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Design of TELESAR V for Transferring Bodily Consciousness in Telexistence

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Abstract— **This paper focuses on design of a dexterous anthropomorphic robot where the operator can perceive the transferring bodily consciousness to the slave robot during a tele-operation. Accordingly, we propose a telexistence surrogate anthropomorphic robot called "TELESAR V", which was designed and constructed by development of the following: a 52 DOF slave robot with a torso, upper limbs, hands and head to model the operator's posture on all parts of the upper body and maintain a 6 DOF accuracy in arm endpoint; a HD Head mounted display with 6 DOF point of view accuracy for wide angle stereovision; and a mechanism for sensing and reproducing fingertip haptic and thermal sensation. This paper describes the development of the TELESAR V system, where the effectiveness has been verified through functional experiments.**

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 actually exist, and to interact with the remote environment [1]. In 1988, an exoskeleton type master-slave telexistence cockpit [2] called TELESAR I was developed. In 2005, a mutual telexistence master-slave system called TELESAR II [3] was developed with human-like arm and hand movements. The system had the functionality to perform conventional verbal communication with a remote participant as well as nonverbal gestures such as handshaking. In 2007, a TORSO with a head [4] was developed with human-like neck movements to visually interact and explore 3-dimensional details in a remote object in a more natural and comfortable manner. With this system, operator was able to feel a natural visual sensation in a tele-operation due to the 6 DOF point of view accuracy (position and orientation) of robot vision.

In general, humans experience the conscious self as localized within their bodily borders. Due to high level of spatial unity perceived with multi sensory inputs makes human to think that the body they see, and can feel touch is their own body. Also, researches have proved that if the same spatial unity is kept with a high level of multi sensory applied to a human, neurological conditions such as Rubber Hand Illusion (RHI) [5] and Body Transfer Illusion [6], [7] can be felt.

In telexistence, if the operator can feel the slave robot as an expansion of his bodily consciousness, and also the ability to freely move and control the slave robot in a similar way to how his body moves, it will increase the throughput of the performed remote task. In order to prove this concept in telexistence, it is essential to have the following fundamental requirements.

1) Operator should be able to freely and independently move his head, upper body, arms and hands. In contrast, slave robot's hands should follow similar movements while maintaining 6 DOF accuracy of arm endpoint.
2) Operator should be able to clearly see a wide angle stereo view of the remote site with 6 DOF point of view accuracy of robot vision. In addition ability to perform binaural, bi-directional verbal communication is required.
3) Operator should be able to grasp and manipulate objects in a similar way to a human hand.
4) Operator should feel fingertip haptic and thermal sensation when touching objects remotely.

In order to address the above points, a master slave robot system with higher level of dexterity is necessary. We developed "TELESAR V", a master slave robot system with a conjunction of 52 DOF to perform full body movements. In addition operator can feel the fingertip haptic and thermal sensation when touching objects remotely.

II. Design Considerations of TELESAR V

Conventional tele-operation system sometimes uses exoskeleton based master system [2] to capture the movements of operator. These systems limits the operator's movements to the exoskeleton system's mechanical constrains. Thus in order to satisfy the first condition, a non-mechanical, not direct attachable measurement system is necessary. This also gives full flexibility to move head, body and arms independently as desired.

In order to map the point of view and arm endpoint 6 DOF, a higher DOF robot is necessary. Conventional dexterous robots [8] are not capable of achieving this due to not having enough DOF in the torso part. A robot that can mimic similar spinal movements (extension, flexion, lateral flexion, and axial rotation) similar to a human is required as robot's torso. In order to address this point, both torso and

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an anthropomorphic robot arm with minimum of 6 DOF is required.

Installing wide-angle full HD cameras on slave robot and a wide angle HD Head Mounted Display (HMD) as the operator vision, the second condition can be satisfied. In conventional robots, [2], [9] in case of requiring a spinal movement, robots performs a locomotive operation using it's mobile platform and navigate towards/away/sides while operator controls the movement using a joystick or similar technology. Since the operator does not move his upper body, it is difficult to maintain a 6 DOF point of view accuracy of robot vision. Thus a 3 DOF head is necessary. Furthermore torso, head, arm and hand should be in a single kinematic chain to obtain the accuracy of each component. Installing microphones as robot's ears and speaker as robot's mouth and similar configuration on HMD will provide bi-directional verbal communication capabilities.

