Master-Slave Robot Hand Control Method based on Congruence of Vectors for Telexistence Hand Manipulation

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Abstract*— This research focuses on robot hand control of telexistence robot to realize precise hand manipulation. A humanoid surrogate robot which possesses large number of DoF and works under master-slave controlling can reproduce operator's hand and finger movements, and therefore it will realize fine and delicate teleoperation as if the work were performed by operator's own hand. However, even though the robot hand moves with dexterity, the body size difference between operator and robot has great influence to the consistency of position and configuration of body-parts such as fingertips between them, and may lead the difficultly of manual teleoperation. The problem is how to manage various operator's body size and maintain the correspondence of the operator to the robot. To overcome this issue, we propose a novel method of robot hand control which is based on congruence of two vectors bellows: (1) thumb tip to opposite fingers and (2) point-of-view to thumb/fingers. Considering that the spatial relationship between thumb and opposite fingers are important to perform precise hand manipulation, to keep the vector makes replication of operator's handshape on the robot hand. Also, because the operator of telexistence robot sees robot's body-parts including hand via eye-camera as his/her surrogate body, to match the vector realizes consistent experiences about hand position and aids intuitive operation. The proposed method was implemented to the control system of newly developed telexistence robot "TELESAR6" and the performance of hand manipulation using the method was evaluated.

Keywords— telexistence, master-slave control, robot hand

I. INTRODUCTION

Telexistence is a concept that refers to the technology, which enables a human to have a real-time sensation of being at a place other than where he/she actually exist, and to interact with the remote environment [1]. Telexistence is realized by using a master-slave controlled robot such as TELESARs [2,3,4,5,6]. By using telexistence robot, operator can virtually exist in a remote location, and perform various manual operations through the robot hands controlled by operator's finger movements. For the operator, the robot hands should work freely and completely like his/her own hands. Therefore, it is important to develop precise robot hand control system.

For achieving skillful manipulation equivalent to human's hand, a lot of anthropomorphic robot hand systems have been developed for decades [7,8,9,10]. These robot hands consist of many joints and have complicated kinematic structures, therefore, it is difficult to generate the motion signals for desired hand manipulation. Therefore, various control methods for robot hand also have been proposed. Most common way is master-slave controlling, that is, a human operator's finger movements are measured via motion sensors and are applied to the robot either immediately (real-time duplication) or later (playback of the motion). This method is useful to acquire human-resemble motion for the robots. However, even though the motion duplicated on the robot is similar to the original motion, the hand shape is not exactly same due to the difference of body size and joint excursion between the operator and robot. This is a large problem for telexistence because skilled hand motions performed by an trained person cannot be reproduced on the robot unless the robot hand imitates the function of the motion. Otherwise, the skilled motion would be degraded. The essential thing is that the mismatch of kinematic parameters causes position and direction errors at the endpoint, that is, fingertip. This leads impediment of intuitive hand manipulation for the robot's operator. To improve the accuracy of reproduced finger movements, a previous study [11] applied calibration procedure of kinematic parameter between operator and robot by using correspondences of predefined finger postures. However, the accuracy was only ensured for the neighborhood of the calibrated postures and not certain for other finger positions.

In this study, we propose a novel master-slave control method of anthropomorphic robot hand system. The key of the method is that the geometrical congruence of polygonal chain consisted of spatial vectors connecting between five fingers is kept for both operator and robot. This is because the distance and direction between thumb tip and opposite fingertips are crucial to perform precise hand manipulation such as pinching action. Furthermore, to maintain spatial positions of fingers seen on the operator's visual field, the vector between point-of-view (POV; i.e., eye/camera) and fingers is also kept. As long as the two constraints are satisfied, even though the differences of kinematic parameters between operator and robot are not negligible, intuitive and precise robot hand manipulation is realized. Further procedure of proposed method is described below.

II. ROBOT HAND CONTROL METHOD FOR TELEXITENCE

A. Limitation of Proposed Method

The target of proposed method is anthropomorphic five-finger robot hand but not limited to the human-like structure, and it can be applied for other types of manipulator as long as the robot has at least two end effectors which can be regarded as thumb and opposite finger. Also, it is desirable that the workspace of each finger is wide enough to cover the moving area of human's finger movement.

