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Design and Development of a Telexistence System to Experience Extended Human Body Schema

by

Charith Lasantha Fernando

Submitted to the Graduate School of Media Design in partial fulfillment of the requirements for the degree of

DOCTOR OF MEDIA DESIGN

at the

KEIO UNIVERSITY

Academic Year 2013

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Design and Development of a Telexistence System to Experience Extended Human Body Schema

by

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Submitted to the Graduate School of Media Design on August 28, 2013, in partial fulfillment of the requirements for the degree of Doctor of Media Design

Abstract

Telepresence and Telexistence are technologies that allow a user to experience a sense of presence in teleoperations where the operator was provided with an immersive stereoscopic display, auditory feedback and the ability to move arms hands and head according to his/her postural changes. Teleoperations in daily life is helpful in visiting hazardous sites, remote surgery, sightseeing without spending much time on travelling, Micro manipulation such as Biotechnology, Microsurgery, Micro assembly and Microchip manufacturing at nanometer scale, etc. “Body Schema” allows a human to keep an up-to-date representation of the positions of the different body parts in space. In teleoperations, “Body Schema” can be used to understand the posture of remote body and perform actions with the awareness thinking that the remote body is your own. Telepresence and Telexistence robots allow having some body schema experience during manipulation. However, in current experience, operator would not feel the entire upper body. Moreover, it is limited to body parts such as arms and head only. Secondly, body schema in teleoperation is not clearly defined. Depending on the manipulation type, the sensations that are needed to build the body schema are unknown, and the advantages of body schema over teleoperation have not been discussed in depth.

This thesis contributes to defining “Body Schema” in teleoperations, designing a “Body Schema Transfer Model” for teleoperations where the model can be used to model Body Schema depending on the teleoperation type, the body parts involved, etc. The model is used to create cross modal perception sensations to achieve the body schema transfer experience in telexistence. By applying the model a telexistence master-slave robot system called “TELESAR V” was designed and implemented with the development of a high speed, robust, full upper body, mechanically unconstrained master cockpit and a 53 degrees of freedom (DOF) anthropomorphic slave robot. TELESAR V was able to provide an experience of user’s body in space and that’s the most simple and fundamental experience for feeling to be someone somewhere.

“TELESAR V” system was evaluated technically to find out the speed limitations, reaching, and grasping capabilities. With the existing system, an initial
evaluation was carried out to prove the effectiveness of “Body Schema Transfer Model”. The effectiveness was evaluated based on the advantage of multi DOF (53) synchronization of master to slave in telexistence, Body schema transfer error and the required training. Conducting a High Precision Peg-in-Hole insertion task and comparing with a standard data set, it was evidenced that the higher dexterity in telexistence systems with no force feedback will have a significant performance increment compared to conventional teleoperated robots with force feedback. Furthermore, this method can be used to compare any telexistence system built with different dynamics under a common index. It was also found that, non-expert subjects natural body schema error shows significant coherent relationship to telexistence mode body schema error. Up to date the system was tried with more than 100 first time users during demonstrations, lab visits, press releases, and media coverage events. The effectiveness of body schema to teleoperations and quality of body schema experience was further discussed through qualitative observations, questionnaires and some unique tasks that the robot can perform. With some case studies, how the subjects perform manipulations without prior training, eye-hand coordination and effectiveness of different subjects with various backgrounds was studied and discussed.

“Body Schema Transfer Model” proposed in this thesis can be used as a framework to build new systems that provides new experiences and raising aesthetic qualities and new operating environments. “Body Schema Transfer Experience” can be used in other disciplinary outside teleoperation giving new experience of controlling devices on personal space, games, next generation computing, etc. The ultimate proposal of this dissertation aims towards creating a new type of experience where users are not afraid of interacting with remote spaces and feel that what you see, hear, feel is real regardless of the provided stimuli. With the new experience, people will feel engaged in activities and the enjoyment that they will have might allow them to embed the remote space to their body.

Keywords: Body Schema, Consciousness, Telexistence, Body Map, Master-Salve Robot Manipulation

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Design and Development of a Telexistence System
to Experience Extended Human Body Schema

by

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Chapter 1

Introduction

1.1 Sense of Presence

Humans experience their presence that is known as the sense of being at some place everyday. Human brain and senses provide this experience of presence in terms of actuation and sensations like colors, sounds, movement, texture, feelings etc. However, until recently humans only experience the actual presence, but the concept of presence has developed over the past decade to be considered by many researchers as the essence of any experience in a virtual environments. In virtual reality the sense of presence is provided through a combination of technological component (motor-sensory) and a psychological experience [1]. These advanced human-centered virtual reality interactions would provide users with a sense of being somewhere, close to if not equivalent to the experience of actual presence.

1.1.1 Expanding the Sense of Presence

To provide sense of presence through virtual reality technologies the term telepresence was defined by Marvin Minsky in 1980. Telepresence refers to the phenomenon that a human operator develops a sense of being physically present at a remote location through interactions with the system’s human interface, user’s actions and the subsequent perceptual feedback he/she receives via the appropriate teleoperation.

1.2 Teleoperations

Teleoperations are a specific type of VR that allow the individual to operate in a distant environment (e.g., in space, in the depths of the sea or harmful locations). User is given the opportunity to command a machine which moves according to the user’s movements and gives both auditory and visual feedback. Such sensory
1.2. Teleoperations

feedback is sufficient to maintain the experience of feeling present in the remote workplace. The operator perceives two separate environments simultaneously: the physical environment where he or she actually is, and the remote environment, which is being presented via virtual reality technologies. Furthermore, the term “telepresence” is used when the virtual experience dominates the real world experience. Thus, it describes the feeling of being in the environment generated by the technology, rather than the surrounding physical environment.

Figure 1.1: (a, b) Button Interfaces, (c) Software Interfaces, (d) Exoskeletons, (e) Touch Screens

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In teleoperation manipulations, the controlled device is called a “Telemanipulator” and most cases it’s a slave robot. Depending on the situation teleoperations can be autonomous, manual or a combination of both resulting hybrid supervisory control methods. In supervisory control [2, 3] teleoperations, human brain is used to guide the robot to carry on the specific task, while robot executes the task by considering a set of rules defined at the robot side for collision avoidance, trajectory speed etc. The manual control of robots in teleoperations as shown in Fig. 1.1 consists of simple button interfaces, joysticks, software GUI interfaces, exoskeleton types and even touch screen based interfaces. Thus, a telerobotic interface can be as simple as a common MMK (monitor-mouse-keyboard) interface. While this method is not immersive, replacing MMK with a joystick can provide a more intuitive navigation scheme for planar robot control. These
methods are mostly used in generic Internet-based [4] or network based [5] telerobotic systems where the remote environment cannot be exactly guessed by the operator. These robots may have haptic feedback, however these systems do not provide any sense of presence as there is no realistic relationship of the operator action and the feedback received.

1.3 Body Consciousness

Consciousness is the quality or state of being aware of an external object or something within oneself [6, 7]. Self is a subject of conscious experiences and every human being can feel these experiences and they are attributed to themselves. Memories play an important role in the ownership and building cognitive links to those thoughts so that humans will remember their ownership by previous experiences. Self-consciousness is cognitive bond between self attributed thoughts and experiences [8]. 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 that they see, feel the touch, is their own body. In this “Psychological Experience” we try to build this self-consciousness artificially in teleoperations, which can be referred to as “Conscious Experience”. By default, conscious experiences are addressed only to oneself, but scientists have been able to create artificial consciousness as well as feel consciousness in body parts [9] that even does not exist.

1.3.1 Artificial Consciousness and Brains

The general belief is that the human brain works as a neural network of several independent processing units. However, most robots at present have software brains, meaning a computer with pre-programmed set of instructions running. These instructions might have limited number of tasks as they are initiated from pre-defined control algorithms and couldn’t change themselves. In other words unlike humans learning is not possible.

Researches have tried to duplicate the human brain neurons and synapses with silicon chips [10] and use artificial intelligence to interact with humans. As shown
1.3. Body Consciousness

in Fig. 1.2 left, in 2003 MIT Artificial Intelligence Lab has done a long-term artificial intelligence robot project called “COG” and his brother [11, 12] “Kismet”. These robots have a set of sensors and actuators that tries to approximate the sensory and motor dynamics of a human body. Kismet and Cog can see, hear and feel touch sensation. According to these inputs it think as a human using it’s artificial intelligence brain and acts accordingly. Kismet has a repertoire of responses driven by emotive and behavioral algorithms that allow it to be able to build upon these basic responses after it is switched on or “born”, learn all about the world and become intelligent.

As shown in Fig. 1.2 right, Project “Leonardo” [13] from MIT, Personal Robots Group is a small adorable robot, which has arms, head, hands and neck movements. Leonardo can recognize its visitors’ faces in real-time [14] that can be trained on the fly via a simple social interaction with the robot. These technologies allow to behaving consciously, but there is no technology to transport those feelings and perceptions of the robot back to a human.

1.3.2 Visual Mirror Self Recognition

It is a common fact that humans can recognize their self by seeing themselves in front of a mirror. This is scientifically called “Visual Mirror Self Recognition Task”. Research has proven that not only healthy humans but also even animals like chimpanzees [15] can recognize their self in a mirror. It is also proven
that in early childhood (below 15 months) humans do not recognize the self as
themselves when seen in front of a mirror. However, with age, not only humans
but also animals recognize self over time. This shows that the visual feedback
vs. kinesthetic sensation of one's own body is a strong evidence to understand
what is self.

