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An Avoidance Method of Singular Configurations in a Master-Slave System Using Intervening Impedance

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Abstract— **It is necessary to naturally avoid singular configurations of each slave robot in order to achieve an ideal telexistence master-slave system. We propose a method for the avoidance of singular configurations by using intervening impedance. In this method, the parameters of the intervening impedance are adjusted by the manipulability ellipsoid. This method is applied to a master-slave robot. As a result, singular configurations are avoided by the proposed method.**

I. INTRODUCTION

Telexistence [1] is a technology by which we can experience advanced realistic sensations of a remote environment by remote operation and remote communication. We have been researching this technology. In telexistence, there is a master-slave relationship between an operator and a remote robot. Information transmitted from the operator to the remote robot and information about a remote environment is transmitted back to the operator from the robot.

Our primary goal for the telexistence master-slave system is to operate at will various types of slave robots by using a single universal master system. Recently, various types of robot systems have been studied and developed; however, a universal master system has hardly been studied. There are some problems in developing a universal master system. A universal master system should be designed universally so as to cover the motion space of all slave robots. However, a slave robot has a state that degenerates the degrees of freedom of the robot, i.e., singular configuration. If a universal master system is designed, the singular configurations of a slave robot will be included in the motion space. Therefore, a method that avoids singular configurations in a master system is required.

The issue of avoiding singular configurations commonly occurs not only in a remote robot system but also in all robots. Self-contained robots and industrial robots also have singular configurations. There are some methods for the avoidance of singular configurations. For example, there are methods that can be used to control or stop motion in the vicinity of a singular configuration and to limit motion to a narrow range to prohibit a robot from attaining a singular configuration. These methods can be effectively used even when the target robot operates itself automatically or when there is only one target slave robot in a master-slave system.

However, in our ideal master-slave system, it is necessary to achieve an avoidance of the singular configuration in slave robots with different configurations. If singular configurations, which are calculated in each slave, are transmitted to the master side and this information is displayed to the operator, the operator will be able to avoid singular configurations. However, by adopting a new control method, the cost might increase and the manipulability of the operator might be impaired. The process that creates and displays this information must be executed as efficiently as possible.

We consider using inherent information in master-slave systems. In a master-slave system, bilateral control is needed for exchanging information between a master and a slave. In bilateral control, an apparent impedance arises in the environment interface between the master and the slave. We focus on this impedance called “intervening impedance” [2].

The operator will experience operating a slave robot through the intervening impedance. In our ideal master-slave system, this intervening impedance should become zero as much as possible because the operator should be able to operate slave robots as if it is own. Tachi and Sakaki have proposed an impedance-controlled bilateral control system [3, 4]. This control method is able to control the intervening impedance by means of control parameters. Therefore, a master-slave system can be realized without the influence of intervening impedance. On the other hand, we try to increase the influence of this impedance. By increasing this influence, the robot manipulability of the operator will be degraded and operation will be limited. Therefore, by increasing the intervening impedance in the vicinity of singular configurations, the operator can naturally avoid the singular configuration of slave robots.

In this paper, we propose a system that can avoid the singular configuration of slave robots by changing the intervening impedance on the basis of the manipulability ellipsoid. We show that the operator can naturally avoid the singular configuration. In addition, we consider the applicability of this method to universal master-slave systems.

II. AN AVOIDANCE OF SINGULAR CONFIGURATIONS USING INTERVENING IMPEDANCE

A. INTERVENING IMPEDANCE IN IMPEDANCE-CONTROLLED BILATERAL CONTROL

In the literatures [3, 4], the intervening impedance in an impedance-controlled bilateral control system is expressed by the following equation:

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$$F_s - F_m = \hat{m}\ddot{X}_{ms} + \hat{b}\dot{X}_{ms} + \hat{k}X_{ms}$$
$$\hat{m} = \frac{2M_d(1-k_m)}{1+k_f},\ \hat{b} = \frac{2B_d(1-k_b)}{1+k_f} \qquad (1)$$
$$\hat{k} = \frac{2K_d(1-k_k)}{1+k_f},\ X_{ms} = \frac{X_m + X_s}{2}$$

where X_m and X_s denote the end position and posture of the master and slave, respectively; F_m and F_s, the received forces of the operator and slave robot, respectively; M_d, B_d, and K_d, the setup local impedance parameters; k_f, k_m, k_b, and k_k, the force gain, acceleration gain, velocity gain, and displacement gain, respectively.