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B. Formularization of Telexitence Robot Control

Previous study regarding telexistence robot [6] indicates that it is important to keep operator's eye-to-arm endpoint vector equal to robot's eye-to-arm endpoint vector so that the operator can always see the robot arms like as his/her own body. This is realized by satisfying two equations regarding POV and endpoint as shown below;

$$ {}^{W}_{sl\_eye}\boldsymbol{T} = {}^{W}_{ms\_eye}\boldsymbol{T} \tag{1} $$

$$ {}^{sl\_eye}_{sl\_endpoint}\boldsymbol{T} = {}^{ms\_eye}_{ms\_endpoint}\boldsymbol{T} \tag{2} $$

where, ${}^{A}_{B}\boldsymbol{T}$ is 4x4 homogeneous transform matrix which describes position and orientation of frame *B* relative to *A*. Equation (1) brings out exact tracking of operator's head motion, whereas (2) leads consistency of end-point's position and orientation seen from the operator's view. Though detailed expressions of them depend on the link structure of the robot, these are expressed as matrix multiplication of frames in terms of joints such as ${}^{0}_{N}\boldsymbol{T} = {}^{0}_{1}\boldsymbol{T}\,{}^{1}_{2}\boldsymbol{T} \cdots {}^{N-1}_{N}\boldsymbol{T}$. For simplicity, we assume that Eq. (1) is always satisfied, and only consider (2) to discuss how to match operator's fingers to the robot. Although Eq. (2) should be satisfied for all fingers, it is quite difficult to realize the ideal matching because most of anthropomorphic robotic finger has just 3 – 5 DOF whereas it is required to 6DOF for each finger to totally satisfy the equation. Also, even though the robotic finger has over 6DOF, size difference between operator and robot (i.e., mismatch of finger length) causes different hand posture between them. Therefore, it is necessary to compromise some factors.

Considering that thumb plays crucial role for the hand manipulation and can move most flexibly among 5-finger, the position and direction of robot's thumb tip must be controlled with high accuracy.

$$ {}^{sl\_eye}_{sl\_thumb}\boldsymbol{T} = {}^{ms\_eye}_{ms\_thumb}\boldsymbol{T} \tag{3} $$

On the other hands, other four opposite fingers just have to follow the positions of the endpoints of operator's fingertips relative to thumb tip to mimic operator's hand manipulation.

$$ {}^{sl\_thumb}\boldsymbol{P}_{sl\_finger} = {}^{ms\_thumb}\boldsymbol{P}_{ms\_finger} \tag{4} $$

where, ${}^{A}\boldsymbol{P}_{B}$ is 4x1 position vector of point *B* relative to frame *A*. Eq. (3) and (4) mean that the polygonal chain of vectors connecting to POV, thumb and fingers is congruence between operator and robot. Fig. 1 shows the schema of the congruence of vectors in the method. As long as finger opposition is kept, the operator can control the robotic fingers as well as own fingers.

C. Motion Range Adjustment of Robotic Finger

Eq. (3) and (4) are not always satisfied because of many factors such as excess of motion range. If the operator's finger is longer than the robot's one, for example, it is difficult to reach the target fingertip position. In order to utilize the workspace of finger motion effectively, the initial finger position of operator and robot should correspond regardless of size difference so that the motion ranges of them are overlapped as wide as possible. However, the adjustment cannot be applied to all fingers. This is because the thumb and finger positions of operator and robot at the same posture are usually different, though all thumb-to-finger vectors between them should be kept. Therefore this is applied to only thumb as expressed below;

$$ {}^{sl\_eye}\boldsymbol{P}_{sl\_thumb_0} = {}^{ms\_eye}\boldsymbol{P}_{ms\_thumb_0} \tag{5} $$

In order to satisfy Eq. (5), the frame of robot hand ${}^{W}_{sl\_hand}\boldsymbol{T}$ in which the root joints of thumb and fingers are belonging should be adjusted so that the position error of thumb between operator and robot at the initial posture relative to the frame origins of the hands ${}^{sl\_hand}\boldsymbol{P}_{sl\_thumb_0} - {}^{ms\_hand}\boldsymbol{P}_{ms\_thumb_0}$ is offsetted as shown below;

$$ {}^{sl\_eye}_{sl\_hand}\boldsymbol{T}\;{}^{sl\_hand}_{sl_{hand'}}\boldsymbol{T} = {}^{ms\_eye}_{ms\_hand}\boldsymbol{T} \tag{6} $$

Fig. 2 illustrates the relationship. Thanks to the adjustment, the motion ranges of fingers are mostly overlapping each other. It is useful to compensate individual hand size differences of operators.

III. IMPLEMENTATION OF PROPOSED METHOD

The proposed method discussed in previous section is implemented into the master-slave robot control system of telexistence robot "TELESAR6". Also, virtual-reality (VR) simulator of the robot is developed together to verify the behavior of entire robot systems. Here, the specification of TELESAR6 and its VR simulator is briefly introduced to clarify the operating environment. Then, the master-slave robot control system for the environment is explained.

