Experiencing ones own Hand in Telexistence Manipulation with a 15 DOF Anthropomorphic Robot Hand and a Flexible Master Glove

Charith Lasantha Fernando* Masahiro Furukawa† Kouta Minamizawa‡ Susumu Tachi§

Graduate School of Media Design
Keio University

Abstract

This paper describes a new type of robust control mechanism for a 15 DOF anthropomorphic robot hand in telexistence manipulations using a flexible fiber based master glove to experience the visual-kinesthetic sensation of one's own hand in remote manipulations. Accordingly, a master-slave telexistence system was constructed with the following: a 14 DOF modified optical fiber based data glove for capturing the complex finger postures of the master operator without any mechanical constraints; a novel finger posture mapping algorithm that is independent from the effects of different finger sizes and digit ratios; and a 15 DOF anthropomorphic slave robot hand for reconstructing the operators finger posture. This paper describes the importance of feeling one's fingers in a telexistence manipulation, control mechanism for accurate finger posture capture/reconstruction where the effectiveness has been verified through a set of experiments and a subjective evaluation.

Index Terms: H.4.3 [Information Systems Applications]: Communications Applications—Computer conferencing, teleconferencing, and videoconferencing; I.2.9 [Artificial Intelligence]: Robotics—Kinematics and dynamics

1 Introduction

Dexterous robot hands are used [7, 3, 2, 6] in traditional teleoperations to perform manipulations that involves fine finger movements. These robot hands are controlled manually by humans or a combination of artificial intelligence driven hybrid semi-autonomous control mechanics. Hybrid control systems does provide much accurate grasping techniques based on the pre-programmed grasp techniques. However, it does not provide any realistic sensation of experiencing that the hand that they see is their own or their presence in the remote environment. In daily life, the coherent relationship between visual-kinesthetic sensation on various body parts allow humans to naturally experience their body awareness. In addition, extending the awareness of their body to a tennis racket or a hammer is possible. Similarly, this eye-hand coordination can be extended for secondary tools in remote side through teleoperation technologies.

The awareness of different body parts in a remote manipulation can be helpful for various tasks. For example, the awareness of the operators head can be helpful to inspect the remote objects in a natural manner with accurate three-dimensional details such as size and distance to object information. Awareness of one's arm is helpful to naturally reach to an object without having to depend on the visual information accuracy. If this awareness is kept continuously throughout the teleoperation, users will no longer need any rehearsal to perform tasks remotely. Operators lifelong experience on doing things (playing games, handling tools etc.) could be continued. In addition, it is possible to use his muscle memories, previous learning so that the training can be minimized or eliminated. Secondly, since there is no thinking or processing overhead and a human brain is used in thinking and processing, it will be able to react to un-excepted dynamic behaviors. With the above advantages, the task effectiveness of teleoperations could be increased.

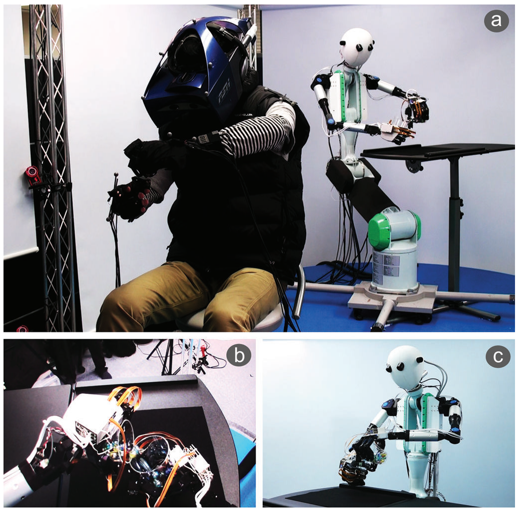

Figure 1: (a) Master-Slave Configuration, (b) Slave Hand as seen from the HMD, (c) Slave Hand used in a Manipulation

Telexistence systems enable a human to have a real-time sensation of being at a place other than where he actually exists and to interact with the remote environment [8, 14] with his entire body. With the development of a master-slave telexistence system "TELESAR" [15, 10, 11, 16, 9, 12] a combination of vision, auditory and kinesthetic sensation was achieved by Tachi et al. The authors also achieved to match the differences of dynamics of the robot and human body by using a force feedback mechanism [13] for arms. With the correct eye-hand coordination and multi-sensory information acting on a user's body, telexistence systems allow a user to experience the remote body as their own body during remote manipulation. The coherent relationship between visual-kinesthetic sensation allows the user to experience his eye-hand coordination synchronization on various body parts. Previous telexistence systems [15, 10, 11, 16, 9, 12] provide these head and arm awareness. However there is no system to have an awareness of operator's fingers and hand during remote manipulations.

In telexistence manipulations, to capture the movements of the operator's fingers, a master hand is used. They can be divided into two categories. Exoskeleton type such as CyberGrasp [18] are bulky and requires the operator to wear a glove to measure the posture of the finger. In contrast, endoskeleton type such as

*e-mail: charith@kmd.keio.ac.jp
†e-mail:m.furukawa@kmd.keio.ac.jp
‡e-mail:kouta@kmd.keio.ac.jp
§e-mail:tachi@tachilab.org

Rutgers Master II [1] type does not require wearing a glove, but also lightweight and compact. However, it does not allow capturing the full finger movements due to the placement of the actuators in the palm and other mechanical constraints. To overcome the constraints caused by the incorrect placement of the actuators in the palm, Nakagawara et al. developed a new type of master hand [7]. The compact exoskeleton mechanism called “Circuitous Joint” introduced by Nakagawara et al. allow the operator to use his fingers in a much wider workspace. However, these systems cannot compensate when the operator’s finger lengths are different and therefore it cannot produce an accurate kinesthetic sensation mapping between the operator and robot hand finger movements.