1.3.3 Rubber Hand Illusion and Full body Illusion

Consciousness can be experienced with partial body parts as well. For exam-
ple when multi-sensory inputs acting on the body and if the same spatial unity
is kept with a high level of multi-sensory applied to a human [16], a neuro-
logical conditions such as Rubber Hand Illusion (RHI) [17] and Body Transfer
Illusion [18, 19] can be felt.

In Rubber Hand Illusion experiment as shown in Fig. 1.3 the subject was shown
a fake “Rubber Hand” in front of him while hiding his hand from his vision. A
touch cue is applied at the same position of the skin of the subject’s real hand
and the fake rubber hand at the same time. After several minutes of stroking
they perceive that the fake hand that they see as their own hand. It has been
proven by when they have shown a sharp object like knife near the fake hand;
they get afraid and shocked and soon remove their real hand thinking that the knife is dangerous. This simple experiment shows that if the same sensory inputs are duplicated (in case of this example, it is visual and touch) it can easily trick the brain to think that the fake hand belongs to your body.

This perception is not only limited to hand, Petkova et.al created an experimental tool [20] using physical mock ups to test full body illusion and study about how the brain represents these changes. With first time attendee subjects it has been proved that this mechanisms can provide a feeling of an entire body as belonging to oneself. This study, address the perceptual and neural underpinnings of full-body ownership and found that the sensation of owning a body seems to be coded by multisensory neurons in the ventral premotor cortex, the intraparietal area and the putamen.

These findings have been used by researchers and experiments about out-of-body experience were conducted with robotic tools. Watanabe et al. examined out of body sensations and interaction with oneself [21]. The above study, authors have examined whether the localization and attribution of the body sensation accrue in an environment with a robot. As a result, they found the localization and attribution of the body occur regardless of the kind of actor that provides the stimulus. Next, they verified this phenomenon in a probing situation and looked for the kind of elements that influence the out-of-body sensation. In this experiment active tactile stimulation by a robot hand was used rather than a passive stimulation by a third person and the subject was allowed to touch his own back with the help of the robotic hand. Consequently, they found that the activity of the person might dominate the localization and attribution of the body.

1.4 Body Schema

Within the context of artificial bodies, study about body consciousness is very complex because consciousness experience is not just only the sensory feedback systems, but has a lot to do with the language, thinking patterns, previous memories, and cognitive link with the brain. For example, when human touches a
cold ice tea cup in hot summer and cold winter the feeling that they get might be
different. This is because the body gets more information from the environment
such as ambient temperature; humidity, etc. In addition, at certain situations
night and day differences might change the way humans perceive senses. Therefore, using a robot to study and model body consciousness in full scale is difficult
with current technologies. Thus, the visual-kinesthetic correlation in the brain
and how this correlation helps a human to understand the position of different
body parts are considered.

The “body schema” allow us to keep an up-to-date representation of the positions
of the different body parts in space. This can be further divided in to “postural
schema” [22, 23], the awareness we have of our bodies’ position in space, and
“surface schema”, our capacity to locate stimuli on the surface of the skin. These
two functional elements used by humans to understand and perform actions with
the awareness of a body’s position at any given moment. Thus, body schema
can be categorized as a subset of body consciousness.

1.4.1 Extended Body Schema and Tool Use

Figure 1.4: Usage of Hammer, Tennis Player, and Baseball Player

Humans naturally extend their body schema to tools that they use. Using tools
several hours per day changes the way you think about the connection between
the body and the tool. As shown in Fig. 1.4, a first use of a hammer, it is
hard to target properly the nail and you might have to try it several times.
However, after few hours of use, humans can naturally use the hammer tool
without thinking about targeting the correct position of the nail, how much
force needed etc. Since the targeting happens inside the brain without relying
on the visual cues, these can be sometimes performed with eyes closed. For example, it is obvious that humans can write characters with a pen with eyes open, but after some practice it is possible to with eyes closed. Same with sports, Tennis players, Baseball players can guess where the ball is coming and they use the body kinesthesia and the Racquets / bat to hit the ball. This shows that the eye to hand coordination scheme on our brain needs to be practiced at first. Once the coordination is practised, it stays in the memory so that consequent trials will no longer need any intensive practise.

1.4.2 Phantom Limb Sensation

Body schema extension has been studied on neuroscience and cognitive science research fields. In this field, a common phenomenon called “Phantom Limb Sensation” defines that an amputated or missing limb patient with an artificial limb moving appropriately with other body parts can still feel having a body part without actually having that body part attached to their body [9]. Even though the patient cannot control the attached body part, with proprioception sensation they can be tricked that the artificial limb is attached to their body.

In a more active approach, there exist myoelectric controlled multifunction robotic arms [24, 25] for amputated or missing limb patients where it can be driven by the brain signals and controllable through their thoughts. In recent scientific discoveries doctors have implanted a robotic lower arm to a woman with a left arm amputation at the humeral neck. With muscle reinnervation for real-time myoelectric control of multifunction artificial arm, she can move the artificial limb and fingers through the brain signals through her thoughts. After a successful implantation and adequate usage the patient described the control as intuitive and the thoughts to action responsiveness was appropriate [26]. Furthermore, even though the patient does not feel anything through the motorized prosthetic limb, she can have pseudo haptic sensations of her fingertips and it can help to regain sensory feedback.
1.4.3 Extended Body Schema in Teleoperation

“Body Schema” in teleoperation can be explained as the awareness of body’s position and posture at any given moment. It is known [27] that there cannot exist a position awareness experience if there are no voluntary movements. This can involve coherent relationship between multiple sensation(s) and how the brain represents those relationships. For example, a typical user will be able to close his eyes and touch his nose. This is because he is aware of his body schema and it helps very much when humans do tasks using arms and hands. Similarly, if a 5cm solid block is put in front of the table and ask a user to grab it with eyes closed, in most cases they can grab with no vision. How a non-expert user will perform these task is that, they imagine the block is in certain position in space, then move the limb with kinesthetic sensation as close as to the guessed location and thereafter use haptics to understand the correct posture of the hand to grab. Once the correct posture is finalized, user can grab it with confidence. Thus in most cases visual-kinesthetic sensation relationship is important to do tasks was explained above.

![Figure 1.5: Extending Body Schema](image)

This correct coordination is important when doing complex tasks not because humans will not use vision, but they can perform multiple limb movements without thinking and looking at everything at once. In teleoperation, this multi sensory coordination and body schema can help operators to perform tasks much more easily with confidence. When the remote robot and the operator is linked with
vision and haptic sensation, in a deeper connection this sensation is attributed to their voluntary movements (kinesthesis). Thus he should experience that arm / hand is his own. However, based on the task, the sensory needed to build the awareness of a body’s posture can vary. As explained in the previous section, for people who don’t have legs but they will experience body schema only on the upper body. Similarly, if there is a body part that is not used in teleoperation it is not necessary to build body schema on that part. Based on this method, we can classify how complex body schema is needed for a given teleoperation.

As shown in Fig. 1.5, the user is supposed to see his hands and arms at the same place that he would expect them to be. In this example, haptic sensation or remote touch is not considered. If vision processing was integrated and perform kinesthetic or trajectory analysis, it is possible to build relationships to understand that robot kinesthesia and vision is coordinated. This sensation can be called artificial body schema, but cannot be transferred to the operator so that one could think as it was done by him. Thus, in this process each sensation is transferred back to the user and let him process the sensory in his brain and let the user feel the remote sensation locally. In case of this example, robot vision is transferred to the user and user kinesthesia is transferred to the robot. So when he moves his limbs he sees robot limbs are moving. After some time he will realize that the remote robot moves exactly the same way as he does, then soon realize that it is an extension of his own body schema. In order to achieve this, there cannot be any significant delays between the user and robot sensations. Posture, position of arms / hands should be mapped perfectly. This overall connection hereafter I define as “Body Schema Transfer Path”

Extension of one’s own body is widely studied in virtual environments. In this paper [28] a virtual long arm is used to touch virtual objects placed far from one’s peripersonal space. After few minutes of virtual object manipulation, they were shown a virtual saw rotating and touching the virtual arm. At the end they were asked if they felt that “it might harmed if the saw touched the virtual arm” and there were positive results. This illusion is called “A very long arm illusion”. Considering all above body schema transfer related research, it shows that it is easy to confuse the brain when it comes to virtual environments. However if
these technologies have to be used in real world application, it is necessary to make available these technologies in real world. There have been several studies with robots on remote places and they have shown promising results.

Using robotic hand, Oztop et al. [29] propose a framework for skills transfer to robots, exploiting the plasticity of the human brain in representing its body parts in the body schema. In the first stage they incorporate the target robotic platform into the subject’s neural representation of their own body. As results they show how dexterous skill transfer can be achieved on a 16-DOF robotic hand, justifying the effectiveness of the proposed method and confirming the flexibility of the human brain in representing the body schema.

Similarly, non-invasive surgery system from Geneva University named “DaVinci Si surgical system” [30] is capable of performing medical surgery remotely. The robotic arms of DaVinci Si surgical system couples with remote surgeons hands with fine grain finger movements [31] while seeing and feeling the patient as they were physically there.