A. Specification of Robot

TELESAR6, developed by JST-ACCEL project [12], is a life-size humanoid robot for telexistence which consists of total 67 DOF mechanism (body:6, head:3, arm:7x2, leg:6x2, hand: 16x2). The head is equipped with stereo camera and bi-

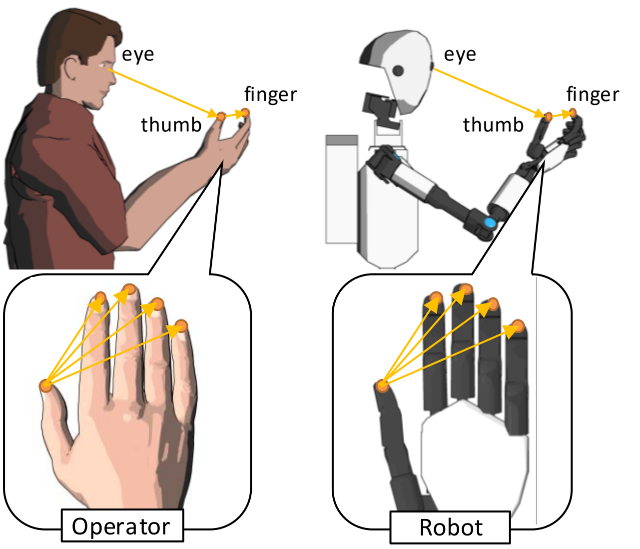

Fig. 1. Vector congruence between operator and robot. The polygonal chain connecting to eye, thumb and finger is identical for both coordinates. Thumb position is described relative to eye, whereas four finger positions are described relative to thumb.

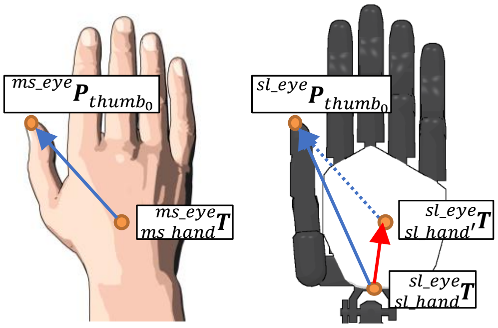

Fig. 2. Motion range adjustment of the robot hand. The frame of robot hand is determined so that thumbtip positions at initial posture are corresponding. Red-colorred vector drawn on the right side means the offset of frame relative to the original location.

naural microphones, and it can move according to the operator's head movement in order to satisfy Eq. (1). The arm can perform reaching movement according to the operator's hand position and orientation in order to satisfy Eq. (2). The endpoint of the arm is equipped with anthropomorphic five-finger robot hand which has 16 DOF (thumb:5, index:3, middle:3, ring:2, little:2, abduction:1). The number of DOF is enough to apply the proposed method.

B. *VR Simulator*

A VR simulator is developed to provide equivalent working environment of TELESAR6. In the simulator, virtual robot is connected to the measurement and control systems and works according to the user's operation same as real robot. Also, the simulator presents POV image of robot's eye-camera to the user as though he/she were actually operating the robot. As shown in previous study [13], VR simulator is useful to verify the robot system. It can also be used to train the operators as well. Fig. 3 shows a picture of the simulator and it's user.

C. *Master-Slave Control System*

Fig. 4 shows block diagram of the master-slave system in which the proposed method is implemented. Operator's body movement is recorded from the measurement systems and the position and orientation data of target body-parts (head, torso, shoulders, hands, fingertips, etc.) are obtained.

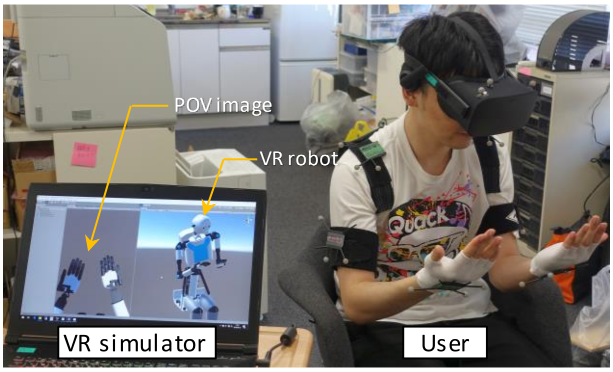

Fig. 3. VR simulator of TELESAR6, develped by using a game engine, Unity. The 3D model in the simulator has same shape and hierarichical link structure of real robot, and their joints moves according to the control signals sent from the master-slave system. Note that the user in this picture is not equipped with finger motion measuement instruments for simplicity

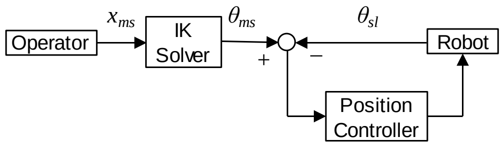

Fig. 4. Block diagram of the master slave system. IK solver outputs desired joint angles of the robot in master side, whereas position controller performs feedback loop to follow the target values in slave side.

