.mech.tohoku.ac.jp)

Daisuke Sato is with the Department of Mechanical System Engineering, Musashi Institute of Technology, Tamazutsumi 1-28-1, Setagaya, Tokyo 158-8557, Japan (e-mail: dsato@sc.musashi-tech.ac.jp)

978-1-4244-1647-9/08/$25.00 ©2008 IEEE.

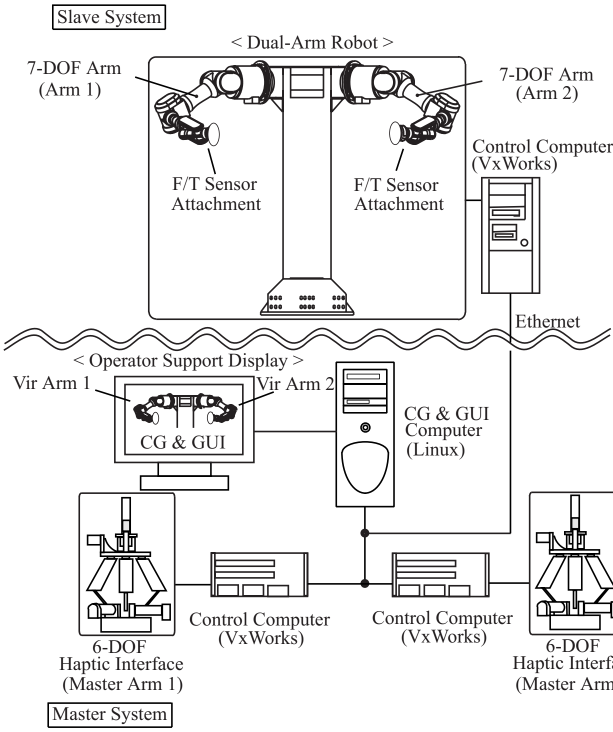


Fig. 1. Overview of the experimental teleoperation system.

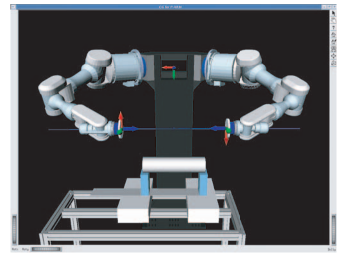


Fig. 2. Overview of the virtual environment.

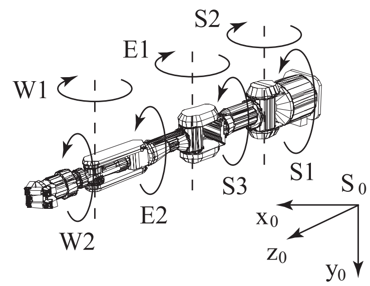


Fig. 3. Name of joints.

II. A TELEOPERATED DUAL-ARM SPACE ROBOT SYSTEM

A concept of teleoperated dual-arm space robot system [9] is shown in Fig. 1. This system is divided into a slave system and a master system. In order to study a time delay problem between a space robot and a teleoperation system on the earth, the dual-arm space robot system can incorporate any length of time delay between the master and slave systems. A model based teleoperation is introduced to avoid instability caused by the time delay. The model based teleoperation system involves a virtual environment of the dual-arm robot in the computer of the master system. The master system consists of two master arms [10], computers to build virtual environment and to control the master arms, and a computer to display virtual environment as well as graphical user interface (GUI). The master arm has a button, a jog-dial, and a 6-axis force sensor in grip. The operator watches virtual environment displayed on monitor and controls the slave arms by using the master arms. Displayed virtual environment is shown in Fig. 2.

The slave system consists of two slave arms, 6-axis force sensors, and a computer to control the slave arms. The PA10 manipulators manufactured by Mitsubishi Heavy Industries, Ltd are used as the slave arms. As the PA10 has 7-DOF, it is possible to avoid the singular configuration by using redundancy without moving end-effector. Two force sensors are attached on the wrist of each slave arm. The joints of PA10 are called, respectively, from the root of arm, S1, S2, S3, E1, E2, W1, W2 and shown in Fig. 3.

III. CONTROL SCHEME

A. Cooperative Control of the Dual-Arm Robot

As mentioned above, a model based teleoperation is introduced to overcome the time delay problem. The motion command generated by operating the master arm is sent to both arms in virtual environment (virtual arms) and arms in slave system (slave arms).