1.5 Telepresence and Telexistence

![Figure 1.6: Classification of Teleoperation Subsets](image-url)
Telepresence and Telexistence are two closely related concepts exist to have a real-time sensation being at another place [32]. In the word definition “Presence” represents specific localization information for something, whereas “Existence” does not represent specific localization information. For example, it is common to say God existed, but my grandparent’s presence was felt. Thus, even though the sensation can be “being in another place”, it can be distinguished by the user’s localization experience.

In a more specific classification, as shown in Fig. 1.6 when we combine consciousness, body schema with teleoperations there can be more detailed disciplinary such as Telepresence and Telexistence. Up to date Telepresence focuses on bringing new technologies and how to connect users and remote robots with minimum latency, scaled robots, control techniques, and some psychological experience component that delivers the sensation like remote presence. On the other side, Telexistence has a balance between this psychological experience and technological component and how to match the body perception such as to understand the size of the remote objects, distance to object, when touching objects to feel same haptic sensation, same thermal sensation etc. Furthermore, it is about how to reproduce the same sensation of being in another place by all means.

1.5.1 Telepresence Systems

Video conferencing technologies such as Skype, Net meeting, and FaceTime are few free teleconferencing technologies available whereas commercial services Polycom [33], CISCO [34] allows the user to see and hear the remote side. Some of these systems provide to control the remote side camera with a remote control. In addition, telepresence robots Kubi [35], QB robot [36], Double [37] and
1.5. Telepresence and Telexistence

Rovio [38] are becoming popular recently due to their mobile capabilities apart from the basic teleconferencing features.

At research, Telecommunicator [39] and Mebot [40] are two robots with hands, that were designed to have an emphasis on being able to convey even non-verbal communication of social environments. In addition to basic audiovisual communication, these systems are able to express body postures, a wide range of head movement and hand gestures. Similarly TRIC [41], Telepresence Robot for interpersonal communication, Telerobot [42] was developed for the purpose of interpersonal communication with the elderly in a home environment. TEROOS [43] uses a human as its remote mobile platform where sitting on a persons shoulder and similar to walking side-by-side with a friend. Above telepresence systems uses button, joystick or touch screen based interfaces to control the remote robots head movements and mobile platform. Thus, the user who controls the robot does not get any awareness of a body’s position, moreover he is aware of his body is being locally while watching a remote feed though a display.

1.5.2 Telexistence Systems

Telexistence is a concept that refers to the technology that 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 [32, 44]. In contrast to Telepresence robots, just using CAVE system [45] as the remote viewer in teleoperation, user can experience high quality visual experience. However, due to lack of multiple sensations it does not provide any extended body schema experience. In contrast, “Dextre” [46], Robonaut [47, 48] and DLR Rollin’ Justin [49, 50] teleoperation systems can give visual and haptic sensation. Still the lack of spatial and temporal mapping keeps these systems from not allowing to have an extended body schema experience. Toshima et al. proposed a acoustic telexistence head [51] where a user can experience the remote acoustic sensation with voluntary head movements, Furthermore, users are able to understand the remote position of where the sound is generated by guessing from their ears. Thus, it creates a kinesthetic acoustic experience where users can have an extended body schema experience without video.
1.5. Telepresence and Telexistence

Similarly, not only acoustics and visual sensation, as shown in Fig. 1.8 with the development of TELESAR master-slave robot system [52–57] a combination of vision, auditory and kinesthetic sensation was achieved by Tachi et al. where no fingertip haptic feedback or touch sensation was present. The authors also achieved to match the differences of dynamics of robot and human body by using a force feedback mechanism [58] for arms. In 2007, Watanabe K. et al. developed “TORSO” [59] with human-like neck movements to visually interact and explore 3-dimensional details in a remote object in a more natural and comfortable manner. These systems allow a user to perceive kinesthetic and remote visual sensations with very low latency. Furthermore, telexistence systems provide extended body schema through visual and kinesthetic sensations for reaching, grasping and tool use by hand. However, there is no telexistence system which can give extended body schema experience when grasping and object manipulation by hand or to provide fingertip haptic and touch sensations.
1.6 Thesis Overview

To build artificial sense of presence, there needs to be a technological and a psychological experience component. The technological component can be of 3D vision, binaural audio, sensory transmission system, control methods or even the dynamics of the slave robot. Psychological experience that is referred to as “Body Schema” is a connection between multiple sensation(s) and coherent relationship with spatial and temporal perception in the brain. These sensations can be auditory, visual, haptic or kinesthetic where smell and taste technologies are still in early stage for remote reproduction. Teleoperation systems such as Telepresence and Telexistence robots allow having some body schema transfer experience during manipulation. However, body schema in teleoperation is not clearly defined.

First, I would like to define body schema in context to teleoperations because we do not need to consider full body schema for teleoperations. For example, if only viewing, it’s not necessary to have arms. what latency? Does the operator need spinal movements? etc. Secondly, decided the sensations, how to model the sensation correlations to achieve desired perception is not known. Since there can be multiple relations between each sensations, it is hard to understand how to model coherent relationship between multiple sensation. Thus, in this thesis with a base model, body schema is studied and extended for general use. The model will be called “Body Schema Transfer Model” hereafter.

Secondly, as a proof of concept, a body schema transfer system should be designed using the above model. When the dexterity becomes high, the amount of presence or fidelity of doing remote tasks increases. However, it is unknown that how the task efficiency is affected by the dexterity of the remote robot. Thus, the body transfer system design should be implemented as a multi-DOF robot and find out the most important DOF’s needed for body schema transfer based on the task.

Finally the system specifications, limitation should be found out by conducting a technical evaluation. With these limitation and specification compared to ordinary teleoperation systems, how effective this system with transferring
body schema should be evaluated objectively and subjectively. Furthermore, any advantages of transferring body schema in a teleoperation, any performance increment should be studied. Next, the quality of body schema that humans feel through day-today direct manipulations can be higher than the experience getting from telexistence manipulations. How much quality can be obtained through telexistence systems should be measured, and what causes the quality to increase should be found for further improvements of the system.

This thesis is divided into 6 Chapters.

- Chapter 1 has presented a set of problems that have motivated my research and basic overview, related research and approach to body schema transferring systems.

- Chapter 2 explains the “Body Schema Transfer Model”, how it can be used to model various body schema transfer systems, and example of real usage using “TELESAR V” telexistence robot system.

- Chapter 3 provides the detailed description of body schema transfer system implementation and the outcome through usage examples.

- Chapter 4 describes the technical evaluation showing the limitations, specifications and possible improvements of the system.

- Chapter 5 describes how the body schema experience is evaluated through subjective and objective evaluation methods. Furthermore, the capabilities of the system, results, demonstrations, press media and the publications supporting the thesis are described in the Appendix section.

- Chapter 6 concludes the thesis by discussing the significant contribution, limitations, future direction, and social benefits, and future plans for improvements.
Chapter 2

Body Schema Transfer System Design

2.1 What is Ideal Body Schema

The “body schema” allow humans to keep an up-to-date representation of the positions of the different body parts in space. This can be further divided into “Postural Schema” [22, 23], the awareness of the bodies’ position in space and “Surface Schema”, the capacity to locate stimuli on the surface of the skin. These two functional elements are used by humans to understand and perform actions with the awareness of a body’s position at any given moment.

According to the related research discussed in Chapter 1, to build artificial body schema and transfer back to a remote entity, it is necessary to understand the type of work that the operator will perform, what body parts will be involved, and what sensations are involved in the manipulation.

2.1.1 Effect of Extended Human Body Schema

As explained in the Chapter 1, there are some teleoperation research that uses body schema in teleoperation. However these artificial body schema is limited to only head or arm. There has been no research focusing on the full upper body schema transfer in teleoperations. Being able to transfer the full upper body schema, operator will understand that the body parts that he see and feel as his own. If this awareness is kept continuously throughout the teleoperation, user will no need any rehearsal to perform tasks remotely. Users’ lifelong experience on doing things (playing games, handling tools etc.) can be continued. In addition, it is possible to use 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 as thoughts it is possible to react for un-expected dynamic behaviors where human thinking is necessary. With these advantages the task effectiveness of teleoperations could be increased.

In a more social impact manner it is possible to replace human presence where human body is dangerous or non reachable such as hazardous places, deep sea, earth core, space explorations etc. Also it can replace human presence where time delays are unacceptable such as Telesurgery or future transportation.

2.2 Defining Body Schema in Teleoperation

To understand the advantage of full upper body “Body Schema” transfer in teleoperation and how to transfer it, a typical example of teleoperation manipulation scenario is considered. To feel the body schema experience the operator should be able to

- Watch the remote operation from his eyes where he can use his head, neck, spinal movements independently to explore 3D space as as he would naturally do and to understand the position, size of the object and distance information.

- Should be able to reach the object location through his arms while seeing the robot hand and forearm at space where he would perceive his real hand through kinesthetic sensation.

- Should be able grasp the object with his fingers while seeing the robot fingers and palm at space where he would perceive his real fingers through kinesthetic sensation.

- Should be able to touch remote objects and perceive the same haptic sensation as he would experience naturally.

According to the definition of body schema in teleoperation example above any manipulation task can be sub categorized based on steps taken to perform the manipulation. They can be written as understanding the remote environment, understanding the properties of the remote objects and decide the manipulation
task to be performed with reaching, grasping, and stroking motion and haptic confirmation for confirming the remote touch. For example, operator sees an object placed on the table. He first has to understand the placement of the object, size, how to grasp, reaching method by thinking. Next, using his arms to reach towards the remote object and to grasp the object with fingers. Finally he confirms the grasping quality with the haptic sensation provided. Depends on the situation and the complexity of the task there can be more steps of even fewer steps.