With the development of a full upper body avatar robot called “TELESAR V” [4] Fernando et al. was able to extend the sensation of feeling the robot body as one’s own to the entire upper body and fingers. In this paper, human like finger posture reconstruction mechanism of “TELESAR V” system [4] was explained and the advantage of human like finger posture to telexistence was discussed. By implementing a 14 DOF optical fiber based data glove and a novel position based mapping algorithm can accurately capture the finger postures normalizing the effects of different lengths of the user’s fingers. Remote side finger posture reconstruction was achieved by constructing 15 DOF slave robot hand. Furthermore, the effectiveness of this system with non-expert has been verified through a set of experiments followed by a subjective evaluation.

2 FINGER POSTURE CAPTURE MECHANISM

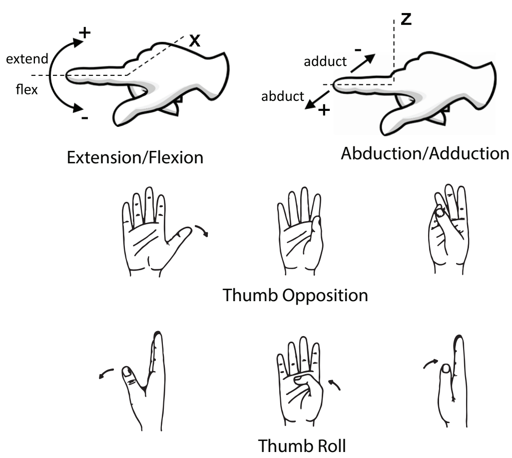

Figure 2: Human Hand Flexion/Extension, Adduction/Abduction, Thumb Opposition and Thumb Roll

Grasping is one of the most important feature in remote manipulation. Even though the robot can reach the target accurately, if it is not possible to grasp objects with normal grasping techniques, operator will frustrate and try to use various techniques based on trial-and-error until he finds the proper way to grasp. In order to reproduce the operator’s finger postures, it is necessary to capture all finger movements. Using traditional exoskeleton [18] and endoskeleton [1, 7] master hands it is possible to capture the finger movements accurately. However, limited dexterity provided by the exoskeleton systems will limit the operator to perform manipulations based on fingers as he would expect to be. Furthermore, depending on different finger lengths and the way of using fingers in a manipulation these unpredicted mechanical constraints would provide a frictional force to the operators’ fingers so that they would not be able to use the fingers as they would like. Therefore, to grasp objects correctly and feel the remote hand as your own, first an ungrounded master is necessary where it can capture finger movements without any mechanical constraints.

Since the human hand dexterity is very high compared to any other body part, it is necessary to capture the full range of movements from the operator side to reproduce the motion back on the robot side. Fig. 2 shows common dexterity types associated with all fingers of human hand. As shown on Fig. 2(top left) the bending towards is known as flexion and opening the fingers fully is known as extension. Also as shown in Fig. 2(top right) all 5 fingers can be bent in opposite axis and it is called adduction and abduction respectively. However, human thumb has much dexterity than flexion/extension, adduction/abduction and one of the most common dexterity that is necessary for manipulation is thumb opposition. Apart from the above mentioned dexterity, thumb rotation (thumb roll) is also used when the thumb tip needs to contact with any other tip or the palm.

2.1 Optical Fiber Based Data Glove System

Existing data glove systems uses optical or resistive based bend approximation. Resistive bending technologies used in “Cyber Glove” [5] products have required sensing capabilities for most of the fingers except for thumb opposition. However, they are very expensive and also no after sales support. Thus, our approach was to use an off-the-shelf data glove system and to modify it so that the opposition sensor can be added and repair can take place at any place. In addition, resistive bending will have a hysteresis decays over time and effectively reduce the accuracy of the sensors. Therefore, in this design, a data glove from “Fifth Dimension Technology (5DT)” 5DT-14 [17] was used. However this glove was also lacking of thumb opposition and thumb roll sensors. Thus, as shown on Fig. 3 sensor 10 was added in order to detect the thumb opposition. With a numerical calculation combining the effect of sensors 1, 2, 3, 10 the thumb roll was calculated. The detail of the calculation is explained in a later section of the paper. Fig. 3 shows the 5DT-14 sensor placement after the custom sensors have been added in order to detect the thumb opposition and thumb roll.

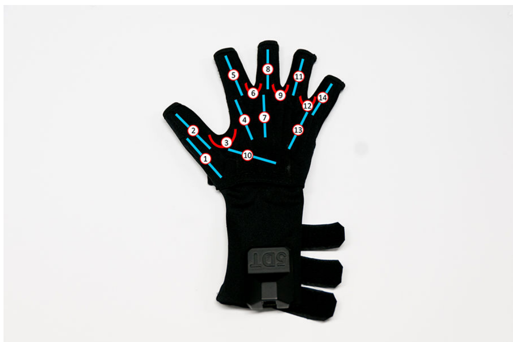

Figure 3: Fiber Sensor Placement of TELESAR V Data Glove after New Sensor Addition

According to human anatomy each finger was structured based on separate sub bones and these are called phalanges. There are 14 phalanges in a hand where three for each finger, and two for the thumb. The names of the phalanges of the three rows of finger bones, from the hand out are proximal, intermediate and distal phalanges while the thumb only contains a proximal and distal phalanx. Fig. 3 blue color sensor shows the flexion type and red color shows the abduction type sensor placement. The detected bend angle is calculated w.r.t to the points, which is similar to the sensor id notation circle as shown in Fig. 3. Sensor 2 detects the thumb angle between proximal and distal phalanx. Sensors 5, 8, 11, 14 detects the 4 fingers intermediate and distal phalanx where as sensors 1, 4, 7, 13 detects the angle between palm to distal phalanx.

After some trials it was found that the angle between palm and ring finger distal phalanx was not commonly used in manipulation. Therefore, that sensor was moved from its original placement to the sensor 10 position as shown in Fig. 3 to detect the thumb opposition and thumb roll. To mount the custom sensor, different types of materials were tested to hold the sensor tube. However, the best performance was given with black stretch lycra material due to the elasticity and compressibility. It was also holding the sensor tightly to the operators finger and not to move around when bending.