Fig. 4 shows the coordinate systems when the slave arms grasp an object. As shown in Fig. 4, the right and left virtual arm, slave arm, and master arm are named Vir Arm 1, Vir Arm 2, Arm 1, Arm 2, and Master Arm 1, Master Arm 2 respectively. Where Σ_0 is the base coordinate system of the slave system, Σ_a is the coordinate system of holding object. Σ_{h1}, Σ_{h2} are the coordinate systems of end-effector of Arm 1, Arm 2. Σ_{m1}, Σ_{m2} are coordinate systems of Master Arm 1 and 2, respectively.

As control scheme for the dual-arm cooperation, we chose non-master/slave coordinated control [11]. Uchiyama and Dauchez analyzed the static force equilibrium when two arms hold an object, introducing the concept of a virtual stick, and defined a generalized force vector including external and internal forces and moments [11]. Then, using the principle of virtual work, they derived a generalized velocity vector including the absolute velocity of the object and the relative velocity between the tips of the virtual sticks. In the scheme, the internal forces are explicitly controlled, and trajectory is decided by focusing on holding object.

In this control scheme, the motion of the holding object is controlled by operating the Master Arm 2.

Conversion from the cooperative mode to the redundancy control mode is carried out by using the jog-dial attached on the master arm. Detail of it is explained later. For internal force and relative position controls, the desired force and

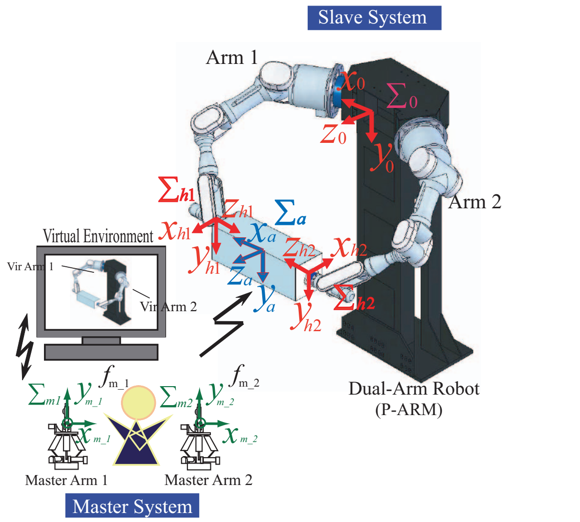


Fig. 4. Coordinates of the system in capturing the object.

position vector are decided previously. Switching between internal force and relative position controls is done by GUI.

B. Redundancy Control in the Cooperative Dual-Arm Robot

$\dot{\boldsymbol{\theta}}_r$, 7×1 joint angular velocity vector in null-space of $\boldsymbol{J}$, is given by (1) when Jacobian matrix of a 7-DOF redundant manipulator is expressed as $\boldsymbol{J}$,

$$\dot{\boldsymbol{\theta}}_r = (\boldsymbol{I}_7 - \boldsymbol{J}^+\boldsymbol{J})k\boldsymbol{\xi}. \quad (1)$$

$\boldsymbol{J}^+$ is the pseudo inverse matrix of $\boldsymbol{J}$, k is an arbitrary scalar value, $\boldsymbol{\xi}$ is a 7×1 arbitrary vector. Whether the system uses redundancy or not is decided by the value of k and $\boldsymbol{\xi}$. The way to calculate $\boldsymbol{\xi}$ is shown in (2), and $V(\boldsymbol{\theta})$ is manipulability measure, shown as (3).

$$\xi_l = \frac{1}{2}V(\boldsymbol{\theta})\sum_{m,n=1}^{6}\left[\left(\boldsymbol{J}\boldsymbol{J}^T\right)^{-1}\right]_{mn}\left({}_l\boldsymbol{J}_m\boldsymbol{J}_n^T + {}_l\boldsymbol{J}_n\boldsymbol{J}_m^T\right), \quad (2)$$

$$V(\boldsymbol{\theta}) = \sqrt{\det\left(\boldsymbol{J}\boldsymbol{J}^T\right)}. \quad (3)$$

Until now, the method is the same as Yoshikawa's work [5]. ξ_l is lth element of ξ, $[x]_{mn}$ is mth row nth column element of a matrix x, $\boldsymbol{J}_m$ is mth row vector of $\boldsymbol{J}$, $\boldsymbol{J}_m$ is mth row vector of $\boldsymbol{J}$, ${}_l\boldsymbol{J}_m$ is a vector given by differentiating partially $\boldsymbol{J}_m$ with respect to θ_l that is the joint angle of the lth element of the arm.