M_d, B_d, and K_d in equation (1) are free to change, as are k_f, k_m, k_b, and k_k. Therefore, it is possible to operate the intervening impedance by changing these parameters, although stability must be maintained.

B. MANIPULABILITY ELLIPSOID

The manipulability ellipsoid [5] is one of characteristics used to obtain the condition of robots.

We consider the set of all end point velocities that can be realized by joint velocities. The set of these velocities is called the manipulability ellipsoid. A long axis along the main axis of this ellipsoid implies that the end point of the arm can achieve a large velocity along the direction of that particular axis. On one hand, a short axis implies that it can achieve only a small velocity along the direction of that particular axis. These axes indicate the extent to which the end point of the arm can freely move, that is, the manipulability of the end point of arm. Fig 1 shows the concept of the manipulability ellipsoid for an elbow joint.

The manipulability ellipsoid is represented by the equation given below:

$$\dot{X}^T (J^+)^T J^+ \dot{X} \le 1 \qquad (2)$$

where J^+ is the pseudo-inverse Jacobian of the robot, and it is a function of the joint angle. The manipulability ellipsoid is decided by a certain joint angle.

Further, the volume of the manipulability ellipsoid is proportional to the manipulability, which is decided by the following equation:

$$w = \sqrt{\det(JJ^T)} \qquad (3)$$

where det() is the determinant of the matrix.

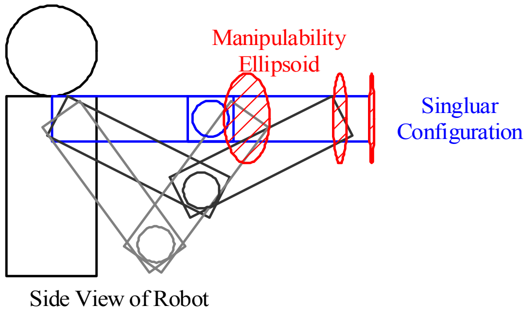

Fig.1: Manipulability ellipsoid at elbow joint

This manipulability factor becomes zero because the rank of the Jacobian degenerates when the robot is in the condition of singular configuration. In the vicinity of a singular configuration, the ellipsoid that has a short major axis is calculated; for a location that is distant from the singular configuration, the ellipsoid that has a long major axis is calculated. Therefore, it is considered that the length of the main axis of the ellipsoid indicates the distance from the singular configuration.

C. SELECTION OF IMPEDANCE PARAMETERS USING MANIPULABILITY ELLIPSOID

It is possible to increase the intervening impedance by the method described in other studies [3, 4]. Because a greater force is needed as the intervening impedance increases, it becomes difficult for the operator to operate the slave robot. Although in general, the existence of intervening impedance becomes a difficult problem, the intervening impedance can solve the problem of avoidance of singular configurations if utilized.

Using the information of the length and direction of the main axis of this ellipsoid, we try to adjust the intervening impedance by using the impedance-controlled bilateral control method. That is, when the calculated main axis is long, local impedance parameters should be provided since the intervening impedance is as close to zero as possible. As the length of the main axis is gradually reduced, its control-like parameters are gradually increased. These operations are executed against each direction of the main axis of the ellipsoid. The operator has to exert more force while operating the robot because of an increase in the intervening impedance parameters; hence, it becomes very difficult for the robot to attain a singular configuration. As a result, the avoidance of singular configuration is realized naturally.