To satisfy the third conditions a higher DOF anthropomorphic robot hand similar to human hand is required. Also fingertip force and temperature can be measured using vision based force sensor and reproduced using vertical and shearing forces on fingertip. Thus forth condition can be satisfied.

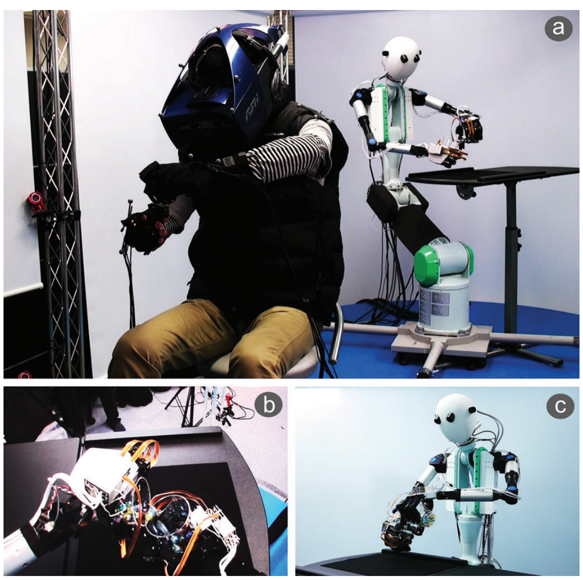

Fig. 1. (a) Master-Slave configurtion, (b) HD wide angle view, (c) Slave robot

We developed a telexistence master-slave system called "TELESAR V" that satisfies the above mentioned four conditions. As shown in Fig. 1(a) operator can freely move in his space while able to mimic the spinal movements and perform human-like body assisted stroke motion. As shown in Fig. 1(b) robot can maintain a 6 DOF point of view and arm endpoint accuracy so that the vector between the two points of vision and arm endpoint is seamlessly mapped to the operators same points. By adding fingertip haptic sensation [10] into the master slave robot system it concludes that TELESAR V can satisfy the above four conditions.

III. Implementation

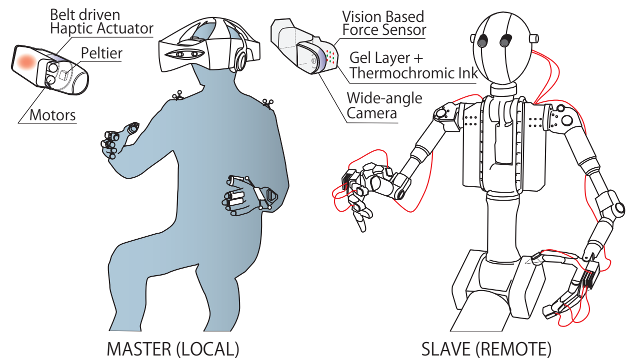

Fig. 2. TELESAR V: System Overview

As shown in Fig. 2, TELESAR V system consists of a Master (Local) and Slave (Remote) system. A 52 DOF dexterous robot is developed with 5 DOF torso, 3 DOF head, 7 DOF arms and 15 DOF hands. Robot also has Full HD (1920 × 1080 pixels) cameras for capturing wide-angle stereovision and stereo microphones situated on robots ears for capturing audio from the remote site. Voice from operator is transferred to the remote site and output through a small speaker installed on robots mouth area for conventional verbal bi-directional communication.

In Master side, operator movements are captured using a motion capturing system (OptiTrack) and are sent to the kinematic generator PC. Finger bending is captured with an accuracy of 5 DOF using "5DT Data Glove 5 Ultra".

A. Development of 54 DOF human sized anthropomorphic robot

As shown in Fig. 3, TELESAR V slave robot consists of 4 main systems. (torso, head, arms and hands). Torso is developed based on a modified "Mitsubishi PA 10-7C Industrial Robot Manipulator" placed upright. First five joints of the manipulator arm is used as torso and last 2 joints with a separately attached DC motor is used as the 3 DOF (roll, pitch, yaw) head.