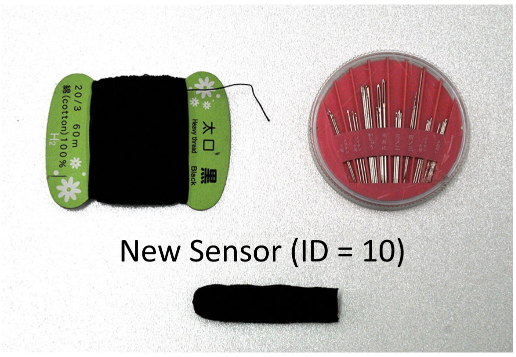

Figure 4: Lycra based Stretchable Sensor Pocket for New Sensor

Fig. 4 shows the new sensor addition and the special pocket created with black stretch lycra to hold the sensor. The pocket was sewed to the glove inside so that the sensor can be replaced easily similar to all other sensors on the glove. Due to the limitations of the A/D converter used in this circuit the maximum bend sensors connected is limited up to 14.

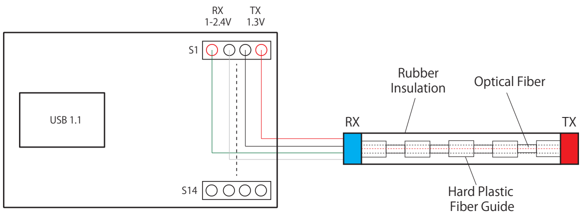

Figure 5: Optical Bend Sensor Internal Structure

Fig. 5 shows the internal structure of an individual bend sensor used on the 5DT-14 Data Glove. At the tip of the sensor, a transmitter IR LED was used to emit the IR light rays. On the other side of the sensor tube, a proprietary photo transistor was placed to measure the intensity of the incoming IR light. When there is no bending on the tube all the light emitted was captured through the photo transistor. When a bending occurs the intensity of IR light will reduce and a change in electrical signal ranging from 1V - 2.4V will be generated. The digitized bend electrical signal is digitized and sent to a PC via a USB connection.

On the PC side, to use the captured raw bending data several signal conditioning were necessary. The raw data was normalized at the fiber calibration step. During calibration, the raw data was captured and maximum and minimum bending values was calculated. Once the min, max raw data was known according to Eq. 1 the normalized bend values between 0 - 1 was further processed for calculating the bend angle.

$$bend_{normalized} = \frac{raw_{val} - raw_{min}}{raw_{max} - raw_{min}}.Max \quad (1)$$

After the user has been satisfied with the bend calibration he confirms the calibration and no further max, min values were captured. The last min, max values will be used for normalizing consecutive incoming raw data unless a recalibration step is performed. The angle calculation is done at the kinematic generation step because the normalized bend data is used in few other routines such as to check the correct calibration of bend sensors, no calibration detection, and faulty bend sensors etc.

3 Finger Posture Reconstruction Mechanism

To touch or grasp objects and mimic human hand finger movements, a higher DOF anthropomorphic robot hand similar to human hand is necessary. Thumb, index finger and the abduction is mostly used in grasping because they have the highest dexterity in human hand compared to other fingers. When performing a remote task with tools the robot hand should be able to grab and use the tools with similar dexterity to a human hand. In addition, it will enable the user to feel that the hand that he sees is his own.

It is obvious that the human hand dexterity is very high compared to existing robotic hands [3, 2, 6]. To control these hands in telexistence manipulations, exoskeleton [18] and endoskeleton [1, 7] master hands can be used without having to consider different finger lengths. However, they are not be suitable due to the mechanical constraints and the reduced work space. In contrast, when using a data glove, depending on the users finger length, the angle calculation can be vary. This becomes complex when it is necessary to capture all finger motion and especially the thumb motion. Thus, it is essential to have a mapping algorithm so that different finger lengths, hand shapes can be normalized and to be mapped to one specific robot hand while giving the same sensation as the hand you are controlling is your own.

3.1 15 DOF Anthropomorphic Robot Hand

Compared to the body and arm, it is very difficult to implement the same dexterity in a robot hand due to the complexity of the mechanics and the smaller size. Thus, TELESAR V hand has mainly focused on increased index, thumb finger dexterity while giving the ability to control the abduction. As shown in Fig. 6 (Right), in TELESAR V a custom designed 15 DOF human sized anthropomorphic robot hand was used. It's thumb has 5 DOF, index finger 3, all other fingers 2 DOF, and the abduction. Fig. 6 (Left) shows the modified light weight data glove that is easily wearable.

Figure 6: Master Glove vs. Slave Hand

Robot fingers are driven by 15 individual DC motors connected with dynamically coupled wires, and a pulley driven mechanism couples the remaining joints that does not directly attach to a motor. Fig. 7 shows the robot hand coordinate frame assignment and the placement of each joints w.r.t. each finger. As shown on Fig. 7, robots proximal phalanx is independently working and the intermediate and distal phalanx is mechanically coupled on 4 fingers except for thumb. This limits the user to move fingers with full flexibility. However, when humans use their fingers in manipulation tasks this two joints are mostly working with coupled motion. Therefore, unless the operator is trying to pose for very specific finger gestures, this mechanical coupling do not raise any issues during most of the manipulations.