In this thesis I would deeply study about the importance of multi DOF robots for body schema transfer, requirements and how to model these systems based on inspection, reach and grasp steps only. It is obvious that the feedback part is important to confirm the action and therefore the system I built to proof the outcome of this thesis does have haptic feedback. However, the quality of the haptic feedback system was not enough to prove the thesis outcome for haptic sensation and therefore haptic transmission system is not described in context with this thesis. Furthermore, haptic sensors and actuators were built by another team whom I work together and my contribution was the haptic data delivery framework so that any haptic sensors and actuators can be integrated easily.

2.3 Body Schema Transfer Model for Teleoperation

The body schema transfer example explained above with context to the thesis boundaries, can be itemized based on the actions performed by the operator.

- **Inspection** - visual-kinesthetic cross modality on head and body.
- **Reaching** - visual-kinesthetic cross modality on body and arm.
- **Grasping** - visual-kinesthetic cross modality on hand and finger.

According to the above example only head, body (spine), arms, hands and fingers are considered. As for the sensation, visual and kinesthetic sensations and their cross modalities are considered. As shown in Fig. 2.1 these relationships can be represented in a matrix view where the total sensations can be listed in two axis.
of sensation 1 and sensation 2. Since a matrix can have cross modality duplicates, only one half of the matrix is considered as the valid cross modal perceptions. These relationships can be more complex when building higher level coherent relationships with many sensation and many body parts. However, it can be easily found with a simple calculations when required sensations are N, there can exist N(N-1)/2 correlations (cross modalities) to be satisfied in order to feel the transferring of body schema experience. For example in the case of above example, N = 2, thus there is only one cross modality as shown in Fig. 2.1, i.e visual - kinesthetic cross modality perception has to be satisfied in order to feel the transferring of body schema experience.

Decided the required cross modal perceptions and what body parts are used in the manipulation, it is necessary to understand how to modal the cross modal perceptions with available sensations. In order to understand that it can further divide the perceptions based on space and time domains. i.e these perceptions can be mapped in spatial and temporal correlations. For example if the operator does not plan to move the head, it is not necessary to consider about the delays involve in head motion such as tilt, roll and pan. Fig. 2.2 matrix shows the visual-kinesthetic sensation divided based on spatial and temporal correlations. Similarly, if N number of cross modalities present, each cross modality can be further divide into spatial and temporal correlations. It has to be noted that most cases the spatial mapping is necessary where as temporal mapping can be ignored if the body part is not moving over time. In that case the temporal
correlations associated with the perception can be ignored.

The above model can be applied to the typical example in teleoperation described above. First, the operator perceives the size, distance, position of the object and how to reach and grasp the object by thoughts. Next, using the arm he reaches the location where he perceived earlier while experiencing the robot hand as his own hand due to the visual-kinesthetic coherent correlation. Finally, fingers were used to grasp the object while experiencing the robot fingers as his own hand due to the visual-kinesthetic coherent correlation. Previously perceived shape, distance and position information is useful on deciding the grasp type, how fingers should be moved etc.

This can be summarized based on the thoughts of the operator as below.

- I feel it is my head and body because (inspection)
  1. I see the object in space. I feel it’s size, position and understands how to reach, and grasp. I can look details when I move my body and head.
  2. I feel the visuals are updating based on my movements over time.

- I perceive it is my arm because (Reaching)
  1. I feel my arms and hands in space where i feel it would be at a given time.
2.3. Body Schema Transfer Model for Teleoperation

2. I feel my arms and hands are moving and feel it is moving according to my own arms and hands all the time.

- I perceive it is my hand and finger because (Grasping)
  1. I feel my fingers are attached to my hands.
  2. I feel my fingers are moving and feel it is moving according to my own fingers all the time.

As explained in the above summary, visual-kinesthetic sensation mapping for the full upper body can be achieved if the operator feels the above during inspection, reaching and grasping movements. However still it is unknown how to model these artificially in a real telexistence system.

2.3.1 Visual and Kinesthetic Sensation Mapping

As shown in Fig. 2.2 condition 1, to build spatial mapping between visual and kinesthetic sensation, slave robots stereo vision feedback has to transfer to the user. This can be done with ordinary cameras and HMD displays. However the vision system should be able to provide a sensation so that the user should be able to understand the distance and relative position to objects in the remote side. When the head is moving, to provide the temporal visual-kinesthetic sensation for building head awareness, the user’s posture has to be captured and build on the robot side. However, by rebuilding the posture, it is not sufficient to have the correct eye-hand coordination at any given time. Therefore, and at any given time the vector from eye-to-hand has to be exact same. Furthermore, video feedback has to be very low latency where the user cannot feel a difference compared to one’s own vision. Secondly, the robot trajectory and the mechanical dynamics has to have a very high update rate which can produce a trajectory that always follows the user motion without any delays. With these conditions satisfied, the user should feel his head, arms and hands are replicated in the robots body that he sees without any lag or position error compared to the perceived kinesthesia.
2.4 Requirements for a Body Schema Transfer System

To verify the model described in the above sections, a telexistence master-slave system was designed. Fig. 2.3 shows the design requirements for modelling inspection, reaching, and grasping systems. In addition, auditory sensation is important for communicating with remote participants. Therefore basic binaural auditory capabilities were added to this system. However, in this context of this research, auditory sensation is not considered as an input sensation to the body schema transfer model.

The design requirements can be breakdown as below.

1. Inspection - visual-kinesthetic coherent correlation on head and body
   - Ungrounded master cockpit
   - Vision transmission system
   - Robot dynamics

2. Reaching - visual-kinesthetic coherent correlation on arms
   - Real-time master arm posture tracking system
   - High dexterity anthropomorphic robot arm
3. Grasping - visual-kinesthetic coherent correlation on hands and fingers
   - Real-time master hand posture tracking system
   - High dexterity anthropomorphic robot hand

2.5 Inspection

2.5.1 Ungrounded Master Cockpit

Conventional telepresence system sometimes uses exoskeleton based master cockpits [54] to capture the movements of the operator. Due to the mechanical constraints of these systems the operator cannot perform remote tasks as desired. Furthermore, it does not provide the same kinesthetic sensation as the operator would feel naturally. In order to satisfy the conditions for inspection and to feel the visual-kinesthetic sensation, a non-mechanically constrained measurement system is necessary. This gives the user with full flexibility to move head, body and arms naturally as desired without feeling constrained.

2.5.2 Visual Information Transmission System

Visual sensation can be provided by installing wide-angle full HD cameras on slave robot and a wide angle HD Head mounted display (HMD) as the user vision. The camera’s position and orientation can be controlled according to the user’s head. This only works if the user feels comfortable with the latency of the system, lag in the response to movements, and the correct visual representation of the remote space. Any issues such as inadequate resolution, latency of the video image, lag in the mechanical and computer processing of the movement and response, optical distortion due to camera lens and head mounted display lenses, can cause the user a “Simulator Sickness” which is expected by the lack of vestibular stimulation during visual representation of motion. It can be very frustrating if the control motion involves multiple parts of the body such as arms, hands, etc. User will experience a frustrating and confusing sensation when he discovers that his kinesthesia does not match the visual feedback from the remote side. To overcome this issue, the user’s eye coordination and robot’s eye coordination should be synchronized without any noticeable lag.
2.5.3 Binaural Auditory Experience

Installing microphones as robot’s ears and speaker as robot’s mouth and similar configuration on the operator’s HMD will provide bi-directional verbal communication capabilities. To perform binaural and bi-directional verbal communication it is necessary to have a synchronisation between the seen video and heard audio. Thus, there should be minimum lag, or the video lag should be matched to sync with the audio lag. Furthermore, as humans can recognise the sound generated position naturally, telexistence experience should provide realistic audio sensation that can estimate the distance via heard binaural sound. Auditory sensation has been considered in the design since it is helpful to build the body schema in teloperations. However this audio-kinesthetic sensation is not evaluated or taken into consideration when designing the body schema model.

2.5.4 Robot Dynamics

A multi DOF robot alone is not sufficient to provide the realistic visual-kinesthetic experience. A mismatch between the user’s motions such as registration errors, lag in movement response due to over-filtering, inadequate resolution for small movements, and slow speed motion can contribute to an invalid visual-kinesthetic experience. Thus, there are several key factors to consider when deciding what type of robot dynamics necessary to experience a body schema transfer sensation.

In terms of joint mechanism belt coupled \[54\] robots such as TELESAR I, II can deliver higher resolution motion. However, the motion acceleration is fixed or limited. Conversely, Pneumatic driven joints \[59\] can have dynamic accelerations, but the position accuracy resolution is very low. In order to mimic the user’s dynamic motion robot joints has to provide dynamic acceleration and a good accuracy. Thus in this design coreless DC geared motors directly coupled with joints were used. To mimic the user’s whole body posture it is necessary to consider the body parts that can be seen in the teleoperation and the parts that can’t. For example, operator will only see his forearm, hands, fingers during manipulations whereas he will have less or no chance to see his upper arm, shoulders, and legs. Thus, while providing the accuracy and dynamic acceleration on the body parts that can be directly seen, any compensated motion can
happen in the body parts that could not be seen by the operator.