A custom designed 7 DOF human sized anthropomorphic robot arm is fixed between the Torso joints 5 and 6 to make it similar to human sized dexterous robot. In order to increase the level of dexterity of the slave robot arm, it is designed with similar limiting angles of each joints compared with ordinary human arm. However we have included a position based electrical limit overriding the mechanical limit to provide extra safety in case of a joint angle overshoot. Table. I shows the mechanical and electrical joint angle limitations in positive and negative direction.

Arm joints are driven with 12V DC motors and first 3 joints (J1, J2, J3) implements Harmonic Gears to maintain a very low backlash and vibration while provide the necessary torque. As for the hand, a custom designed human sized anthropomorphic robot hand is used. The hand is having similar number of joints compared to an ordinary human

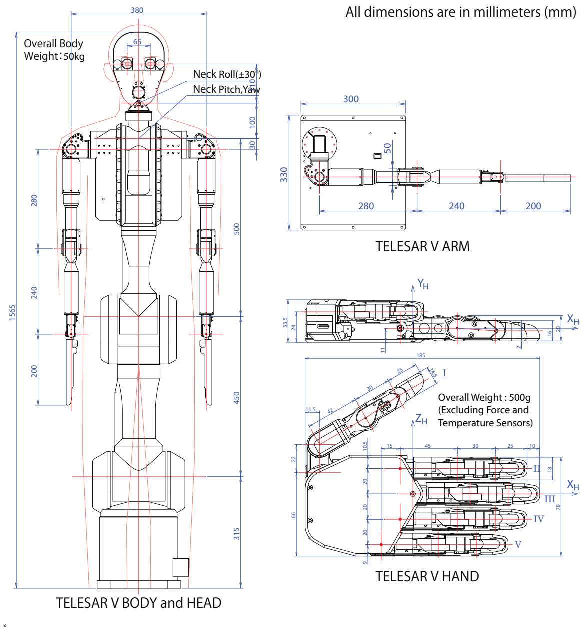

Fig. 3. Kinematic Configuration of Head, Body, Arm and Hand

hand. Robot fingers are driven by 15 individual DC motors and a dynamically coupled wires and a pulley driven mechanism couples the remaining joints that does not directly attach to a motor. (Note: Mechanical components of Arm, Hand and Head are developed in KAWABUCHI Mechanical Engineering Laboratory, Inc.)

TABLE I
JOINT LIMITS OF 7 DOF ANTHROPOMORPHIC ROBOT ARM

Joint	Mechanical Angle limit		Electrical Angle Limit	
	Negative	Positive	Negative	Positive
J1 (Shoulder)	-90°	145°	-90°	+145°
J2 (Shoulder)	-100°	+20°	-100°	+18°
J3 (upper arm)	-152°	+32°	-150°	+30°
J4 (elbow)	-135°	-2°	-130°	0°
J5 (lower arm)	-93°	+93°	-90°	+90°
J6 (wrist)	-15°	+45°	-15°	+40°
J7 (wrist)	-45°	+60°	-40°	+60°

All the DC motors are connected to standard DC motor drivers with a combination of optical encoders and potentiometer reading as position measurement. Furthermore voltage and current consumption is monitored at each motor and torque at motor shaft is calculated. Communication between the motor drivers and PC is carried out through a PCI-Express x1 bus.

B. Development of the wide angle HD sterovision system

In order to capture Full HD video from the robot, a CMOS camera head (Model no: TOSHIBA IK-HK1H) and a wide angle lens (Model no: FUJINON TF4DA-8) configuration as the robot's eye were used. Two camera's were installed parallel to each other having a distance of 65mm.

To provide a HD wide-angle stereovision sensation to the operator, a HD (1280 × 800 pixels) wide-angle Head Mounted Display was developed (Fig. 4). In order to provide the wide angle and maintain a small footprint, we have used 5.6" (inch) LCD display (Model no: HV056WX1-100) and increased the length of optical flow using a special lens arrangement. HMD has two parallel virtual projection planes located 1m far away from two eye balls, to obtain stereoscopic vision independently between the eyes, thus operator can feel correct distance [11]. A knob is provided at the front side of HMD so that the operator can adjust the convergence angle of left and right eye for a clear stereovision. At the output stage of the HMD, a video flipper (Model no: XC1 Sio) for each eye is used to correct the vertical flip due to the lens configuration.