Then scalar value k is derived as follows. Since $\dot{\boldsymbol{\theta}}_r$ is in the null space of $\boldsymbol{J}$, $\dot{\boldsymbol{\theta}}_r$ can not affect on the end-effector velocity $\dot{p}$, i.e. $\boldsymbol{J}\dot{\boldsymbol{\theta}}_r = \boldsymbol{0}$. Therefore $\dot{\boldsymbol{\theta}}_r$ given by (1) is utilized to avoid singularity. The joint angular velocity command is given as follows.

$$\begin{aligned}\dot{\boldsymbol{\theta}}_{vir\_i} &= \dot{\boldsymbol{\theta}}_{vir\_coop\_i} + \dot{\boldsymbol{\theta}}_{vir\_r\_i} \\ &= \dot{\boldsymbol{\theta}}_{vir\_coop\_i} + (\boldsymbol{I}_7 - \boldsymbol{J}^+_{vir\_i}\boldsymbol{J}_{vir\_i})k_{vir\_i}\boldsymbol{\xi}_{vir\_i},\end{aligned} \quad (4)$$

where i = 1 or 2 is the number of the virtual arm. $\dot{\boldsymbol{\theta}}_{vir\_i}$ is a 7×1 joint angular velocity command vector of Vir Arm i. $\dot{\boldsymbol{\theta}}_{vir\_coop\_i}$ and $\dot{\boldsymbol{\theta}}_{vir\_r\_i}$ are 7×1 joint angular velocity command vector of Vir Arm i for cooperative control and for redundancy control. $\boldsymbol{J}_{vir\_i}$, k_{vir_i} and $\boldsymbol{\xi}_{vir\_i}$ are the Jacobian matrix, an arbitrary constant, and an arbitrary vector for Vir Arm i. $\boldsymbol{J}^+_{vir\_i}$ is the pseudo inverse matrix of $\boldsymbol{J}_{vir\_i}$. By inputing angular velocity to jth axis of Vir Arm i, (5) is proposed.

$$\begin{aligned}[\dot{\boldsymbol{\theta}}_{vir\_i}]_j &= [\dot{\boldsymbol{\theta}}_{vir\_coop\_i}]_j \\ &\quad + [(\boldsymbol{I}_7 - \boldsymbol{J}^+_{vir\_i}\boldsymbol{J}_{vir\_i})\boldsymbol{\xi}_{vir\_i}]_j k_{vir\_i},\end{aligned} \quad (5)$$

where $[x]_j$ is the jth component of a vector x. The angular velocity command to redundant axis is generated from the force applied to the Master Arm i as follows.

$$[\dot{\boldsymbol{\theta}}_{vir\_i}]_j = K_a[(\boldsymbol{I}_6 - \boldsymbol{S}_1)]_{3,3}[\boldsymbol{f}_{m\_i}]_{z_{m\_i}}. \quad (6)$$

$[\boldsymbol{f}_{m\_i}]_{z_{m\_i}}$ is a force along z-axis of the Master Arm i applied by the operator. K_a is a constant to convert force to velocity, $[(\boldsymbol{I}_6 - \boldsymbol{S}_1)]_{3,3}$ is 3rd row 3rd column element of $(\boldsymbol{I}_6 - \boldsymbol{S}_1)$. $\boldsymbol{S}_1$ is selection matrix explained later. From (5), the scalar value k_{vir_i} is given as follows:

$$k_{vir\_i} = \frac{[\dot{\boldsymbol{\theta}}_{vir\_i}]_j - [\dot{\boldsymbol{\theta}}_{vir\_coop\_i}]_j}{[(\boldsymbol{I}_7 - \boldsymbol{J}^+_{vir\_i}\boldsymbol{J}_{vir\_i})\boldsymbol{\xi}_{vir\_i}]_j}. \quad (7)$$