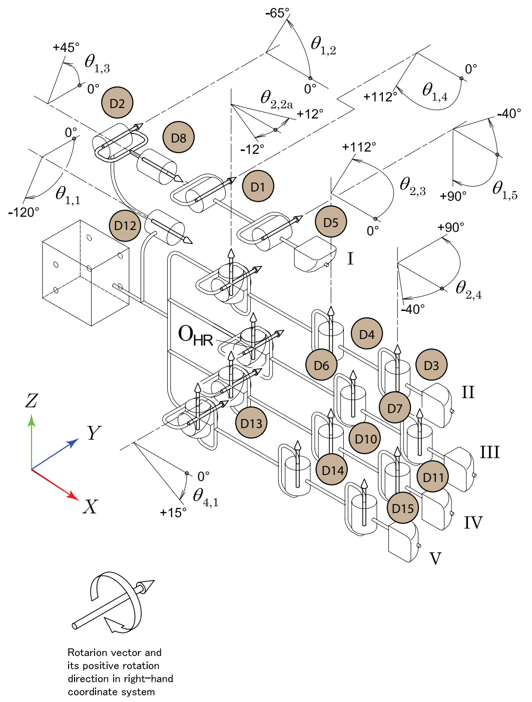

Figure 7: 15 DOF Anthropomorphic Robot Hand Coordinate Frame Assignment

Table 1: Joint Limits of 15 DOF Anthropomorphic Robot hand

Joint	Drive	Mechanical limit		Electrical Limit	
		Negative	Positive	Negative	Positive
J1	D12	-125°	5°	-120°	0°
J2	D2	-70°	2°	-65°	0°
J3	D8	-2°	47°	0°	45°
J4	D1	-5°	115°	0°	112°
J5	D5	-45°	90°	-40°	85°
J6	-	-	-	-	-
J7	D4	-5°	115°	0°	112°
J8	D3	-45°	90°	-40°	85°
J9	-	-	-	-	-
J10	D6	-5°	115°	0°	112°
J11	D7	-45°	90°	-40°	85°
J12	D13	N/A	16°	0°	15°
J13	D10	-5°	115°	0°	112°
J14	D11	-45°	90°	-40°	85°
J15	D14	-5°	115°	0°	112°
J16	D15	-45°	90°	-40°	85°

Being the robot fingers proximal phalanx to be 25mm, intermediate phalanx to be 30mm, the four fingers have a 45mm long distal phalanx where as thumb distal phalanx is 42mm. Each finger is 20mm wide and thus approximately equal to a human finger. Due to the two joints of each finger being mechanically coupled with a ratio of 0.7x, it was impossible to obtain a valid joint angle using numerical inverse kinematics. Thus, trigonometric and analytical inverse approach was used to obtain the inverse angle values. Thumb, index, ring and small fingers can move on the z-direction where as middle finger was fixed. To simplify the problem, z-direction motion on all fingers were fixed and it was later added to the calculations. Eq. 2,3 shows the formula for getting the x,y coordinates based on the current joint angle. Thus when the bending is provided by the 5DT sensor, robot joint angles were calculated to reach the target fingertip position.

$$Fn_x = 45 \cdot \cos(\theta_{1.1}) + 30 \cdot \cos(\theta_{1.1} + \theta_1) + 25 \cdot \cos(\theta_{1.1} + \theta_1 + \theta_2) \tag{2}$$

$$Fn_y = 45 \cdot \sin(\theta_{1.1}) + 30 \cdot \sin(\theta_{1.1} + \theta_1) + 25 \cdot \sin(\theta_{1.1} + \theta_1 + \theta_2) \tag{3}$$

As shown in Fig. 7 there are 16 Joints driven by 16 drives denoted through D1 - D16 where 2 joints (D9 - J9, D16 - J6) were not used in the current configuration. Those joints being the palm to distal phalanx on index and middle finger, it was very fragile and easy to break. In addition, when in manipulation this palm to distal joint was not used frequently. Thus, the joint was electrically fixed at 0 deg. Therefore, the experiments carried out in the next sections only uses 14 DOF's out if 15 DOF's. Table. 1 shows the complete joint to drive mapping, joint limits of the hand, motor and joint assignment based on the kinematic configuration. Each finger's motion limit angles are decided based on the maximum working area of an ordinary human hand.

TELESAR V Hand uses all Brushless DC motors. Thus it was necessary to implement motor control logic. Unlike most robotic applications, a closed loop control between a PC and robot hardware was used. The most common method is to run PID loops at hardware layer and control the motors on the hardware. This method will have advantages over speed. However, dynamic changes to the control algorithm cannot be done on PC side. Therefore it has to re-program on the hardware level every time when the parameters needed to change. Also to be able to use the system as a learning tool, the challenge was taken by implementing a closed loop control between a PC and the hardware Motor. This challenge was tricky when windows based PC's were used for all implementation as windows does not provide accurate timing which is required by robotics application. A shared memory based dynamic memory mapping technique and low level C++ routines were used together with Windows Multimedia Timer to overcome this issue.

Current controlled PWM logic was used in order to control the current of each motor. Potentiometer reading is sent to the PC as 16-bit value. Motor current is sensed at the motor driver chips using a hall-effect sensor. For communication between the PC and hardware a special communication system called "TexART NCord" was used. It has both hardware and software C++ support to read and write data between hardware and PC. The main processor used in the hand was a FPGA (Xilinx Spartan - 6 XC6SLX75). Sensor data is updated at a frequency of 8KHz parallel for each motor. Each Terminal in FPGA communicates via 6 dedicated full duplex RS485 buses at a speed of 20MBps. In order to translate the RS485 signals to PC compatible format, a RS485 to PCI-Express x1 converter board was used. Thus, when the system is operating normally PC sends target information (motor current) at every 1ms and retrieves the buffered position data at every 1ms. The time between each read/write data cycle is 500us. In our setup the RS485 to PCI-Express converter box is placed at the robots' back.