These target values are inputted to the inverse-kinematics (IK) solver, and it generates desired joint angles of the robot. The IK calculation proceeds in stages as shown below;

1. 6DOF body joints and 3DOF head joints in the robot are determined by using operator's head position and orientation (6DOF) and torso orientation (3DOF) in order to satisfy Eq. (1).
2. 7DOF arm joints in the robot are determined by using operator's hand position/orientation (6DOF) and shoulder direction (1DOF) in order to satisfy Eq. (2). In addition, the endpoint of arm is slightly shifted from operator's wrist as shown (6) in order to satisfy Eq. (5).
3. 5DOF thumb joints in the robot are determined by using operator's thumb position (3DOF) with thumb tip direction (1DOF) in order to satisfy Eq. (3). The redundant DOF can be used for keeping finger opposition.
4. 3DOF finger joints in the robot are determined by using operator's finger position (3DOF) in order to satisfy Eq. (4). Note that the robotic finger is a 3-link planar manipulator, therefore there are only 2DOF in terms of position. Thus, this is performed with the aid of an abduction joint to shift laterally.

To apply above, the vector congruence described in Section II is realized for the robot. As shown in Step 1 and 2, the body (equipped with the head) and the arm (equipped with the hand) are involved with the method.

IV. Demonstration of Duplicated Hand Posture

By using proposed method, operator's finger movement is duplicated on the robot hand. However, because of size difference between operator and robot, the overall finger shape is not always same. This means that the posture of middle and proximal phalanxes as well as palm are not congruent between operator and robot. Still, proposed method guarantees to match the fingertip positions of them. Fig. 5 demonstrates some examples of corresponding hand postures. Operator's position and orientation data were measured by optical motion capture system (OptiTrack), and calculated target values were applied to virtual robot in the VR simulator. As shown in Fig. 4, operator's hand manipulation (pinching an eraser on different side) is functionally duplicated by the robotic fingers.

V. Conclusion

In this study, a novel robot hand control method was proposed to realize precise hand manipulation under master-slave controlling telexistence operation. This method is based on the congruence of spatial vectors between operator's coordinates and robot's ones.

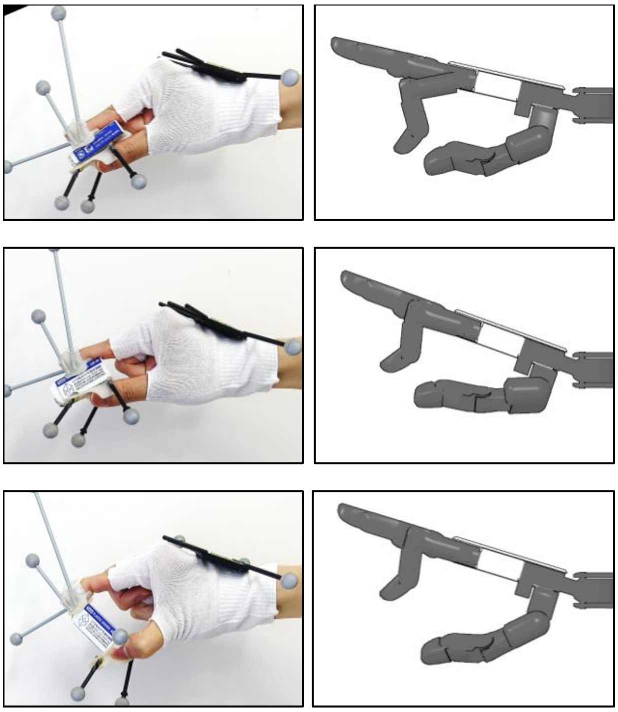

Fig. 5. Examples of corresponding hand postures. Although the overall hand shape is different, the length and direction between thumb to index finger keeps same. Note that other fingers (middle, ring, little) are not controlled in the example because of the limitation of measurement.

The proposed method was implemented to a robot control system for a telexistence robot and the effectiveness is evaluated by using VR robot simulator. However, the method has not been tested on the real robot hand because the robot is under development. Therefore it is necessary to perform further evaluations of hand manipulation in the real situation.

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