Substituting (6) into (7), k_{vir_i} is obtained. From (4) and (7), joint angular velocity command to virtual arm i is calculated as (8),

$$\begin{aligned}\dot{\boldsymbol{\theta}}_{vir\_i} &= \dot{\boldsymbol{\theta}}_{vir\_coop\_i} + (\boldsymbol{I}_7 - \boldsymbol{J}^+_{vir\_i}\boldsymbol{J}_{vir\_i}) \\ &\quad \boldsymbol{\xi}_{vir\_i}\frac{[\dot{\boldsymbol{\theta}}_{vir\_i}]_j - [\dot{\boldsymbol{\theta}}_{vir\_coop\_i}]_j}{[(\boldsymbol{I}_7 - \boldsymbol{J}^+_{vir\_i}\boldsymbol{J}_{vir\_i})\boldsymbol{\xi}_{vir\_i}]_j}.\end{aligned} \quad (8)$$

Desired joint angular velocity for slave arm i is given in the same way, and shown as (9).

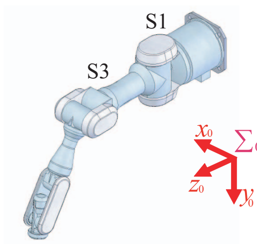
$$\begin{aligned}\dot{\boldsymbol{\theta}}_{s\_i} &= \dot{\boldsymbol{\theta}}_{s\_coop\_i} + (\boldsymbol{I}_7 - \boldsymbol{J}^+_{s\_i}\boldsymbol{J}_{s\_i}) \\ &\quad \boldsymbol{\xi}_{s\_i}\frac{[\dot{\boldsymbol{\theta}}_{s\_i}]_j - [\dot{\boldsymbol{\theta}}_{s\_coop\_i}]_j}{[(\boldsymbol{I}_7 - \boldsymbol{J}^+_{s\_i}\boldsymbol{J}_{s\_i})\boldsymbol{\xi}_{s\_i}]_j}.\end{aligned} \quad (9)$$

When k_{vir_i} and $\boldsymbol{\xi}_{vir\_i}$ are obtained, (1) is calculated and has answer as $\dot{\boldsymbol{\theta}}_{vir\_r\_1}$, $\dot{\boldsymbol{\theta}}_{vir\_r\_2}$ in each arm. The 14×1 joint angular velocity command vector $\dot{\boldsymbol{\theta}}_{vir}$, $\dot{\boldsymbol{\theta}}_s$ of virtual arm and slave arm of dual-arm robot are give as (10) and (11),

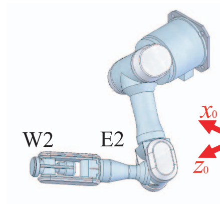
$$\dot{\boldsymbol{\theta}}_{vir} = \dot{\boldsymbol{\theta}}_{vir\_coop} + \boldsymbol{S}_2[\dot{\boldsymbol{\theta}}^T_{vir\_r\_1}\ \dot{\boldsymbol{\theta}}^T_{vir\_r\_2}]^T, \quad (10)$$

$$\dot{\boldsymbol{\theta}}_s = \dot{\boldsymbol{\theta}}_{s\_coop} + \boldsymbol{S}_2[\dot{\boldsymbol{\theta}}^T_{s\_r\_1}\ \dot{\boldsymbol{\theta}}^T_{s\_r\_2}]^T. \quad (11)$$

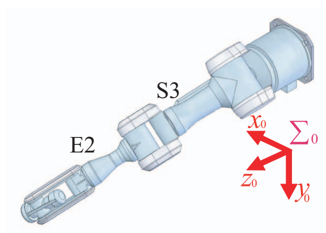
where $\boldsymbol{S}_2$ is a 14×14 matrix. The way to switch between cooperative control and redundancy control is discussed. When the operator puts up jog-dial lever of the master arm, $\boldsymbol{S}_1$ and $\boldsymbol{S}_2$ are given as $\boldsymbol{S}_1 = \boldsymbol{0}$ and $\boldsymbol{S}_2 = \boldsymbol{I}_{14}$. And input from master arm switches to input to redundant axis. As a result, from (6), (10) and (11), control mode switches to redundancy control mode. When the operator puts down jog-dial lever of master arm, $\boldsymbol{S}_1 = \boldsymbol{I}_6$ and $\boldsymbol{S}_2 = \boldsymbol{0}$. And input from master arm switches to input to representative point of holding object. As a result, control mode switches to cooperative mode.