When the intervening impedance parameters are updated, they cannot simply be changed according to the direction along which the intervening impedance increases by using the manipulability ellipsoid. The robot and the operator will not be able to move from there because the intervening impedance parameters continue to maintain very large values, i.e., to maintain a very “firm” state in the singular configuration.

Therefore, we consider a method to change the intervening impedance parameters in compliance with the direction of force. Now, it is assumed that the end of the arm of the robot is to be fluctuated along a certain direction. Then, the fluctuation in each joint angle is given by the following equation:

$$\Delta\Theta = J^+ \Delta X \qquad (4)$$

where delta X is the fluctuation along the positive or negative axes in the Cartesian coordinate system. The details of the coordinate system are described in Section III.

The Jacobian $J(\Theta + \Delta\Theta)$ is re-calculated by using this angle variation, and the main axis of the manipulability ellipsoid is also calculated. The intervening impedance parameters are updated by using the component of variation along the direction of the main axis obtained upon process. As a result, it becomes possible to setup the impedance parameters along the direction of variation of force. When the arm moves away from the vicinity of a singular configuration, it can move toward any point other than the singular configuration because the length of the main axis of the ellipsoid that is calculated increases along the direction away from the ellipsoid.

In this study, we use local impedance parameters to change the intervening impedance parameters. The local impedance parameters are setup parameters M_d, B_d, and K_d in equation (1) and the common value in the master-slave system. Fig. 2 shows the control diagram of impedance-controlled bilateral control. For changing the local impedance parameters for the main axis of the manipulability ellipsoid, we use the following weighting function:

$$impedance\ weight = \exp(\frac{a}{x^2}) \quad (5)$$

where a is a constant and x is the input value.

The length of the axis is provided as input to equation (5) and the returned value is multiplied by the base local impedance parameters. For a location that is distant from the singular configuration, equation (5) returns a value of nearly 1.0. Then, the operator can manipulate the system using the initial parameters in the normal operation. The initial parameters should be set such that the intervening impedance is decreased as much as possible. Therefore, at a location that is distant from the singular configuration, the operator can operate the system while maintaining a low value of intervening impedance. In the vicinity of a singular configuration, the input to the function becomes nearly 0.0 and the returned value increases at a faster rate. As a result, the intervening impedance parameters increase and the operator can avoid the singular configurations.

Among the intervening impedance parameters in equation (1), stiffness $\hat{k}$ should become zero at a location that is distant from a singular configuration. If $\hat{k}$ is not equal to zero, the operator always experiences a reactive force while operating the system.

Therefore, the parameters should be set such that $\hat{k}$ becomes zero. As shown in equation (1), $\hat{k}$ is controlled by three parameters—K_d, k_f, and k_k. Either $K_d = 0$ or $k_k = 1$ must be satisfied to achieve $\hat{k} = 0$. $K_d = 0$ is undesirable from the viewpoint of control stability. Hence, we set k_k to 1.0.

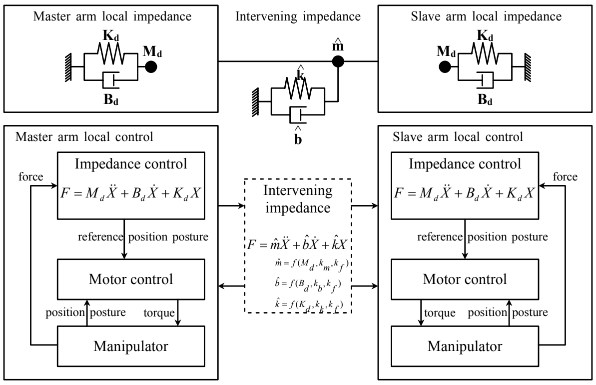

Fig.2: Control diagram of impedance-controlled bilateral control

However, if $\hat{k} = 0$, the operator does not experience a reactive force even if the arm is in the vicinity of a singular configuration. If the velocity and acceleration of the end point were to become zero at the vicinity of a singular configuration, the arm would move toward a singular point. To describe briefly, there is a risk that the arm may attain a singular configuration. To avoid this situation, we adjust the gain k_k by using the following equation:

$$gain\ \ weight = 1.0 - \exp(-b \cdot x) \quad (6)$$

where b is a constant and x is the input value.