Not only the joint type, the control logic is important to provide the simultaneous dynamic acceleration. Most industrial robots uses individual PID controllers per each joint. These PID’s are mostly implemented in a microcontroller built inside the joint and hard to dynamically change the parameters. Thus, a high speed serial PID controller chain were used where the PID is implemented in a PC and the parameters can be changed dynamically. Next, the Kinematic solver has to be fast, yet accurate to mimic the same posture of the user. In robotics, general teleoperations \cite{47, 48} uses pre-defined trajectory \cite{49, 50} driven motion paths. These are accurate, but they need to generate the trajectory offline and confirm before robot and it is slow. In order to avoid this delay, a numerical based kinematics solving method was used and analytical filtering was used for selecting the valid solutions matching the correct user posture. This operation has to be done very fast, and accurately to produce the accurate operator’s posture to provide the realistic kinesthetic experience. Furthermore, flexible joint movements were considered because interacting with humans, it is necessary to have human like flexible joints rather than rigid joints with very high standing torques.

2.6 Reaching

To comfortably reach an object, user should be able to freely and independently move his head, upper body, and arms. In contrast, slave robot should follow similar movements with no delays while maintaining 6 DOF arm endpoint accuracy.

2.6.1 Multi DOF Anthropomorphic Robot Body, Arm

When the user frees from mechanical constrains he can move his body as desired. In order to synchronize to any posture of the user, a fast moving, multi DOF robot is necessary. To reproduce the same posture as human a structure similar to human such as anthropomorphic robot is necessary. Conventional dexterous robots \cite{60} are not capable of achieving this due to not having enough dexterity in the torso part. However, when the operator requires to perform spinal and
locomotive motion with these robots [54, 61] he uses the robot’s mobile platform to move towards, away and sides using a joystick or keyboard. This will create a temporary conflict on the operator’s thoughts by not allowing his natural motion to perform the spinal movement and therefore the awareness will be dislocated. Therefore, to keep the awareness of the body that the operator has, the body schema transfer system should provide the seamless motion flexibility throughout the upper body. Finally, when manipulating tools made for humans it is necessary to have human sized arms and hands. Also having human structured arms and hands will allow the operator to have thoughts similar to one’s own hand size in remote manipulations. Thus a life sized robot is required.

2.7 Grasping

2.7.1 Capturing Hand Postures

Grasping is one of the most important feature in remote manipulation after reaching a remote target accurately. If the operator is not possible to grasp objects with normal grasping techniques he will frustrate and try to use various techniques based on trial-and-error methods until the correct grasping technique is found. Therefore, it is necessary to capture the operator finger posture and reproduce on the robot fingers. Therefore, an ungrounded master is necessary where it can capture finger movements without any mechanical constrains. However, when using unconstrained capture techniques such as data gloves, it is important to normalize the fingertip position errors caused by different finger lengths, and finger manipulation patterns.

2.7.2 Multi DOF Anthropomorphic Robot Hand

To touch or grasp objects and mimic human hand finger movements, a higher DOF anthropomorphic robot hand similar to human hand is necessary. In grasping thumb, index finger and abduction is mostly used because they have the highest dexterity in human hand. 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. However, it is obvious that the human hand dexterity is very high compared to existing robotic hands [62–64]. Therefore, it is essential
to have a mapping algorithm so that a multi DOF robotic hand and ordinary
human hands’ can work together with different shapes and finger lengths. Fur-
thermore, if the speed of the robot fingers can be matched with operator fingers,
it is possible to feel the robot finger motion as your own finger motion while
watching through the HMD.

2.8 Design Summary

In general teleoperations user’s upper body, arms, hands and fingers will be
involved. Since the user does not see his body, upper arms or head it is not
important how these parts move. To produce a extended body schema experience
for a typical teleoperation example which uses inspection, reaching and grasping
steps, a system that provides visual-kinesthetic coherent sensation is necessary.
In order to satisfy the above needs, a telexistence master-slave system with
a ungrounded master cockpit, a higher dexterity anthropomorphic slave robot
for providing realistic kinesthetic sensation; a high definition 3D stereoscopic
vision feedback and a wide angle HD stereo head mounted display to provides
visual and auditory sensation was built. With the above hardware design, body
schema transfer experience can be achieved by modeling the visual-kinesthetic
cross modality perception.
Chapter 3

System Construction

In the previous Chapter, important design requirements and considerations for implementing a Body Schema Transfer Telexistence system was discussed. In this Chapter, implementation details of that master-slave Telexistence system were discussed and the system therefore called as “TELESAR V”. There are few design considerations which was decided while in the implementation phase as to further increase the performance and therefore it can be seen in this Chapter.

3.1 System Overview

![TELESAR V: System Overview Diagram](image)

As shown in Fig. 3.1, TELESAR V system consists of a Master (Local) and Slave (Remote) system. A 53 DOF dexterous robot is developed with 6 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 robot’s 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 robot’s mouth area for conventional verbal bi-directional communication.

In Master side, operator movements are captured using a motion capturing system (OptiTrack) in coordinate space and the joint space is calculated using inverse kinematics. Finger bending is captured with an accuracy of 14 DOF using an optical bend sensor based Data Glove. In the next sections each sub component is discussed in details.

Fig. 3.2 shows the typical scale of the robot and the operator. As it can be seen that the humanoid robot exactly represents a average human scale. In specific, TELESAR V is 1565mm high (when standing) and each arm is 720mm long from shoulder to middle finger tip. The TELESAR V system is not used in standing pose as it does not have legs to walk. The default posture of the TELESAR V system for remote manipulations can be seen on Fig. 3.2 which the operator has freendedome to move in to any posture as long as he is sit on the master chair.

The size and scale is quite important when building body schema. If the robot has a more wider arm compared to operator he might get confused sometimes. For example, if the operator sees a 100mm wide box and he tries to grab a small
ball from the box. He sees it as it is 100mm, and with correct body schema transfer method, he would think that it is possible to grab the ball inside that box. But when he reaches the goal, soon he realizes that his hand is bigger than the box and then he started to confuse. In order to overcome these issues, “TELESAR V” was designed with same scale factors as an ordinary human.

![Figure 3.3: System Overview](image)

As shown in Fig. 3.3(b), in a typical remote operation, TELESAR V, operator can see the remote environment as first-person-view and perform remote manipulation naturally (Fig. 3.3(b)). As shown in Fig. 3.3(c) the slave robot will perform the task in the remote environment while the operator will be provided a visual feedback from the robots eyes.

### 3.2 Measurement System

Table. 3.1 shows a comparison of what measurement technologies being used, and compared with the most advanced telexistence and teleoperation robots in the world. As can be seen on Table. 3.1 most master cockpits, operator motion is captured using exoskeleton mechanisms. As explained in the previous
3.2. Measurement System

Chapter, with an exoskeleton driven mechanism it is possible to provide accurate measurements, provide force feedback and match the impedance of robots limbs to operators limbs. Note that * indicates Joystick controlled DOF’s.

Table 3.1: Comparison of Measurement Systems and Slave System Dexterity

<table>
<thead>
<tr>
<th>System</th>
<th>Measurement System</th>
<th>Robot System (DOF)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Body</td>
<td>Hands</td>
</tr>
<tr>
<td>TELESAR I</td>
<td>Exoskeleton</td>
<td>Exoskeleton</td>
</tr>
<tr>
<td>TELESAR II</td>
<td>Exoskeleton</td>
<td>Exoskeleton</td>
</tr>
<tr>
<td>TELESAR III</td>
<td>Exoskeleton</td>
<td>-</td>
</tr>
<tr>
<td>TELESAR IV</td>
<td>Opti Track</td>
<td>Opti Glove</td>
</tr>
<tr>
<td>ROBONAUT R2</td>
<td>RC-SW</td>
<td>Glove</td>
</tr>
<tr>
<td>Rollin’ Justin</td>
<td>Exoskeleton</td>
<td>Opti Glove</td>
</tr>
<tr>
<td>SAR 400</td>
<td>Exoskeleton</td>
<td>Exoskeleton</td>
</tr>
</tbody>
</table>

In teleoperations, it is important to match the mechanical impedance of the robot to the operator when robot dynamics does not match the human dynamics. However most exoskeletons have a break-in-torque so that when the operator moves the robot it creates a constraint. Exoskeleton systems also reduces human dexterity and limits the operator movements to the exoskeleton mechanical dexterity. For example, if the operator was asked to reach a target using eyes open and eyes closed, with eyes open he will be able to reach and with eyes closed it will sometimes have a displacement. One reason for this is due to the kinesthetic displacement. But most cases due to the exoskeleton limited dexterity, it will guide the operators body to the target. When eyes open, operator sees visual cue and he will eventually try to correct it over time and final target will be reached. To avoid these constrains, TELESAR V uses an open air tracking system with no mechanical constrains.

3.2.1 Opti Track Motion Capture System

In “TELESAR V”, master side, operator movements are captured using a motion capturing system (OptiTrack) and are sent as multicast data via a LAN network to other PC’s. As shown in Fig. 3.4, TELESAR V system uses a rectangular
3.2. Measurement System

shape master cockpit with dimensions of 2m (W) × 1.5m (D) × 2m (H) and the entire volume is tracked using 14 individual cameras. User body, head and arm motion is tracked at 5 points. The tracking points were defined using 5 rigid bodies containing 3 markers per each solid mass. Since they are very light weight (50g) and not mechanically constrained, operator does not feel wearing anything special or his motion is constrained. The head rigid body marker is built on to the HMD, Wrist rigid body markers are already attached to Data Gloves and a special Jacket is used for placing the shoulder markers. At the beginning of a teleoperation, operator first wears the special jacket containing the trackers, then wear Gloves and finally put the HMD and follow the onscreen instructions.