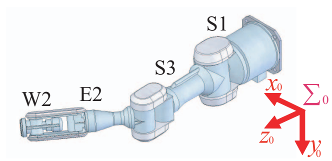
(a) S1 and S3 rotate about the same axis, and S1 is at 0 or 180 (°). Moreover S3 is at 90 (°) rotation from S1.



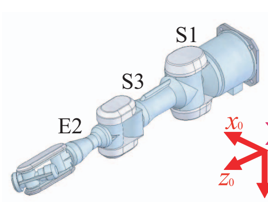
(b) E2 and W2 rotate about the same axis, and W2 is at 0 or 180 (°). Moreover E2 is at 90 (°) rotation from W2.



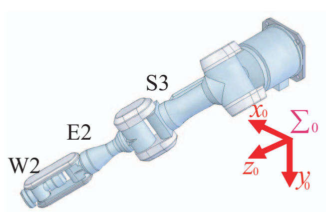
(c) S3 and E2 rotate about the same axis.



(d) S1 and S3 rotate about the same axis, and E2 and W2 rotate about the same axis.



(e) S1, S3 and W2 rotate about the same axis.



(f) S3, E2 and W2 rotate about the same axis.

Fig. 5. Singular configuration of PA10.

IV. METHOD FOR SINGULARITY AVOIDANCE

During cooperative control of a teleoperated dual-arm robot, if either of the arm is in singular configuration, there is a possibility that the singularity brings a catastrophe and the holding object is broken. Under the circumstances that robot is surrounded by many obstacles, arms may collide with them if the arms avoid singularities autonomously without any consideration on the obstacles.

So we propose the method that even during cooperative control task, the operator can choose the new arm configuration for avoiding singularity. For the purpose, the proposed redundancy control is adapted for avoiding singular configuration.

A concept of the method is as follow. When arm is close to the singular configuration, arm stops. Then control scheme switches to redundancy control. By inputing angular velocity from the master arm to a redundant axis, the operator can choose the new arm configuration for singularity avoidance.

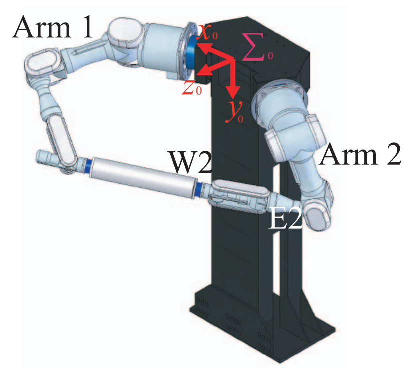


Fig. 6. Singular configuration at dual-arm cooperation.

The greatest characteristic of the method is that the operator can choose new arm configuration by himself for avoiding singularity even in cooperative control.

Fig. 5 shows the possible singular configurations of PA10. In the 6 types of singular configuration, (b) is the most possible singular configuration in cooperative control of dual-arm robot as shown in Fig. 6. So we choose S3 axis of the slave arm PA10 for redundant axis.

V. EXPERIMENT OF REDUNDANCY CONTROL IN THE COOPERATIVE DUAL-ARM ROBOT

Before using the proposed control scheme for singularity avoidance, the experiment has to be carried out to prove that when the proposed redundancy control scheme is introduced to teleoperated dual-arm robot system of Fig. 1, redundancy control works well without interfering cooperative control task.

A. An Experimental Methodology

In this experiment, while slave arms are holding object using internal force control, redundancy control is carried out by inputing joint angular velocity from master arm to redundant axis of slave arm. By commanding plus and minus angular velocity to Arm 1 and Arm 2, redundancy control is executed. In this experiment, desired internal force is 50.0 N in the direction of x_a with respect to Σ_a, and desired internal forces and moments for other directions are 0 N and 0 Nm respectively. Holding object is 590×20×200 mm rectangular solid styrene foam. Both side of styrene foam are gripper points and covered with acrylic plate, size of 2×200×200 mm. As a result the gross weigh of holding object is 1.23 kg. As gripper points are covered with acrylic plate, grip force is not absorbed so much.