As mentioned above, k_k should be 1.0 so that $\hat{k}$ becomes zero at the vicinity of a singular configuration. k_k should be approximately 1.0 to set the constant value b properly. In the vicinity of a singular configuration, k_k becomes less than 1.0; consequently, $\hat{k}$ becomes greater than zero. Because K_d also simultaneously increases by equation (5), considerable stiffness appears in the vicinity of a singular configuration. As a result, the arm is thrust back along a direction that departs from a singular configuration, and the risk of the arm attaining a singular configuration is eliminated.

III. IMPLEMENTATION AND EVALUATION

In this section, we evaluate the proposed method of singular configuration avoidance by simulation and application to an actual robot. In particular, the avoidance of elbow singular configuration is described.

The system configuration image is shown in Fig. 3. The system comprises a master robot, a slave robot, and a network; the master and slave robots exchange reciprocal information. The information transmitted not only includes position, posture, and force but also the main axis of the manipulability ellipsoid.

We employed the master-slave system "TELESAR II" [6], which was developed in our laboratory, for the implementation. The TELESAR II system comprises a master side and a slave side. The master robot has a pair of exoskeleton arms with 6° of freedom. The slave robot has a pair of humanoid arms with 7° of freedom. Each joint has a motor with an encoder and a potentiometer. The end point of each arm has a 6-axis force/torque sensor (BL Autotech, Inc.). The master side and the slave side are controlled by separate PCs. Each PC (Pentium 4, 2.4 GB processor) is connected by MEMLINK (1 MB/s). The lengths of the arms are shown in Table1.

The axes of coordinate systems for the master and slave side are directed as shown in Fig 4. We define the X coordinate along the front direction and the Z coordinate along the vertical upward direction. The base coordinate system origins are attached to the point of intersection of shoulder pitch and roll joints. To evaluate the avoidance singular configuration of the elbow joint, the master arm is moved only along the X direction. Using simulations, we estimate the operational force required to move the arm at a constant velocity along the direction to the right of the X-axis. From this evaluation result, we can determine the effect of the intervening impedance parameter $\hat{b}$ in the vicinity of a singular configuration. In this evaluation, the manipulating velocity is set to 0.01 m/s. We evaluate not only the force that approaches a singular configuration but also the force that recedes from a singular configuration because we want to determine the effect of the direction of the intervening impedance parameters. Further, we estimate the operational force that is required to remain stationary at an arbitrary point on the X-axis (velocity and acceleration is zero). From this evaluation result, we can determine the effect of the intervening impedance parameter $\hat{k}$ in the vicinity of a singular configuration. In the implementation, we estimate the operational force along with the simulation. The experimental setup and the global coordinates are shown in Fig. 4.

The initial impedance control parameter settings are shown in Table 2. Parameter a of weighting function (5) is set to 1/64, and the parameter b of weighting function (6) is set to 64.

IV. RESULT AND DISCUSSION

Fig. 5 and Fig. 6 show the local impedance parameters $\hat{b}$ and $\hat{k}$, respectively, in the vicinity of a singular configuration when the master arm is moved at a constant velocity. Further, Fig. 7 shows the operational force of the operator when the arm is moved at a constant velocity. Fig. 8 shows the operational force of the operator when the arm remains stationary at a point on the X-axis. In each figure, the horizontal axis represents the X-axis position of the end point, and the vertical axis represents the intervening impedance (Fig. 5 and Fig. 6) and operational force (Fig. 7 and Fig. 8). The simulation result and the implementation result are shown in a single figure. We define the force that approaches a singular point as “forward” and the force that moves away from a singular point as “backward” in each figure.