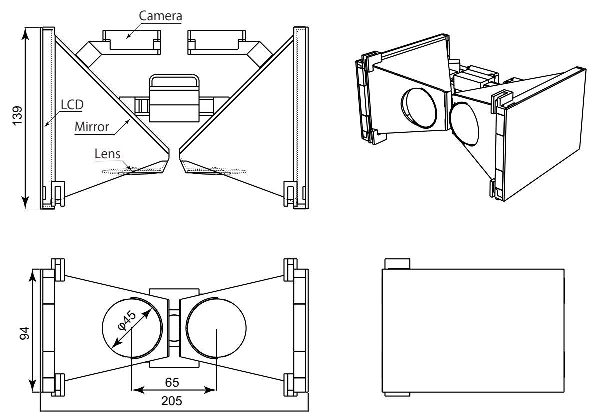

Fig. 4. TELESAR V: HMD Assembly view

With the above specifications, we were able to produce a wide angle of H×V (61×40)°(degrees) for each eye where as the original captured video field of view was H×V (62×48)°(degrees). In addition, two cameras were installed on the front side of HMD. This is useful when the operator needs to turn his vision into a video see-through mode. A complete spefication of the stereovision system is listed as shown in the Table. II

C. Development of thermal and haptic transfer system

Robot's fingers are installed with a vision-based cutaneous sensor [12] to sense both force vector and temperature of fingertip. As shown in Fig. 5(a) a CCD camera is continuously tracking green and red markers placed on a transparent elastic body. A white LED attached to the fingertip illuminates the markers. In addition, another layer of thermo sensitive ink is wafered in between elastic body and outer surface. The outer surface is fabricated with black color elastic material, which has similar tactile sensation characteristics to a human finger when touched. (Fig. 5(b))

Remote fingertip proprioceptive sensation is reproduced using vertical and shearing forces generated by motor driven belt mechanism [13]. As shown in Fig. 6, a rotation in opposite direction generates vertical stress while a rotation in

TABLE II
STEREOVISION SYSTEM SPECIFICATIONS

	HMD (master)	Cameras (slave)
Field of vision H×V [deg]	61° × 40°	62° × 48°
Sensor dimension [inch]	5.6 LCD	1/3 CMOS
Focal length [mm]	114	10 ∼ ∞
Convergence ratio [%]	89	89
Interocular distance [mm]	59 ∼ 69	65
Body weight [mm]	1.2	N/A
Pixel resolution [px]	1280 × 800	1920 × 1080
Viewing angle H×V [min/px]	2.9 × 3.0	1.9 × 2.7
Scanning frequency H×V [Hz]	49.2k × 60.00	67.43k × 59.94
Sound input/output [ch]	In 1 / Out 2	In 2 / Out 1

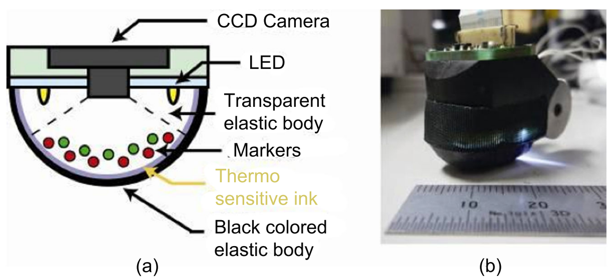

Fig. 5. (a) Vision-based cutaneous sensor configuration [12], (b) external appearance

same direction generates shearing stress. The fingertip temperature is reproduced using thermoelectric cooling (Peltier) actuators placed on the bottom side of operator's fingertips.