B. Results of Experiment

The movement of the slave arms during the experiment, from 292 s to 304 s, is shown in Fig. 7. It is represented that redundancy control is carried out with holding object. This interval (i) is indicated in Fig. 9 and Fig. 10. Fig. 8 shows that master arm commands plus and minus angular velocity to S3 axis of of Arms 1 and 2. Fig. 9 shows that the desired and current internal force in the direction of x_a keep around 50 N during the interval (i). As shown in Fig. 10, indicate position

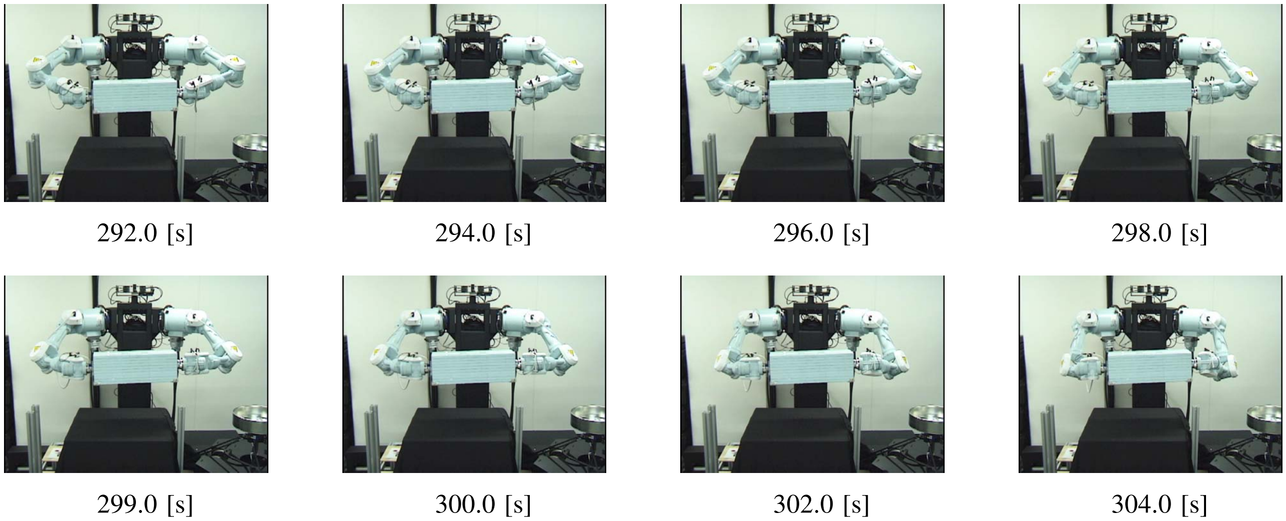


Fig. 7. Redundant control experiment during cooperative control of a teleoperated dual-arm robot.

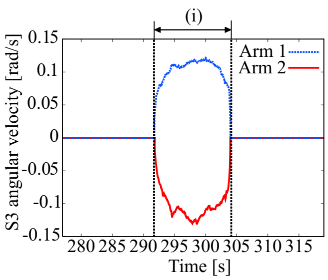


Fig. 8. S3 angular velocity commanded from the master arm.

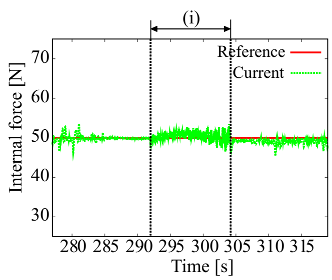
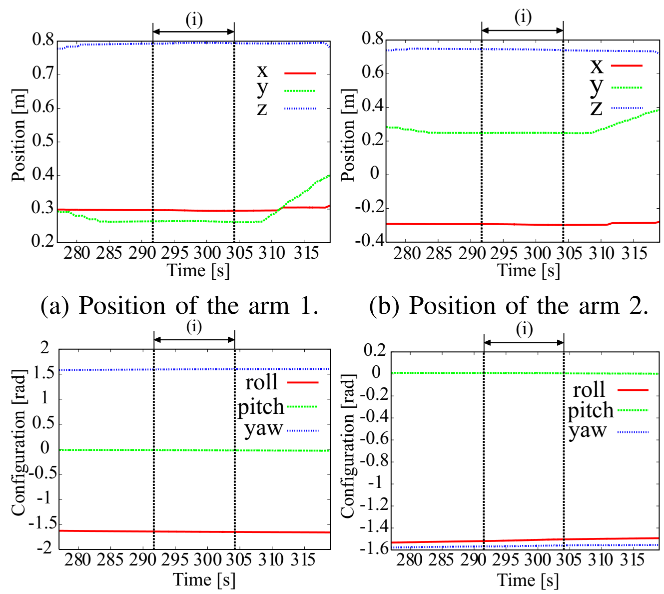


Fig. 9. Internal force in the direction of x_a.