As shown in Fig. 3.4 the 14 Cameras are indicated with 1-14 numbers surrounded by black circles. In optical tracking systems, if the thruss volume is C where the cameras are installed, the tracking volume without any errors is limited to 1/9Cth of C. In reverse, if the operators whole upper body (2m (W) × 2.0m (D) × 2.5m (H) with open arms pose) has to be tracked, approximately 9 × 2.0m (W) × 2.0m (D) × 2.5m (H) thruss is necessary. This will generally create the master cockpit very large, instead in TELESAR V master cockpit design, only necessary movements were considered in a typical seated configuration and arranged the cameras to create the best cross volume. The result was the camera configuration shown in Fig. 3.4.

Opti Track Calibration

In order to get accurate data the camera positions and angles should be static over time. However is not the case and they move over time, thus recalibrating the tracking system and calculating new positions and orientations for the cameras was necessary.

Fig. 3.5 shows the Natural Point Tracking Tools Software’s typical view from all 14 cameras during calibration. During calibration step, a user was asked to sit on the cockpit and check if all cameras are creating a cross volume pairs and covers all possible moves during operation. As can be seen from Fig. 3.5 each camera is paired with a counter camera to create the cross volume efficiently.

Once the camera placement is fixed, it is necessary to remove all lighting sources
3.2. Measurement System

Figure 3.4: Master Cockpit Camera Placement Diagram

Figure 3.5: Calibration Window in Natural Point Tracking Tools Software
3.2. Measurement System

to reduce the external reflections and disturbances. With all lighting sources removed, a 3 point wanding (camera calibration technique used in Natural Point Tracking Tools Software) was performed over about a period of 3 minutes to re-calculate the position and orientation information. Table 3.2 below shows the important custom parameters used in the wanding process.

Table 3.2: Natural Point Tracking Tools Software Configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Calibration</th>
<th>Tracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lens Type</td>
<td>3.5mm Wide</td>
<td>N/A</td>
</tr>
<tr>
<td>Wand Type</td>
<td>500mm Long</td>
<td>N/A</td>
</tr>
<tr>
<td>Calibration Quality</td>
<td>Very High (Slow)</td>
<td>N/A</td>
</tr>
<tr>
<td>FPS</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Exposure</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>LED</td>
<td>5</td>
<td>3-5</td>
</tr>
</tbody>
</table>

Finally, if still static disturbances created by own IR sources, reflective materials or even bright light sources are presented in the tracking volume it is necessary to remove or block them in the software using the block visible option.

After setting these parameters, wanding can be started and at least within 3 min it will be completed. During wanding, it is necessary to cover the entire cross volume that you are planning to use during teleoperations. Also it is important to wand in a way that most cameras can see the wand as wanding calibration calculates the camera position as well as orientation depending on how it is seen by other cameras. Once calibration has finished, if block visible is used, first it has to be removed and reapply with ambient lighting conditions. Furthermore, Exposure and threshold settings can be adjusted until a minimum disturbances tracking volume is generated. It is important to note, when block regions added to the volume, it will be a dead space, which will not be tracked. Thus having many blocked regions are not good for stable tracking.
3.2. Measurement System

3.2.2 5DT 14 Data Glove System

Capturing finger motion precisely is one of the most difficult issue in the data gathering step of TELESAR V. In the past researches have used exoskeleton type finger motion sensors, but when it becomes more and more degrees of freedom to match, the mechanical design becomes very complex and the system becomes very big. Thus specially it was not suitable for building the body schema and the limited dexterity provided by the exoskeleton will limit the operator to perform finger manipulation as he would expect to be. The solutions were to use optical tracking, resistive bending, fiber optic bending or colour marker based computer vision techniques. However vision based tracking methods such as “Leap Motion” was not really efficient and robust specially for robotic applications because the data provided by these methods are fluctuating and sometimes vanishing due to finger occlusion and real space object occlusion. Therefore such systems were avoided.

A hardware sensor based method might be the best option as the most robust tracking. There were only two types of hardware sensing technologies, namely resistive and fiber optic based bending. Resistive bending technologies used in “Cyber Glove Inc” products seems enough sensing capabilities on all fingers, but however they are very expensive, and also no after sales support. In our development environment, after sales support was very important as if the sensors were broken it should be able to fix by our own. Also resistive bending will have a hysteresis decays over time and effectively reduce the accuracy of the sensors. Therefore to use fiber optic bend sensors from “Fifth Dimension Technology (5DT)” was decided which also had after sales support, and have very low hysteresis effects on their sensors due to optical based bend sensing.

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. 3.6 shows common dexterity types associated with all fingers of human hand. As shown on Fig. 3.6(left) the bending towards is known as flexion and opening the fingers fully is known as extension. Also as shown in Fig. 3.6(right) all 5 fingers can be bent in opposite
3.2. Measurement System

Figure 3.6: Human Hand Flexion/Extension, Adduction/Abduction

axis and it is called Adduction and Abduction respectively. However human
thumb has more dexterity than Flexion/Extension, Adduction/Abduction and
one of the most common dexterity is called Thumb Opposition. Apart from
the above mentioned dexterity, there is thumb rotation, thumb roll and these
gestures are used when the thumb tip needs to contact with any other tip or the
palm.

The goal was to capture all these complex motion precisely from the human
hand and map with the robot hand. There are various robot hands in the
world that can mimic complex human hand dexterity \[62–64\]. However almost
all these robot hands are controlled with pre-modeled motion trajectories and
thus the need of capturing real time operator finger motion was not necessary.
However, In telexistence it is necessary to use the human postures rather than
pre-programmed trajectories and therefore a solid hand gestures capturing sys-
tem and mapping algorithms was needed.

There was no existing off-the-shelf type of glove system that will capture all the
above dexterity of the hand. In most existing glove systems it measures the
Flexion/Extension, Adduction/Abduction but no system was able to capture
the thumb roll and opposition. Therefore in TELESAR V, a data glove from
“Fifth Dimension Technology (5DT)” 5DT-14 was used. However this glove was
also lacking of thumb opposition and thumb roll sensors. Thus, as shown on
Fig. 3.7 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 details of the calculation is explained in the Robot
Dynamics section. Fig. 3.7 shows the 5DT-14 sensor placement after the custom
3.2. Measurement System

Figure 3.7: 5DT-14 Data Glove Modified Fiber Placement for TELESAR V

sensors have been added in order to detect the thumb opposition and thumb roll.

Figure 3.8: Different Fiber Bending Sensor Types

Fig. 3.8(right) shows the different fiber types used in one glove system. 3 main types of fibers were used. 80mm long flexion sensor type (5DT-5), 40mm flexion sensor type (5DT-14) and 40mm long bent abduction sensor type (5DT-14). These sensors can be interchanged depends on the bend requirement and currently TELESAR V uses $14 \times 40$mm type flexion and abduction type sensors. In earlier implementations, 80mm type was used and it was found that they are easy to break due to the long length.

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 3
for each finger, and 2 for the thumb. The names of the phalanges of the 3 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. 3.7 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 seen on Fig. 3.7. 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 analyzing 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 it’s original placement to the sensor 10 position as shown in Fig. 3.7 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 the the same material used by the original glove (Black Stretch Lycra) because the elasticity and compressibility provided by Stretch Lycra was just perfect for the sensor to hold tight and not to move around when bending.

Figure 3.9: Thumb Opposition Sensor Addition

Fig. 3.9 shows the new sensor addition and the special pocket created with black
3.2. Measurement System

stretch lycra to hold the sensor. The pocket was sew to the glove inside so that at any point the sensors can be removed similar to all other sensors on the glove. Fig. 3.8(left) shows the data capturing circuit used in grabbing the raw bend data for all 14 sensors. Due to the limitations of the A/D converter used in this circuit the maximum bend sensors connected is limited up to 14.

![Figure 3.8: Data Capturing Circuit](image)

Fig. 3.8(left) shows the data capturing circuit used in grabbing the raw bend data for all 14 sensors. Due to the limitations of the A/D converter used in this circuit the maximum bend sensors connected is limited up to 14.

Fig. 3.10 shows the internal structure of the bend sensor. At the tip of the sensor, a transmitter IR LED was placed which will emit the IR rays always. On the other side of the sensor tube, a proprietary photo transistor which will measure the intensity of the incoming IR light was placed. 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 of electrical voltage is measured from a electrical signal ranging from 1V - 2.4V and the digitized data is sent to a PC via a USB connection.

On the PC side, to use the captured raw bending data several signal conditioning were necessary. First the raw data has to be normalized. This was done through the fiber calibration step. When the calibration was enabled in the TELESAR system the raw data was captured and during the bending, maximum and minimum bending values was calculated. Once the min, max raw data was known according to Eq. 3.1 the normalized bend values between 0 - 1 was further processed for calculating the bend angle.

\[
bend_{\text{normalized}} = \frac{raw_{\text{val}} - raw_{\text{min}}}{raw_{\text{max}} - raw_{\text{min}}} \cdot Max \tag{3.1}
\]

![Figure 3.10: Optical Bend Sensor Internal Structure](image)
After the user was satisfied with the bend calibration he confirms the calibration and no further max, min values were monitored. The last min, max values will be used for normalizing all incoming raw data. 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 bend sensor correct calibration, bend sensor uncalibrated detection, bend sensor break detection etc.