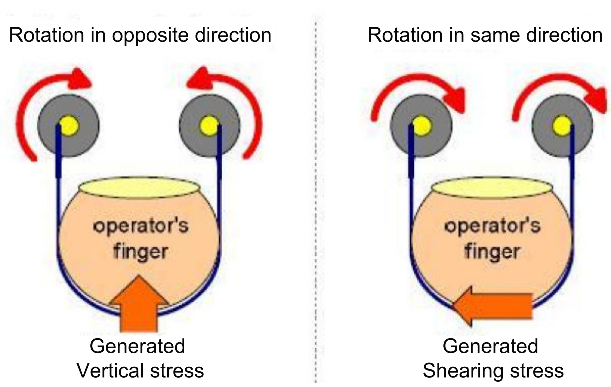

Fig. 6. Vertical and shearing forces generation [13]

D. Trajectory Generation

In the trajectory generation for torso first condition is to freely move without constrains while robot should follow the operators spinal movements (extension, flexion, lateral flexion, and axial rotation). This is achieved by modified numerical kinematics for 6 DOF serial-chain. In order to maintain a 6 DOF accuracy in point of view and arm endpoint, the robot has to follow the opertors head while maintaining the shoulder coordinate frame in a close relation while the arm endpoint should be exactly same as the operators. Considering the above condition and to improve the service task effectiveness we have used position-based impedance control. This method addresses the difficulty of obtaining the complete dynamic description when parametric uncertainties of the robot dynamic model occur.

In order to achieve the required accuracy and to maintain a higher stability of trajectory generation, we have used 2 closed form inverse kinematic models for torso and arm. In this model, as the first step it performs a direct search on free joints, and secondly apply the performance criteria to filter any singular solutions and finally the inverse solution is generated. As for the first performance criteria we stick to the method of distance from a singular measure as there is only one redundant joint and fine-tuned for upper limb using the "Measure of Transmissibility" (MOT) value. As for the second performance criteria, it does a forward kinematics and confirms the arm endpoint 6 DOF accuracy while checking for invalid joint angles for an upper limb.

Even though the kinematics is solved separately in two serial chains, the base point (position and orientation) for both arm and torso (i.e shoulder center) is shared in real-time to keep the serial chain integrity. In manipulation task, torso has a higher priority compared to arm inverse kinematics. Thus when arm inverse kinematics cycle needs to calculate the joint space, the new current position and orientation of base point is available. The final compliant trajectory generated by the impedance controller is tracked by a high-speed PID control loop.

E. 6 DOF point of view accuracy and 6 DOF arm endpoint accuracy

In a tele-operation it is important to have the operator's eye-to-arm endpoint vector equal to robot's eye-to-arm endpoint vector to see the robot arms are always follwing his own in a dynamic behavior. As shown in Eq. 1 point of view accuracy is obtained by exactly following the operator's head in 6 DOF.

$$ {}^{w}_{sl-eye}T = {}^{w}_{ms-eye}T \tag{1} $$

Thus the remaining 5 DOF torso and 7 DOF arm should provide the 6 DOF accuracy of arm endpoint. As shown in Eq. 2 it is also considered that the operator should be able to see robot's lower arm vector in a similar way to his own lower arm in order to feel the same kinesthetic sensation.

$$ {}^{sl-eye}_{sl-hand}T = {}^{ms-eye}_{ms-hand}T \tag{2} $$

In order to model the above kinematic conditions we perform the following order.

1) Operator's head is mapped to slave robot head in 6 DOF accuracy. (Eq. 1)
2) Robot's eye-to-hand vector is mapped with operator's eye-to-hand (Eq. 2) vector where lower arm vector is same.

3) The error is compensated using the remaining DOF of upper arm and torso.

It is also known that the human anatomy, wrist joint is mostly restricted to movements of less than 180° (degrees). Like most of the slave robots, in TELESAR V, wrist is restricted with 60 $\sim$ 105 °(degrees) respectively due to mechanical restrictions. The above model can overcome this mechanical limitation because of the remaining DOF compensation model.