(a) Position of the arm 1. (b) Position of the arm 2.

(c) Orientation of the arm 1. (d) Orientation of the arm 2.

Fig. 10. Position and orientation.

and orientation of the end-effector of Arms 1 and 2, They are nearly stationary during the interval (i). This experiment proves that redundancy control, by using proposed control scheme, is carried out with stabilizing internal force. It means that by commanding angular velocity to redundant axis, the operator can change the arm configuration without interfering cooperative control of dual-arm.

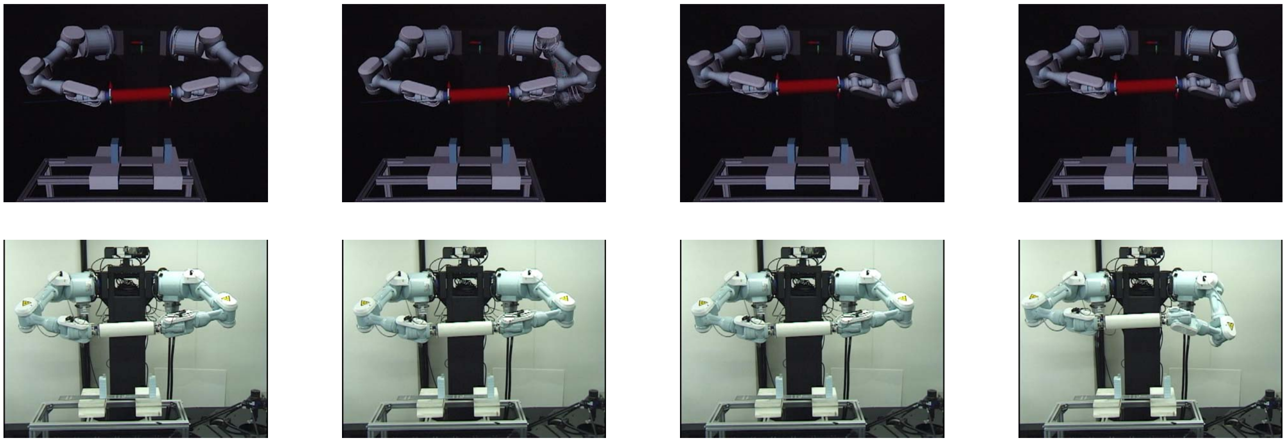
VI. System for Avoiding Singular Configuration

As it is proved that proposed redundancy control works well, experiment to avoid singularity by inputing angular velocity to a redundant axis during cooperative control is carried out. Fig. 11 shows appearance of virtual and slave arms during experiment. For this experiment, new function is needed. In virtual environment, wire frame model is newly developed to display new arm configuration to the operator during singularity avoidance, as shown in Fig. 12. Then the virtual arms are displayed as solid model.

In this experiment, first of all, dual-arm robot holds object by using cooperative control, then the operator brings either of arm close to singular configuration on purpose. When either of arm is close to singular configuration, slave and virtual arms stop.

Secondly, control mode is switched from cooperative control mode to redundancy control mode, and proposed redundancy control is carried out to avoid singularity. However it is dangerous to move slave arm suddenly by using redundancy control. Hence redundancy control is examined in virtual environment in advance. Virtual arm is also stopped, and wire frame model emerges instead, as shown in Fig. 12. The operator puts up jog-dial lever of the master arm and control mode switches to redundancy control mode. Wire frame model is controlled by the same control scheme as virtual arm. Thus, redundancy control is operated by using wire frame model and wire frame model displays the new arm configuration to the operator. To sum up, this system shows the operator the new possible arm configuration, by using wire frame model, during singularity avoidance in advance. Then the operator selects the new arm configuration from them, moves virtual arm to the new configuration and checks trajectory of virtual arm, from stopping configuration to new configuration, is safe.

Finally, this system makes slave arm move toward the



245.0 [s] 263.0 [s] 276.0 [s] 300.0 [s]

Fig. 11. Experiment of singularity avoidance during cooperative control of a teleoperated dual-arm robot.

selected arm configuration. Then the operator puts down jog-dial lever of the master arm and control mode switches to cooperative control mode.

The detail of experiment shown in Fig. 11 is discussed.