As observed from Fig. 5 and Fig. 6, the intervening impedance parameters increase drastically when the end point position approaches the vicinity of a singular configuration.

Table 1： The length of arm

	Master	Slave
Upper arm	0.45[m]	0.32[m]
Lower arm	0.35[m]	0.25[m]

Table 2： Initial local impedance parameters and control gain

Impedance parameters		Control gain	
M_d	1.0 [kg]	k_m, k_b, k_f	0.5
B_d	21.2 [N/(m/s)]	k_k	1.0
K_d	50.0 [N/m]		

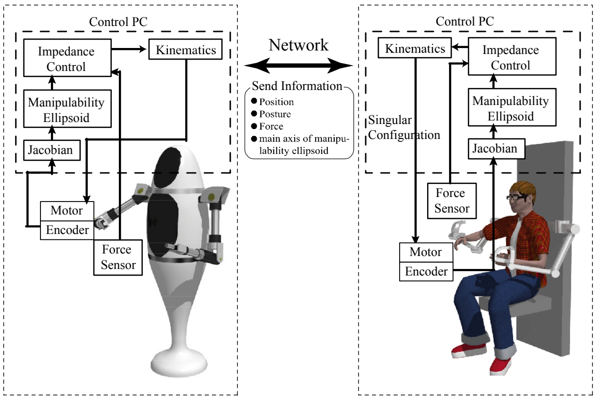

Fig.3: System configuration

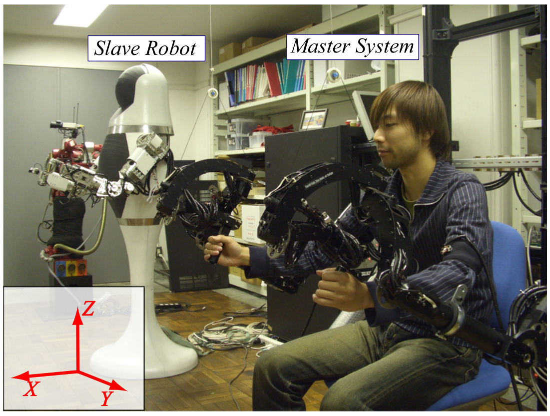

Fig.4: Experimental setup

Consequently, as observed in Fig. 7, the operational force of the operator increases so that it can approach the singular configuration. From the simulation result, at 0.45 m, a control force of approximately 0 N is needed, while at 0.545 m, a control force of approximately 15.0 N is needed. A similar trend is observed in the implementation result; at 0.45 m, a control force of approximately 1.0 N is needed, while at 0.535 m, a control force of approximately 20.0 N is needed. Based on the values shown in Table 2, the end point position is found to be approximately 0.57 m. Apparently, it becomes difficult for the arm to attain a singular configuration. The operational force which human able to exert as 300 N high as [7]. By contrast, our system can produce the reactive force larger than human’s force through the powerful motor application if the output from motor is sufficient. Therefore, it is impossible for user to reach the singular configuration.

In simulation, the forward force increases in the vicinity of a singular configuration, but the backward force is relatively less. Thus, the direction of the intervening impedance parameter proposed in chapter 2 is reflected in the system. However, the proposed method not only employs the direction of the intervening impedance parameters but also the method that utilizes the stiffness only in the vicinity of singular configurations. Hence, the thrust-back force works in the vicinity of singular configurations, as shown in Fig. 8. From Fig. 8, it is observed that in the vicinity of a singular configuration, if the arm remains stationary, the operational force increases because the intervening impedance parameter $\hat{k}$ increases there (Fig 6). The backward force of implementation in Fig. 7 changes, maintaining the positive direction due to the effect of this thrust-back force. As a result, the backward intervening impedance parameters of the implementation in Fig. 5 and Fig. 6 are approximately equal to the forward intervening impedance parameters.