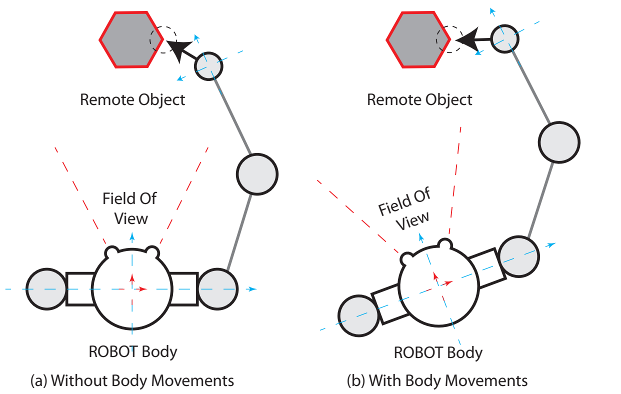

Fig. 7. Orientation accuracy obtained through upper body compansation

In the method explained above while compensating, it is important to nearly match the master torso and slave torso posture. If the posture is different, due to the mechanical limitations of joints, the level of dexterity will reduce and resulting a very narrow space constrain to the operator. We solve this issue by measuring the shoulder rotation (roll, pitch, yaw) of master and model a close possible upper body match. This method was really effective when the operator tries to rotate his spine clockwise and counter clockwise. As shown in Fig. 7(a), operator tries to reach the remote object through correct orientation, but due to the joint limitation of the wrist it is not possible. This kind of a situation is naturally resolved by humans by use of spine to rotate the body and approach using the extended right hand. As shown in Fig. 7(b), such situation can be naturally resolved. With this setup, we have achieved a high level of dexterity and less complexity in object manipulation.

$$ {}^{sl-sh}_{sl-hand}T = {}^{sl-eye}_{sl-sh}T^{-1} \cdot {}^{ms-eye}_{ms-hand}T \quad (3) $$

After the torso and head joint space is decided, as shown in Eq. 3 the shoulder-to-hand vector is calculated in real-time and perform numerical kinematics for 7 DOF serial-chain for obtaining the arm joint space.

F. Communication Protocol and performance

Calculated joint space, robot's fingertip force, fingertip temperature, joint encoder, joint force data are arranged in a special protocol and sent via UDP Multicast at a speed of 1KHz. The data cycle speed is limited just to preserve the bandwidth when doing real-time operations, but there is no design limitations to increase this speed. These Multicast data is received Hardware Clients who drives the torso and arm/hands and also a seperate client who runs the TELESAR V Simulator environment. The system is implemented with a point-to-point network configuration so that the Master and Slave can be physically located at different places in the world.

However the HD Video link is currenty transmitted locally to the Master side because to minimize the latency. We have been testing the video link with network streaming, but only up to VGA resolution (640 × 480 pixels) was successful in reproducing the 3D vision with a minimum latecy which was sufficient for telexistence operations.

IV. Achievements of TELESAR V

A 6 DOF point of view accuracy, 6 DOF arm endpoint accuracy, ability to use the spinal movement and feel haptic and thermal sensation, we found that TELESAR V can perform many new interactions.

A. Body compensated hand movements with fixed head orientation

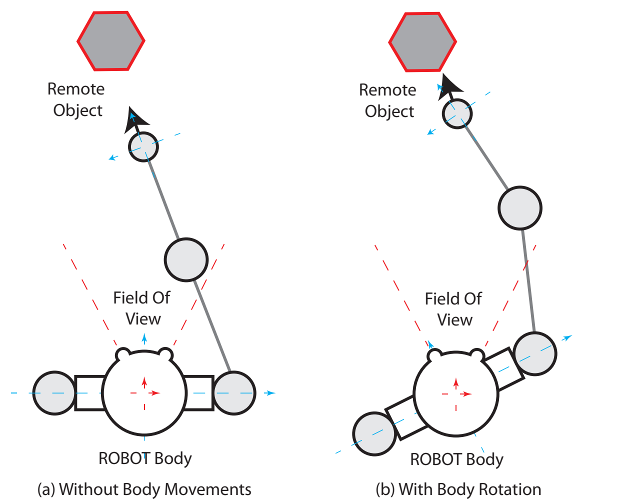

Fig. 8. Extend the reachability using body Axial rotation

As shown in Fig. 8(a), conventionally when the operator is not able to reach a remote object by fully stretching the arm, he needs to move the robot base close enough to reach in its fully extended arm. But TELESAR V can rotate it's body with an axial rotation as shown in Fig. 8(b) and extends the reach easily. This eliminates the use of moving the robot base and preserves the human natural body movements. In addition operator can see the remote object clearly and does not need to change his head orientation while making axial rotation.