3.2 Hand Hybrid Control Logic Block

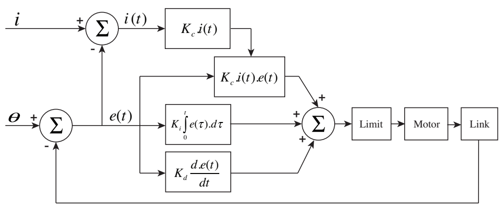

Figure 8: Control Logic Block Diagram for 15 DOF Hand

Fig. 8 shows the control logic for Hand. The hand controller outputs 15 channels of current, position and 8 channels of contact force information. Current controlling for hand was very important. For example during manipulation some operators will squeeze their fingers, but if there is no proper current control it will break the objects due to uncontrolled high torque. Due to the higher number of motors per one terminal it was not possible to receive current information at the PC side and no feedback current controller was implemented. In order to avoid uncontrolled torque, a position based feed forward current controller was implemented so that when the joint is not moving it will not increase the torque. This technique was successfully implemented for all joints and it was tuned in a way that the first joint of each finger has the highest limiting torque where as 2, 3, 4 joints have much less torque limits. Since there was no current feedback, if the limits were very low fingers will start to move very slow. This is again unacceptable on a telexistence ystem because the operator can easily understand the lagged fingers he see is not his own. Therefore, first joint torque limit was increased because to have a faster finger motion.

The very low torque limit on fingertip joints allows to steadily touch the object surface, then it will stop at the same torque which it contacted until the operator releases his fingers. Good contact area between the fingertip and the object not only helps to accurate grasp, but also to detect the contact force, tactile and thermal information. In TELESAR V system these haptic information was used to reproduce the fingertip haptic sensation on the operators fingertip. Finally, in order to make finger pinch posture it is necessary to move the fingertip joint in opposite direction. However, the data glove does not detect the opposite finger bend. However, when the operator tries to pinch fingers, robot hand will naturally bend its finger tips due to very low toque limiting on last joints and higher torque limits on the first joint. With this method the pinch finger gestures were naturally achieved without modelling the opposite direction bend.

3.3 Hand Trajectory Generation Algorithms

As explained in Eq. 2, 3 the normalized bend data is used to calculate the bend angle. As shown in Table. 1 the 2nd joint angle of each finger is limited to 0° - 112° and the last joint of each finger is limited to -40° - 85°. Computing forward kinematics on index finger, it was found that fingers can move in a trajectory similar to as shown in Fig. 9. Thus, it was impossible to get an inverse solution with just position data. Therefore, trigonometric based analytical Inverse approach was used to determine the joint angle. Knowing the required bend range accuracy, the operator side bend angle was modeled based on the normalized bend values with the form of an equation as shown on Eq. 4. In this approach, it was found that the normalized bend values were not linear and thus the closest match was "arcsin" curve.

$$Bend_{modeled} = A + \arcsin(Bend_{normalized}) \cdot B \qquad (4)$$

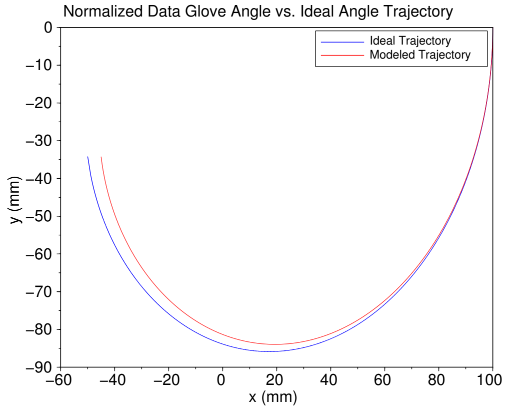

Figure 9: Normalized Data Glove Angle vs. Ideal Angle Trajectory

Modeled joints vs. the ideal joints were plotted in order to understand the error of the modelling. As shown on Fig. 9 the modeled trajectory has a very slight mismatch in modelling the data. However when used with many operators, the bend values read by the same bend angle of the 2nd joint was different. After analyzing the data it was found that the differences of finger lengths causes this issue. An ordinary humans finger length can be vary depending on the ethnicity, sex and even the characteristics of the person. This was quite a common occurrence in most of the operators and therefore a solution was studied to overcome it.

The "Digit Ratio" is the ratio of the lengths of different digits or fingers typically measured from the midpoint of bottom crease where the finger joins the hand to the tip of the finger. In most cases the 2nd (index finger) and 4th (ring finger) can be taken as an index to derive a users other finger length and therefore the digit ratio can be calculated by dividing the length of the index finger of the right hand by the length of the ring finger. A longer index finger will result in a ratio higher than 1, while a longer ring finger will result in a ratio of less than 1. This ratio has a notation called "2D:4D" digit ratio. In general, women ring and index finger tend to be about the same length where as in most men the index finger is usually shorter.

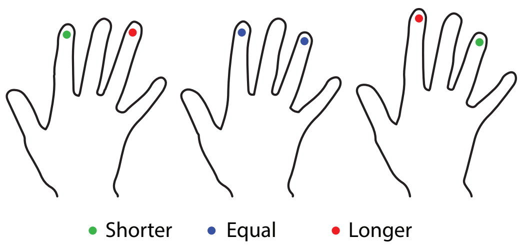

Figure 10: Digit Ratio Pattern of Male and Female

Fig. 10 shows a typical digit ratio pattern of distribution among male and female over various ethnic grouping. More over, the small finger length and the thumb length is also vary depend on the users. Thus it was necessary to calibrate the fibers and bend angle for each finger.

The 15 DOF hand in TELESAR V was made with the digit ratio 2D:4D of 1. However, out of the different operators the system was tested, no one was found to be of digit ratio of 1. To determine which type of calibration is needed, robot grasping a cylindrical coffee can with its 5 fingers were modeled. As shown on Fig. 11

the most important fingers for grasping objects are the index and thumb. The higher dexterity of these two allows to perfectly align and grasp objects while the palm and other 3 fingers act as a support to the grasping. Furthermore, middle, ring and small finger works similar to the index finger in most people.