At the time of 245.0 s, Arm 2 is led close to singularity, and velocity input from master arm to end-effector of both slave and virtual arms becomes zero. As a result, both arms stop moving automatically. In order to judge whether the arm is close to singularity or not, the manipulability measure given by (3) is used. In this experiment, if manipulability measure $V(\boldsymbol{\theta})$ is less than 0.1, the system judges that the arm is close to singularity.

From 245.0 s to 263.0 s, shortly after both slave and virtual arms stop, wire frame model emerges and input from master arm switches to angular velocity to redundant axis of wire frame model. By adapting proposed redundancy scheme to wire frame model, possible arm configuration is displayed in virtual environment and the operator chooses the new arm configuration.

From 263.0 s to 276.0 s, the operator simulates avoidance trajectory of virtual arm from stopping configuration to new arm configuration displayed by wire frame model. And if the avoidance trajectory is found out to be safe, move virtual arm to the new configuration.

From 276.0 s to 300.0 s slave arm is moved the same trajectory as virtual arm.

VII. CONCLUSIONS

In this paper, we construct the system that the operator intervenes in singularity avoidance and seek the method from control standpoint. For the purpose, we proposed the redundancy control scheme to input angular velocity to redundant axis during cooperative control of teleoperated dual-arm robot, and proved the scheme is effective through the experiment. Then we adapt the scheme to avoid singularity, and it is shown in the experiment that when slave arm is close to singularity, the operator can choose new arm configuration for singularity avoidance. In this experiment, we choose S3 axis as redundant axis, but by switching redundant axis depending on situation, effective singularity avoidance will be carried out.

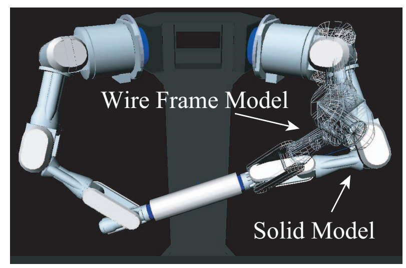


Fig. 12. Singularity avoidance support graphics.

REFERENCES

[1] T. Yoshikawa, "Manipulability of robotic mechanism," *Int. J. of Robotics Research*, vol. 4, no. 2, pp. 3–9, 1985.

[2] M. Shahamiri and M. Jagersand, "Uncalibrated visual servoing using a biased newton method for on-line singularity detection and avoidance," *Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 2682–2687, 2005.

[3] Y. Tsumaki, P. Fiorini, G. Chalfant, and H. Seraji, "A numerical sc approach for a teleoperated 7-dof manipulator," *Proc. of IEEE Int. Conf. on Robotics and Automation*, pp. 1039–1044, 2001.

[4] D. N. Nenchev, Y. Tsumaki, and M. Uchiyama, "Singular-consistent behavior of telerobots:theory and experiments," *Int. J. of Robotics Research*, vol. 17, no. 2, pp. 138–152, 1998.

[5] T. Yoshikawa, "Analysis and control of robot manipulators with redundancy," *Robotic Research: The First International Symposium (M. Brady and R. Paul ed.)*, pp. 735–757, 1984.

[6] Y. Nakamura, H. Hanafusa, and T. Yoshikawa, "Task-priority based redundancy control of robot manipulators," *Int. J. of Robotics Research*, vol. 6, no. 2, pp. 3–15, 1987.

[7] D. N. Nenchev, "Redundancy resolution through local optimization: A review," *J. of Robotic Systems*, vol. 6, no. 6, pp. 769–798, 1989.

[8] A. A. Maciejewski and C. A. Klein, "Obstacle avoidance for kinematically redundant manipulators in dynamically varying environments," *Int. J. of Robotics Research*, vol. 4, no. 3, pp. 109–117, 1985.

[9] W. Yoon, Y. Tsumaki, and M. Uchiyama, "An experimental teleoperation system for dual-arm space robotics," *Int. J. of Robotics and Mechatronics*, vol. 12, no. 4, pp. 378–384, 2000.

[10] Y. Tsumaki, H. Naruse, D. N. Nenchev, and M. Uchiyama, "Design of a compact 6-dof haptic interface," *Proc. of IEEE Int. Conf. on Robotics and Automation*, pp. 2580–2585, 1998.

[11] M. Uchiyama and P. Dauchez, "A symmetric hybrid position/force control scheme for the coordination of two robots," *Proc. of IEEE Int. Conf. on Robotics and Automation*, pp. 350–356, 1988.