B. Body compensated hand movements with dynamic head orientation

Sometimes operator needs to explore the grabbed objects carefully before or after picking it up. (For example picking up a chemical container and reading the label). In a similar situation, humans will naturally use a combination of head

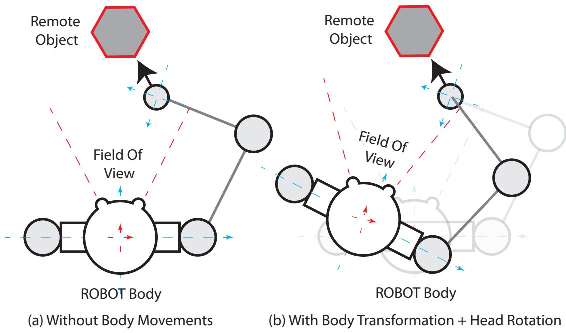

Fig. 9. Expanding field of view through combined body and hand movements

and arm movements to rotate and explore the entire 360-degree rotation. As shown in Fig. 9, a similar scenario can be executed with TELESAR V by first grabbing the object and keeping hand posture fixed and move the body and head around to see around the object. Since the operator does not move his hand position and orientation in world coordinates slave robot preserves the arm endpoint.

C. Active compliant force

When manipulating objects humans usually use their body as a support structure for arms and legs. (i.e back muscle supports the arm movements.) It helps to generate impulse forces when necessary. Similarly as shown in Fig. 10, with TELESAR V the operator can induce an accelerated force at the end point by a combined movement of body and arms. This is not possible if the combined forces have a delay or if the body and arm has different posture from the operator.

$$F_{resultant} = F_{body} \times cos(\theta) + F_{arm} \tag{4}$$

As can be seen in Eq. 4 the tangential force component created by the body rotation adds to the arm trajectory and accelerates the end point movement. These accelerations help to generate stroke and impulse motions.

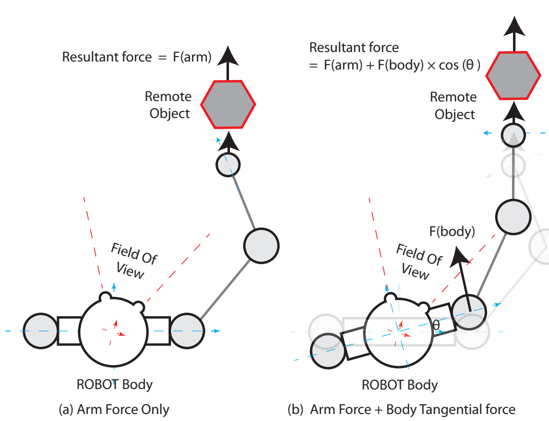

Fig. 10. Accelerated force during combined body and arm motion

This type of accelerated motion is also useful to perform remote tasks faster compared to when using just arm motion.

V. Functional Experiments of TELESAR V

With all the above enhancements enabled we have performed few functional tests to explore how the visual, auditory, haptic and kinesthetic sensation enriches in a telexistence operation.

A. Remote glass ball pouring and stacking bricks

As shown in Fig. 11(a), operator grabs 2 cups placed on the table and pours the glass balls from one to another. In this experiment the placement of the cups on the table did not matter because operator can see the cups and he can extend his upper body and arms to reach the object. Due to the accuracy of the system operator was confident enough to perform a over-the-air ball pouring by holding 2 cups in a vertical distance of around 15cm. In addition, due to the haptic transfer system, operator can feel the tactile feedback when glass balls hit the cup.

We have performed a similar test where there are 3 cubes placed (Fig. 11(b)) on the table and ask the operator to stack one over each. Operator could easily perform the task. Secondly, one block was visually blocked but placed in a reachable position. Operator first tried to reach the visually blocked object by approaching through sides and saw a little portion of the block. Having able to perceive the kinesthetic sensation and have a sense of the robot arms position he was able to grab it without any mistake.