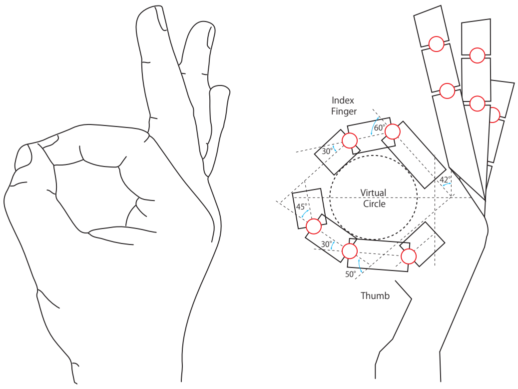

Figure 11: Finger Digit Ratio Calibration Method

On the robot side, when index and thumb edges touches each other and it creates an approximate circle as shown in Fig. 11. If this condition is satisfied when the user makes an "OK Sign" with his index and thumb finger it should be similar for other fingers. The circle shape is decided because index, middle, ring and small fingers cannot independently bend from the 3rd joint and it is coupled with the 2nd joint with an ratio of 0.7. Thus the robot hand will not be able to make any other shapes with the 4 fingers except for the thumb. The best shape the robot hand can make is a circle and therefore the counter part (thumb) has to make the other half of the circle. It also intuitive to the user to ask to pose for the "OK sign" and it is known by many people.

Thus during the finger calibration process the operator was asked to pose for "OK Sign" with all fingers, i.e first touch thumb and index finger tips and make other 3 fingers co-aligned with the index finger. At this point the system will take the normalized bend data and decide the A and B parameters of the Eq. 4. This will be done for all fingers and it gave the best calibration. One disadvantage when using this method is that the user has to create a near equal circle.

4 Experiments and Evaluation

4.1 Evaluation of Robot Finger Posture Representation Accuracy

To experience one's own hand in telexistence manipulation it is necessary to capture the same finger posture from the operator and reconstruct in an anthropomorphic robot hand. In the previous sections using an optical fiber based flexible master glove and a robot hand the reproduction of the same finger posture was discussed. However, based on different users the effectiveness of the normalization algorithm was unknown. In order to find out the effectiveness of the finger-mapping algorithm on multiple users hand, random grasping tests with 4 users were carried out.

At first, the users were briefed about the nature of the manipulation and proceeded to the finger calibration by asking them to pose for the "OK Sign" with all fingers. Once the calibration is verified on a simulated environment they were connected to the slave robot. As the first verification step, they were asked to check the thumb-index finger pinch and thumb-middle finger pinch. Some users initial trial was not accurate as the calibration was not successfully performed. Therefore, the finger calibration step was repeated while connected to the robot until the correct pinching was achieved. Approximately with 3 calibrations users were able to pose for the gestures of pinching thumb-index and thumb-middle fingers.

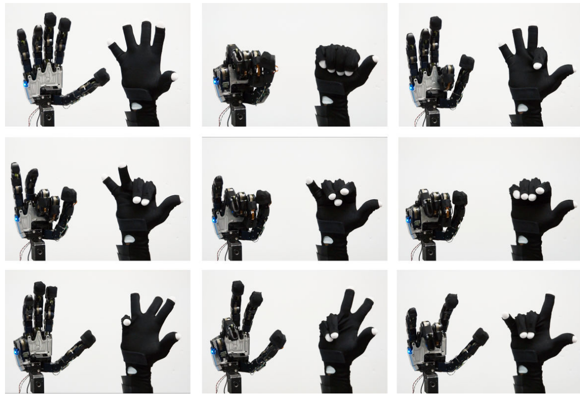

Figure 12: Counting Examples

Fig. 12 shows 9 counting examples that the operator hand was posing and the resultant slave representation. Each example shows the master posture on to the right and the slave posture on to the left side. As can be seen from the Fig. 12, the slave hand and the master glove is capable of successfully showing the counting sequences by fingers. Furthermore, specific gestures such as "Peace" in Japan and "Rock" gesture in states, fist gestures can be performed. Mimicking counting gestures on a remote slave robot while correcting through visual feedback was possible even in robots with pre-programmed trajectories. However, the ability to perform these gestures in a repeated and dynamic manner without visual feedback is very helpful in telexistence manipulations for building awareness of the body.

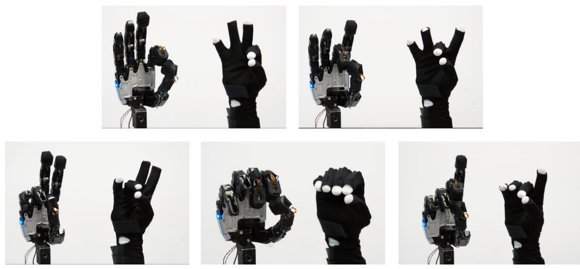

Figure 13: Fingertip-fingertip Pinching and Rolling Examples

Next, with the same calibration user was asked to do thumb to other finger pinch gesture. As shown in Fig. 13 finger-finger pinch can be done with finger combinations thumb-index, thumb-middle and even thumb-ring fingers. thumb-small finger pinch was not possible as the electrical limit of J1 does not permit to reach the target position. However, thumb-small finger pinch usage is very rare even by bare hands. For each finger combination total of 10 repetitions was performed.

During the previous experiment it is also found that the operator can even roll their fingers over from index finger to ring finger. This will allow the operator to roll objects on fingertips. To test the finger rolling a small rubber ball with a diameter of 15mm was used as shown in Fig. 14. Operator was able to do 2 finger, 3 finger roll with the 15mm rubber ball and even roll the ball from index finger to middle finger.

As shown in the above examples to perform these actions, the operator does not have to be taught. He naturally understands that what fingers to be used, what type of finger movements needed in order to perform the required task and continue with the grasping

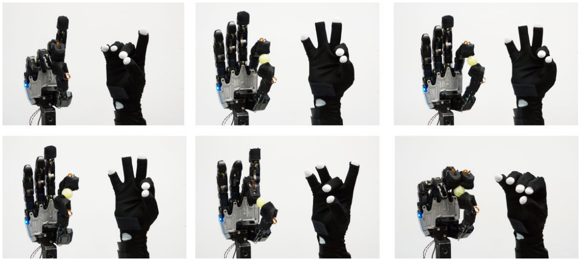

Figure 14: Two Finger, Three Finger Grasping and Rolling Examples

tasks as he wish. Furthermore, the ability of mimicking one's own finger motion and seeing it through the robot's eye will allow the operator to have the correct eye-hand coordination and also eye-finger coordination over time. Furthermore, having able to manipulate the remote fingers with similar dexterity compared to one's own fingers helped the operator to perform manipulations much easily.