Fig. 9 shows the manipulability of the simulation and implementation. The horizontal axis represents the X-axis position of the end point; the vertical axis, the manipulability. The manipulability, which is given by equation (3), also decreases in the vicinity of a singular configuration

Although the implementation result of the operational force shows a similar trend to the simulation result, the implementation result does not entirely correspond to the simulation result. At a location that is distant from a singular configuration, a constant operational force is required of the operator. Moreover, in the vicinity of a singular configuration, the measured operational force is smaller than that of simulation result.

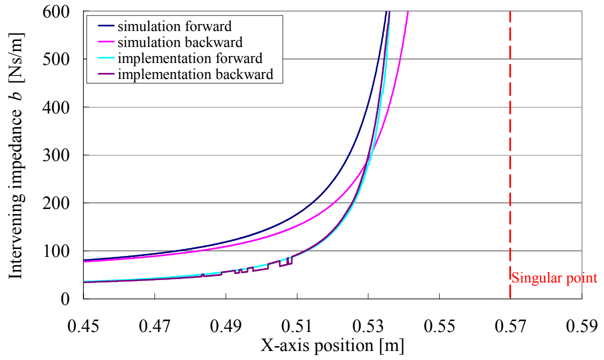

Fig.5: Intervening impedance parameter $\hat{b}$

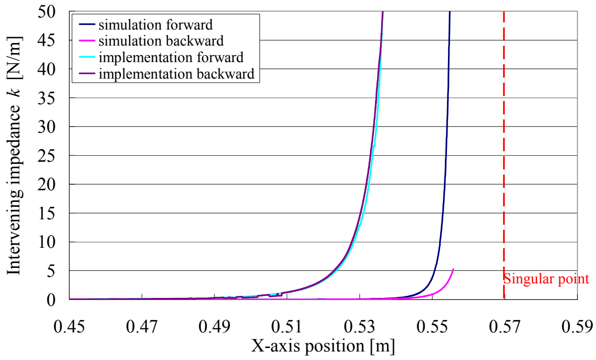

Fig.6: Intervening impedance parameter $\hat{k}$

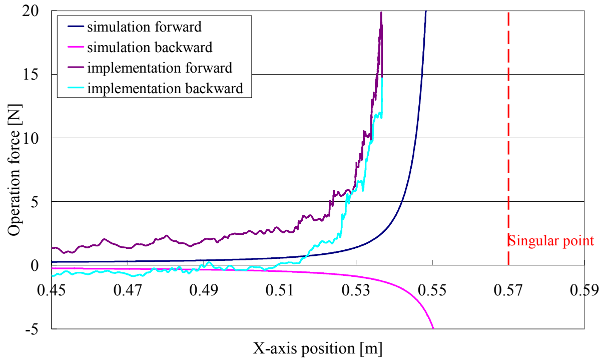

Fig. 7: Control force of the operator

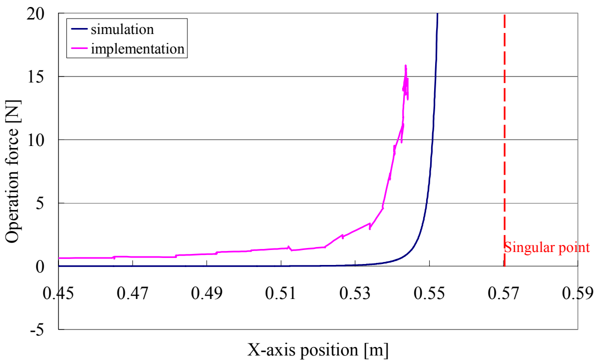

Fig. 8: Operation force of the operator (remain stationary)