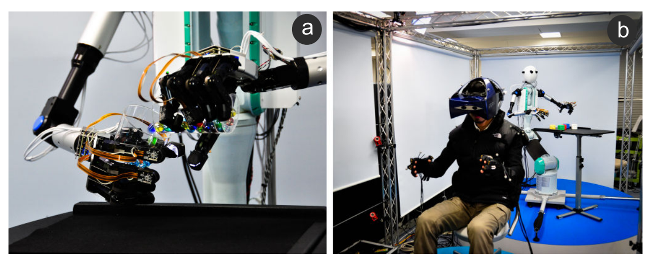

Fig. 11. (a) Ball pouring, (b) stacking up bricks vertically

B. Writing Japanese Calligraphy using a brush and ink

In this experiment operator was given a brush, ink tank and a piece of paper to write Japanese calligraphy. In general, writing characters using a brush and ink requires some practice, as the applied force has to be maintained at a constant level above the paper surface. As shown in Fig. 12(a), operator was able to pick up the brush from holder, dip into the ink tank gently and write Japanese calligraphy. During the writing operator was using his left hand as a support so that the paper does not move due to the stroke. In this experiment operator was using active compliant force when he was writing an narrow brush stroke where the ink trail has to be gradually modify from thick to very narrow. The extended reach was used when he wanted to dip the brush into the tank. Fig. 12(b) shows the completed calligraphy.

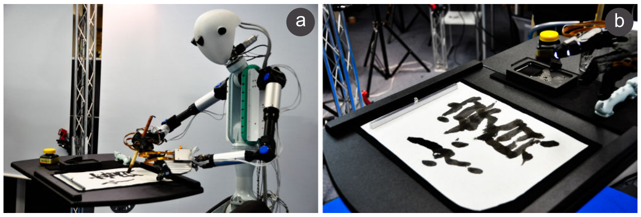

Fig. 12. (a) Japanese Calligraphy, (b) Completed Calligraphy

C. Manipulating small objects in densed environment

In this experiement, operator was given a Japanese Chess board (Shogi) where he has to participate in a chess game with a remote participant. The board dimensions were 313mm×280mm×13mm (L×W×H) while the largest wedge-shaped piece being 30mm×26mm×5mm and smallest wedge-shaped pieces being 20mm×16mm×5mm. As shown in Fig. 13(a), operator was able to pick and place shogi pieces up to middle size. The second experiment as shown in Fig. 13(b), operator was given a pile of sticks diameter ranging from ϕ4mm to ϕ8mm. In this experiment, operator was able to use fingertip haptic sensation to not to apply over pressure to sticks. If the pressure is applied without any control the stick will simply flip around.

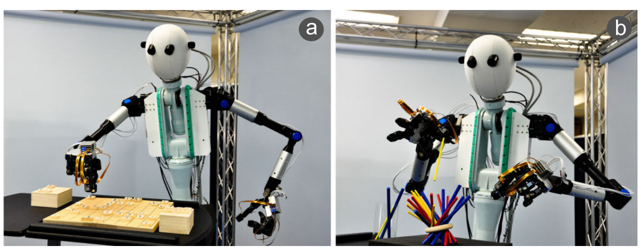

Fig. 13. (a) playing Japanese chess (shogi), (b) picking thin sticks

VI. Conclusion

We proposed a dexterous anthropomorphic master slave robot system where the operator can extend his bodily border to the slave robot during a tele-operation.

In order satisfy the above condition, we designed and constructed a 52 DOF telexistence surrogate anthropomorphic robot called "TELESAR V" where we were able to map the vector between master's point of view and arm endpoint to the same vector of the slave robots'. In addition the operator can feel auditory, visual, haptic and kinesthetic sensation through the sensory and actuator arrangement. With the higher level of multi sensory input and the accuracy of the above mentioned criteria the operator was able to perform basic tasks with confidence and no prior prctise. Even though the system is not currently evaluated under a psychophysical experiment, participants who tried the system felt their body consciousness is extended up to the robot during a tele-operation. Furthermore through out the experiments that we have carried out, we prove that this technology is helpful for carrying out tele-operations with confidence and experience the real extended body consciousness.

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