4.2 Accuracy of Reaching and Grasping in Teleoperation without the Visual Feedback

4.2.1 Experimental Setup

In the previous experiment the subjects were using visual feedback in the manipulation. However, most humans can grasp simple objects with eyes closed. A preliminary study was conducted with 10 subjects and a cylinder with diameter 65mm and height 125mm was placed in front of them at the reaching distance. They were asked to grasp the cylinder with eyes open repeated with eyes closed. All the subjects were able to grasp the cylinder even with eyes closed. When a visual cue is given they imagine the size, distance information and then with eyes closed they think how the fingers should be moved to grab that object. Similarly, if the fingers are mapped accurately and the visual feedback has the same characteristics as human, grasping might be possible in telexistence manipulations without visual feedback.

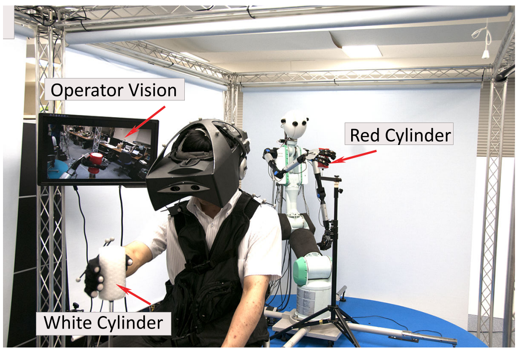

Figure 15: Experimental Setup

To evaluate this, an experiment with 9 subjects (6 male, 3 female), first time users was conducted. However this experiment is not meant for evaluating the perception accuracy error grasping error, but just a measure of if the system capable of delivering the experience to the first time users so that they can reach and grasp an objects. The average age was 26 (SD = 2.23) and height was 169cm (SD = 9.7) where all the subjects have used 3D displays before such as 3D TV, 3D Cinema etc. However, only 7 subjects have had used HMD's. Three of them have controlled robots in the past and 8 of them was trying TELESAR V system for the first time. The remaining participant had one time experience 1 year before. The average reaching speed was around $10cms^{-1}$.

4.2.2 Experimental Procedure

The subjects were connected with the slave robot with head, body, right arm and hand only. Once connection was established, they were asked to check the finger calibration accuracy by touching the thumb-index and thumb-middle fingers and check the corresponding robot posture. Finger calibration was repeated (max 3 times) until the correct posture is mapped. As shown on Fig. 15 a red cylinder with diameter 65mm and height 125mm was placed exactly 500mm apart from the robots body, and 200mm down the eye level. A similar size white cylinder was placed on the users side. The experiment was carried out with three conditions. First condition was to confirm the spatial position of the two cylinders are correct and for that the subjects were asked to grasp the cylinder with visual cue. In the first condition subjects were restricted for going closer, or back as well as sides. The visual cue was confirmed with the display shown in Fig. 15 and a black screen was provided when visual cue is disabled. After confirming the position, the subject side cylinder was removed and the step was repeated until they could successfully reach, grasp and lift the object up from their right hand. Next, subjects were asked to position their head (roll, pitch, yaw) so that they can see the whole object clearly and in a comfortable manner. Next, they were asked to place their left hand and virtually hold the remote object and while holding the vision was cut-off (provided a black screen) and asked to grab and lift the object and wait until the vision is back. The step was carried out with 3 trials.

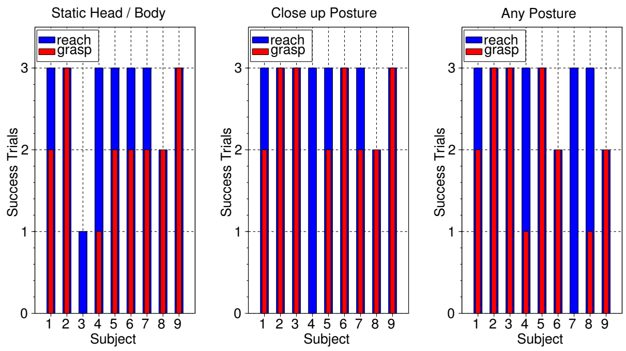

Figure 16: Reaching Success vs. Grasping Success (left) No body dexterity, (mid) front/back dexterity, (right) full upper body dexterity

In next conditions, the same steps were carried out. But they were only allowed to move their body in x-axis. i.e going closer or far apart and 3 trials were carried out. Finally, in the third condition the subjects were not restricted and were asked to go in to any posture and perform the same steps. The experiment always started with condition 1, but the order of condition 2, 3 was randomized for each subject.

4.2.3 Experimental Results

As shown in Fig. 16(left) the experiment results when movement freedom limited to only head. The reaching and grasping success accuracy was found as 89% and 63% respectively. Fig. 16(middle) shows when the subjects were given freedom in head, and spinal movements (i.e closeup/far-apart). The reaching and grasping success accuracy was found as 96% and 74% respectively. As shown as in Fig. 16(right), when full upper body freedom was given the reaching and grasping success accuracy was found as 93% and 63% respectively. Furthermore, the Condition 2 and 3 order was randomized for each users.