### 3.3 Audio / Video Transmission System

#### 3.3.1 Audio / Video Setup on Robot Head

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 were installed parallel to each other having a interpupillary distance of 65mm. Two Microphones are placed at the robots ears to capture the stereo surround sound from the remote environment. These microphones are covered with a shell similar to human external ear so that the noise from back will be reduced and the priority audio will be from front and sides.
3.3. Audio / Video Transmission System

3.3.2 Head Mounted Display

Many existing HMD’s (Head Mounted Displays) in the market were used in our previous versions of telexistence research. Yet, the wide angle view and the resolution was not enough to provide a immersive experience close to actual presence. For example, if the vision that the operator sees on the remote side is very narrow, he would not feel that the vision provided was close to his own vision. Also it is necessary to see a wide view on the remote side at a glance to understand the entire setup on the remote side. Next, high resolution displays were necessary for seeing small objects clearly during manipulations.

To satisfy the above requirements and to provide a HD wide-angle stereovision sensation to the operator, a custom designed HD (1280 × 800 pixels) wide-angle Head Mounted Display [65] was used. In order to provide the wide angle and maintain a small footprint, in this design, a 5.6" (inch) LCD display (Model no: HV056WX1-100) has been used. In addition this design was providing an increased optical flow length using a special lens arrangement as shown in Fig. 3.12. 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 [52]. A knob was presented at the front

Figure 3.12: TELESAR V: HMD Assembly view [65]
side of HMD so that the operator can adjust the interpupillary Distance of left and right eye for a clear stereovision.

Table 3.3: TELESAR V Audio/Visual System Specifications

<table>
<thead>
<tr>
<th></th>
<th>HMD (master)</th>
<th>Cameras (slave)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of vision H×V [deg]</td>
<td>61° × 40°</td>
<td>61° × 40°</td>
</tr>
<tr>
<td></td>
<td>(raw: 62° × 48°)</td>
<td></td>
</tr>
<tr>
<td>Sensor dimension [inch]</td>
<td>5.6 LCD</td>
<td>1/3 CMOS</td>
</tr>
<tr>
<td>Focal length [mm]</td>
<td>114</td>
<td>10 ~ ∞</td>
</tr>
<tr>
<td>Convergence ratio [%]</td>
<td>89</td>
<td>89</td>
</tr>
<tr>
<td>Interpupillary Distance [mm]</td>
<td>65 (59 ~ 69)</td>
<td>65</td>
</tr>
<tr>
<td>Body weight [kg]</td>
<td>1.8</td>
<td>N/A</td>
</tr>
<tr>
<td>Pixel resolution [px]</td>
<td>1280 × 800</td>
<td>1280 × 800</td>
</tr>
<tr>
<td></td>
<td>(raw: 1920 × 1080)</td>
<td></td>
</tr>
<tr>
<td>Scanning frequency H×V [Hz]</td>
<td>49.2k × 60.00</td>
<td>67.43k × 59.94</td>
</tr>
<tr>
<td>Sound input/output [ch]</td>
<td>In 1 / Out 2</td>
<td>In 2 / Out 1</td>
</tr>
</tbody>
</table>

The raw video feed (resolution: 1920px × 1080px and FOV: 62° × 48°) from robot camera’s were down sampled and converted to 1280 × 800 resolution and 61° × 40° Field of view using a video flipper (Model no: XC1 Sio). Furthermore to correct the vertical flip of each eye due to the lens configuration, a post processing horizontal flip was used. To hear the remote side, a noise cancelling headphone (Model no: Bose QC15) used. This enables to cut down any motor noise, background noise of the user environment and hear the remote side clearly.

In addition, two cameras was available on the front side of this HMD to be used in video see-through mode. A complete specification of the stereo-vision system is listed as shown in the Table. 3.3 [65]. The Interpupillary Distance of the HMD can be adjusted between 59 ~ 69 depending on the users Interpupillary Distance.

After several months of usage, a commercial version of this display was developed with Kyokko Denki Inc. [65]. Fig. 3.13 left side shows the prototype design
3.4 Mechanical Architecture

As shown in Fig. 3.14, 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 six joints of the manipulator arm is used as torso and last joint with a separately attached two DC motors are used as the 3 DOF (roll, pitch, yaw) head. Custom built 7 DOF arms and 15 DOF Anthropomorphic Robot limbs are used for tool manipulation.

3.4.1 6 DOF Torso and 3 DOF Head

The coordinate frame assignment for the 6 DOF torso and 3 DOF head is shown in Fig. 3.15, based on the Denavit-Hartenberg (DH) convention. Corresponding DH-parameters with 6 DOF torso and 3 DOF head are listed in Table 3.4. For consistency, DH convention used in TELESAR V is defined as

- \( a_{i-1} \) The distance from \( z_{i-1} \) to \( z_i \) measured along \( x_1 \),
- \( \alpha_{i-1} \) The angle between \( z_{i-1} \) and \( z_i \) measured about \( x_1 \),
3.4. Mechanical Architecture

Figure 3.14: Mechanical Configuration of Head, Body, Arm and Hand
3.4. Mechanical Architecture

Figure 3.15: Mitsubishi PA10 Coordinate Frame Assignment
3.4. Mechanical Architecture

- $d_i$: The distance from $x_{i-1}$ to $x_i$ measured along $z_1$.
- $\theta_i$: The angle between $x_{i-1}$ and $x_i$ measured about $z_1$.

Table 3.4: TELESAR V, Torso and Head DH Parameters

<table>
<thead>
<tr>
<th>Link</th>
<th>$a_{i-1}$</th>
<th>$\alpha_{i-1}$</th>
<th>$d_i$</th>
<th>$\theta_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\theta_1$</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>-90</td>
<td>0</td>
<td>$\theta_2$</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>90</td>
<td>450mm</td>
<td>$\theta_3$</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>-90</td>
<td>0</td>
<td>$\theta_4$</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>90</td>
<td>480mm</td>
<td>$\theta_5$</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>-90</td>
<td>0</td>
<td>$\theta_6$</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>90</td>
<td>325mm</td>
<td>$\theta_7$</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>90</td>
<td>0</td>
<td>$\theta_8$</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>90</td>
<td>110mm</td>
<td>$\theta_9$</td>
</tr>
</tbody>
</table>

These DH parameters represents the link parameters which used to derive Inverse Kinematics for torso and head in the next sections.

PA10 being an Industrial Manipulator, it can perform long hours with very good position accuracy. However due to the velocity limits of each joint it cannot perform very fast movements. This is not a problem in industry as the overall time is concerned. But when using PA10 in TELESAR V, a joint speed limit issue can occur for the shoulder frame and head. Usually the operator should be able to move his head faster compared to his spinal movements. In PA10 the tool link J7 is very fast because it is meant to use by attaching tools. Thus J7 was sued as the head pan motion. Using J6 as tilt was tried in the past, but however it was slow compared to operator head motion, thus the operator could feel the lag. In order to remove this lag on the tilt and roll, two separate joints were added on top of J7 to complete a 9 DOF kinematic chain. This 9 DOF kinematic chain will act as the spine, body and the head of TELESAR V.
3.4. Mechanical Architecture

3.4.2 7 DOF Anthropomorphic Robot Arm

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. As shown in Fig. 3.14 the entire length of the arm is 520mm from shoulder to wrist joint. Additionally a 200mm long hand is fixed on the wrist joint.

![7 DOF Anthropomorphic Robot Arm Coordinate Frame Assignment](image)

Fig. 3.16 shows the kinematic configuration and the coordinate frame assignment of the 7 DOF Anthropomorphic Robot Arm. Table 3.5 shows the DH parameters for TELESAR V, 7 DOF Arm. This DH parameters represents the length until the tool point, i.e. until the wrist joint of TELESAR V. The tracking point used in Opti Track system is mounted on the outer arm of the operator and thus to calculate the accurate center point it is necessary to translate the coordinate frames. On robot side, palm center to wrist joint distance was measured as 67mm. Thus additional +67mm of coordinate frame along z-axis and a 20mm along Y-axis is translated in order to generate the palm mid center point. This corrected point position and orientation is fed to the inverse solver to calculate the arm position in space.

In most humanoid robots, the joint angles limits are smaller compared to typical
Table 3.5: TELESAR V, Arm DH Parameters

<table>
<thead>
<tr>
<th>Link</th>
<th>( a_{i-1} )</th>
<th>( \alpha_{i-1} )</th>
<th>( d_i )</th>
<th>( \theta_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>-190mm</td>
<td>( \theta_1 )</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>90</td>
<td>0</td>
<td>( \theta_2 - 90 )</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>-90</td>
<td>280mm</td>
<td>( \theta_3 - 90 )</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>90</td>
<td>0</td>
<td>( \theta_4 )</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>-90</td>
<td>240mm</td>
<td>( \theta_5 )</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>90</td>
<td>0</td>
<td>( \theta_6 + 90 )</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>90</td>
<td>0</td>
<td>( \theta_7 )</td>
</tr>
</tbody>
</table>

human workable space. This is due to a precaution measure not to have unwanted motion on the robot as well as to maintain a higher stability. However limiting the angles of each joints will reduce the dexterity of the robot. In order to increase the level of dexterity of the slave robot arm, TELESAR V arms were designed with similar limiting angles of each joints compared with an ordinary human. Table. 3.6 shows the mechanical and electrical joint angle limitations in positive and negative direction where electrical joint limits are implemented as a precaution in case of a control loop overshoot out of the mechanical area. Thus operator is free to move in any posture as he would like and the system is limiting any motion on the master side. This gives a great flexibility to the operator to perform remote manipulations without having to worry about the mechanical constrains and limits.