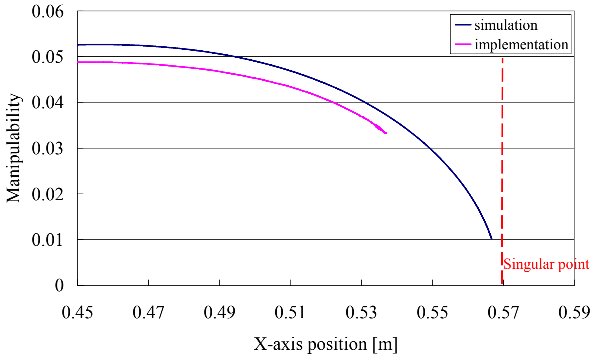

Fig. 9: Manipulability

Table 3: Cycle time and overhead in control loop

	without the proposed method	with the proposed method
cycle time	1.16 [ms]	1.25 [ms]
overhead		7.74 [%]

These results can be attributed to selected motor control, control parameters, and environment setup. In this evaluation, the end position of the operator's arm does not correspond to that of the slave arm because we have selected PD control. In addition, the adjustment of the control parameters is unclear. If the motor control method and the control gain were properly selected, the operational force would approach that in the simulation result. However, it is difficult to select the method and parameters because the stability of control and fluctuation in the sensor values must be considered. We plan to solve this issue along with the optimization of other control parameters in a future study.

Even if the system was ideal and the conditions were optimum, the proposed weighting function gives a very small output value at locations that are distant from singular configurations. Hence, it is difficult to make the operational force equal to zero by using the proposed method. By setting the threshold to apply the weighting function, the operational force becomes zero. We will evaluate this method in a future study.

This method cannot distinguish the force caused by the vicinity of singular configurations from the interaction force. In the near future, we will evaluate in detail whether this distinction is needed.

Table 3 shows the overhead of the cycle time that arises by using this method. The values in Table 3 are the averages of 10000 repetitions of cycle time in the control loop. As observed in Table 3, the loop time is 1.25 ms when this method is applied, and 1.16 ms when not applied. Therefore, the increase in the processed time is approximately 7.74%; thus, the overhead of this method is less. In the near future, even if a loop time of 1 ms is required in a master-slave system, this method can be applied. Hereafter, a further evaluation, including application, will be needed for providing a quantitative proof.

V. RELATED WORKS

Many researches have been conducted on the avoidance of singular configurations [8-11]. In these researches, the main aim was the characteristic clarification of the singular configuration and formulation. Nakai et al. attempted to avoid singular configurations by using properly selected kinematics in [12]. Further, Hwang et al. kinematically analyzed and evaluated the singular configuration existing in a single-master-multi-slave system [13]. However, there are few examples of the implementation of a humanoid robot with 7° of freedom. A virtual fixture was also proposed [14]. It is relevant to our research with respect to the limitation of motion space. It has been implemented in the arm with 1° of freedom. The intervening impedance was formulated [5]. However, there are few researches on its applications to information displays.

We focused on the avoidance of singular configuration in a humanoid robot with multiple degrees of freedom and on the intervening impedance in a bilateral control system. We propose a system that can avoid the singular configuration of a slave robot by changing the intervening impedance on the basis of the manipulability ellipsoid. In this regard, our study is unique.

VI. CONCLUSION

We proposed a method that utilizes the intervening impedance existing in bilateral control systems to avoid the singular configuration of robots. In our proposed method, by applying the impedance-controlled bilateral control method to the manipulability ellipsoid, it is possible to limit the motion that causes singular configurations.

We implemented our proposed method using a telexistence master-slave system. As a result, the intervening impedance parameters were increased in the vicinity of a singular configuration and the operator could avoid singular configuration. In this evaluation, in the vicinity of a singular configuration, an operational force greater than 20.0 N was needed. Moreover, the overhead of control time by applying this method was 7.74%. Therefore, the overhead of the proposed method was less.

In future, we will evaluate this method quantitatively by comparing it with other methods. In addition, to verify its advantage in universal master systems, we will estimate its influence on the switching of different slave robots. Further, we will consider a better displaying method for a singular configuration in order to realize intuitive sensation.

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