Overall result of 9 subjects showed that when the users were not allowed to move their body the reaching accuracy was less and it was increased when they were given the freedom. This was because, the subjects had different arm lengths and they were not comfortable when they were not given any freedom. Furthermore, it was observed that, when they were given full freedom, they naturally adjust their body as they wish to comfortably perform the manipulation action. When subjects reach closer, the grasping accuracy was increased. However, when they were given full body motion freedom some subjects were unable to perceive the size of the object because they were too close. With that it was confirmed that the systems accuracy is optimal when the eye-to-object distance is between 400mm - 500mm and the full body motion was naturally used by all subjects. The results can be concluded that there is a trend that the grasping accuracy was increased when the users were given more freedom. It was further evidenced that, even though there was an accurate reaching there might be differences in the fingers and could not accurately grasp. The results showed that by allowing the subject to use the body motion without any constraints resulted in deciding accurate perception distance and the size of the object. This was evidenced due to the success rate of grasping with no visual feedback. Therefore, the results can be concluded that if the fingers are mapped accurately and the visual feedback has the same characteristics as human, humans can grasp remote objects without visual feedback in telexistence manipulations.

5 Conclusion

This paper describes a new type of robust control mechanism for a 15 DOF anthropomorphic robot hand in telexistence manipulations using a flexible fiber based master glove to experience the visual-kinesthetic sensation of one's own hand in remote manipulations. To overcome the work plane constraints and the frictional component of exoskeleton and endoskeleton type master hands, a 14 DOF optical data glove based master hand was developed. Due to very low hysteresis errors, easy replacement/modifications and the higher dexterity of the sensor system allow the capture system to correctly model the thumb and other fingers and therefore the full hand posture reconstruction was achieved. The evaluation showed that the novel finger length and bending normalization calibration algorithm shows trends that it can be effectively used by even first time subjects for object manipulations without visual feedback in telexistence. By mapping the human finger motion to a 15 DOF anthropomorphic robot hand accurately and providing visual feedback with the same characteristics as human, subjects were able to quickly adopt to remote robot hand as they were using their own hand for remote manipulation. In the future a follow up experiment should be conducted and if the trend can be generalized, the method proposed by this paper can be used in telexistence manipulations where the users can adapt to teleoperations reaching and grasping mush faster through experiencing the remote hand as their own.

Acknowledgements

This project is supported by JST-CREST Haptic Media Project.

References

[1] M. Bouzit, G. Burdea, G. Popescu, and R. Boian. The rutgers master ii-new design force-feedback glove. *Mechatronics, IEEE/ASME Transactions*, 7(2):256–263.

[2] L. B. Bridgwater, C. A. Ihrke, M. A. Diftler, M. E. Abdallah, N. A. Radford, J. M. Rogers, S. Yayathi, R. S. Askew, and D. M. Linn. The robonaut 2 hand - designed to do work with tools. In *Proceedings of IEEE International Conference on Robotics and Automation, ICRA'12*, pages 3425 –3430, may 2012.

[3] A. Caffaz and G. Cannata. The design and development of the dist-hand dextrous gripper. In *Proceedings of IEEE International Conference on Robotics and Automation, ICRA'98*, volume 3, pages 2075 –2080 vol.3, may 1998.

[4] C. L. Fernando, M. Furukawa, T. Kurogi, S. Kamuro, K. Minamizawa, S. Tachi, et al. Design of telesar v for transferring bodily consciousness in telexistence. In *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference*, pages 5112–5118. IEEE, 2012.

[5] C. S. Inc. Cyberglove iii, next generation data glove technology, Jan. 2010.

[6] M. Jagersand. Hierarchical uncalibrated predictive display for a 16 dof utah/mit hand. In *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS '99*, volume 1, pages 124 –129 vol.1, 1999.

[7] S. Nakagawara, H. Kajimoto, N. Kawakami, S. Tachi, and I. Kawabuchi. An encounter-type multi-fingered master hand using circuitous joints. In *Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference*, pages 2667–2672. IEEE, 2005.

[8] S. Tachi. *Telexistence*. World Scientific, 2010.

[9] S. Tachi and H. Arai. Design and evaluation of a visual display with a sensation of presence in tele-existence system. *Journal of Robotics and Mechatronics*, 9(3):220–230, 1997.

[10] S. Tachi, H. Arai, and T. Maeda. Development of an anthropomorphic tele-existence slave robot. In *Proceedings of International Conference on Advanced Mechatronics, ICAM'89*, pages 385–390, may 1989.

[11] S. Tachi, H. Arai, and T. Maeda. Tele-existence master-slave system for remote manipulation. In *Proceedings of 1990 IEEE International Workshop on Intelligent Robots and Systems. 'Towards a New Frontier of Applications'*, volume 1, pages 343–348, jul 1990.

[12] S. Tachi, N. Kawakami, M. Inami, and Y. Zaitsu. Mutual telexistence system using retro-reflective projection technology. *International Journal of Humanoid Robotics*, 1(1):45–64, 2004.

[13] S. Tachi, N. Kawakami, H. Nii, K. Watanabe, and K. Minamizawa. Telesarphone: Mutual telexistence master-slave communication system based on retroreflective projection technology. *SICE Journal of Control, Measurement, and System Integration*, 1(5):335–344, 2008.

[14] S. Tachi, K. Minamizawa, M. Furukawa, and C. L. Fernando. Telexistencefrom 1980 to 2012. In *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS '12*, pages 5440–5441. IEEE, 2012.

[15] S. Tachi, K. Tanie, K. Komoriya, and M. Kaneko. Tele-existence (i): Design and evaluation of a visual display with sensation of presence. In *Theory and Practice of Robots and Manipulators*, volume 1, pages 245–254. Springer, june 1985.

[16] S. Tachi and K. Yasuda. Evaluation experiments of a telexistence manipulation system. *Presence*, 3(1):35 –44, feb 1994.

[17] F. D. Technologies. 5dt-14dg, 5dt data glove 14 ultra, Nov. 2011.

[18] Z. Zhou, H. Wan, S. Gao, and Q. Peng. A realistic force rendering algorithm for cybergrasp. In *Computer Aided Design and Computer Graphics, 2005. Ninth International Conference on*, pages 6–pp. IEEE, 2005.