The entire arm, including drive mechanics and hardware components is only 2.1Kg and has a payload of 1.2Kg. (Note: Mechanical components of Arm, Hand and Head are designed by Tachi Laboratory and fabricated in KAWABUCHI Mechanical Engineering Laboratory, Inc.).

Next, when designing the mechanical system, the size was kept at a very small scale, and keep a nice smarter look closer to a human. Bulky arms, wrist joints will give performance boost, but however in contrast it will damage the body schema image when the user try to operate his limbs as his own. Table. 3.7
shows the used motor types, their stall torque, gear ratio and torque/current constant. First 3 Arm joints are driven with 12V DC motors having a torque of 80.00 mNm at the motor shaft. J4 is driven with 12V DC and it has a torque of 48.3 mNm at the motor shaft. First 4 joints speed capability is very important to track the user movements in real time. If it is slow (with high gear ratio) or if it is not capable of delivering the desired torque it will start lagging. Note that all the torques mentioned above is stall torque, which is the full load (no motion) torque. It also known as the start-up torque. The maximum torque which can produce a better speed and torque is calculated as the “Rated torque” which is in between the no load torque and stall torque. This is equivalent to stall torque / 2. Also this torque is at the shaft, but not on the final link, thus it has to multiply by the corresponding gear efficiency factor.

J1, J2, J3 joints implements Harmonic Drive (Strain Wave Gearing) to maintain a very low backlash and vibration while provide the necessary high torque. J5, J6, J7 are driven with 6V DC motors having a torque of 40.0 mNm at the motor shaft. Each motor has it’s own planetary gear head of 0.85 efficiency. Thus, when calculating the actual torque at the link we have to consider the gear efficiency, rated torque (0.5 × stall torque). This calculations have been used when comparing the torque values on each joint on the technical evaluation

### Table 3.6: Joint Limits of 7 DOF Anthropomorphic Robot Arm

<table>
<thead>
<tr>
<th>Joint</th>
<th>Mechanical Angle limit</th>
<th>Electrical Angle Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Negative</td>
<td>Positive</td>
</tr>
<tr>
<td>J1</td>
<td>-90°</td>
<td>145°</td>
</tr>
<tr>
<td>J2</td>
<td>-100°</td>
<td>20°</td>
</tr>
<tr>
<td>J3</td>
<td>-152°</td>
<td>32°</td>
</tr>
<tr>
<td>J4</td>
<td>-135°</td>
<td>-2°</td>
</tr>
<tr>
<td>J5</td>
<td>-93°</td>
<td>93°</td>
</tr>
<tr>
<td>J6</td>
<td>-15°</td>
<td>45°</td>
</tr>
<tr>
<td>J7</td>
<td>-45°</td>
<td>60°</td>
</tr>
</tbody>
</table>
3.4. Mechanical Architecture

Table 3.7: 7 DOF Arm Motor Specifications

<table>
<thead>
<tr>
<th>Joint</th>
<th>Motor Type</th>
<th>Gear Ratio</th>
<th>Stall Torque [mNm]</th>
<th>Torque Const [mNm/A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>2342S012CR IE2-256</td>
<td>1:570</td>
<td>80.0</td>
<td>13.40</td>
</tr>
<tr>
<td>J2</td>
<td>2342S012CR IE2-256</td>
<td>1:570</td>
<td>80.0</td>
<td>13.40</td>
</tr>
<tr>
<td>J3</td>
<td>2342S012CR IE2-256</td>
<td>4:825</td>
<td>80.0</td>
<td>13.40</td>
</tr>
<tr>
<td>J4</td>
<td>2232R009SR IE2-256</td>
<td>3:1100</td>
<td>48.3</td>
<td>16.0</td>
</tr>
<tr>
<td>J5</td>
<td>1724E006SR</td>
<td>27:4805</td>
<td>40.0</td>
<td>6.61</td>
</tr>
<tr>
<td>J6</td>
<td>1724E006SR</td>
<td>27:5600</td>
<td>40.0</td>
<td>6.61</td>
</tr>
<tr>
<td>J7</td>
<td>1724E006SR</td>
<td>3:637</td>
<td>40.0</td>
<td>6.61</td>
</tr>
</tbody>
</table>

This motors, gear configurations and limiting angle can ideally provide required results. However in practical conditions such as friction, wear and tear etc. these conditions are far more perfect. Thus how the motors are controlled in hardware, update rate and what kind of feed forward and feedback control methods are used in hardware is very important. Furthermore, if the robot dynamics were modelled correctly on the software and if the control algorithms of motors are perfectly fine tuned for accuracy and speed, we can expect good results. The types of controlling techniques used, hardware communication protocols, target update rate, PID loops information is described in the “Electrical System Architecture” section.
3.4. Mechanical Architecture

3.4.3 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. TELESAR V Hand has mainly focused on increased Index, Thumb finger dexterity while giving the ability to control the abduction. As shown in Fig. 3.17 (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. As described earlier in measurement section and as shown in Fig. 3.17 (Left), a very small, wearable and light weight data glove was used so that the user do not feel any mechanical constrains. This gives great flexibility to move fingers independently on the robot side and grasp many objects.

Figure 3.17: Master Glove vs. Slave Hand

As shown in Table. 3.1, when comparing just the robot hands, TELESAR V hand is not the highest DOF hand, however it is the only hand which can be controlled with high fidelity, high dexterity in real-time in a teleoperation. The additional dexterity on Thumb is greatly helpful in real-time manipulation and mapping to the user posture. 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.

Fig. 3.18 shows the Robot Hand Coordinate Frame assignment and the placement of each joints w.r.t. each finger. As can be seen on the above Figure, 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, but however when humans use their fingers in manipulation tasks, this two joints are nearly working with coupled motion. Thus, unless the operator is trying to pose for very specific finger gestures, this mechanical coupling is not a big issue.

Each fingers proximal phalanx is 25mm, intermediate phalanx is 30mm. The four fingers have a 45mm long distal phalanx whereas 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 (0.7x) it
3.5. Electrical System Architecture

was impossible to obtain a valid joint angle using numerical inverse kinematics. Thus, trigonometric and analytical inverse approach was used to obtain the angle data. Thumb, Index, Ring and Small fingers were moving 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. 3.2,3.3 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.

\[ F_{nx} = 45 \cdot \cos(\theta_{1,1}) + 30 \cdot \cos(\theta_{1,1} + \theta_{1}) + 25 \cdot \cos(\theta_{1,1} + \theta_{1} + \theta_{2}) \]  \hspace{1cm} (3.2)  

\[ F_{ny} = 45 \cdot \sin(\theta_{1,1}) + 30 \cdot \sin(\theta_{1,1} + \theta_{1}) + 25 \cdot \sin(\theta_{1,1} + \theta_{1} + \theta_{2}) \]  \hspace{1cm} (3.3)  

As shown in Fig. 3.18 there are two motors which is not used in the current configuration of the 15 DOF hand. Initially the hand had 16 motors and thus it was a 16 DOF hand. But however the 16th joint being the palm to distal phalanx on index finger, it was very fragile and easy to break. Also when in manipulation this palm to distal joint is not used. Thus the joint was fixed at 0 Deg all the time. Thus the dexterity of the hand became 15 DOF. Another virtual joint between palm and distal on middle finger is marked according to the Fig. 3.18, but this had to be fixed at the mechanical design as the middle finger should not be moving over the z-direction over time.

Table. 3.8 shows the joint limits of the hand, motor and joint assignment based on the kinematic configuration shown on Fig. 3.18. Similarly to the arm, here also each finger motion limit angles are decided based on the maximum working area of ordinary human hand.

3.5 Electrical System Architecture

In order to explain the electrical system architecture the entire hardware was divided into two sections, i.e body part (Mitsubishi PA10) and the custom Arm / Hand system. Like conventional Industrial Manipulators, the body part does
Table 3.8: Joint Limits of 15 DOF Anthropomorphic Robot hand

<table>
<thead>
<tr>
<th>Joint</th>
<th>Drive</th>
<th>Mechanical Angle limit</th>
<th>Electrical Angle Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Negative</td>
<td>Positive</td>
</tr>
<tr>
<td>J1</td>
<td>D12</td>
<td>-125°</td>
<td>5°</td>
</tr>
<tr>
<td>J2</td>
<td>D2</td>
<td>-70°</td>
<td>2°</td>
</tr>
<tr>
<td>J3</td>
<td>D8</td>
<td>-2°</td>
<td>47°</td>
</tr>
<tr>
<td>J4</td>
<td>D1</td>
<td>-5°</td>
<td>115°</td>
</tr>
<tr>
<td>J5</td>
<td>D5</td>
<td>-45°</td>
<td>90°</td>
</tr>
<tr>
<td>J6</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>J7</td>
<td>D4</td>
<td>-5°</td>
<td>115°</td>
</tr>
<tr>
<td>J8</td>
<td>D3</td>
<td>-45°</td>
<td>90°</td>
</tr>
<tr>
<td>J9</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>J10</td>
<td>D6</td>
<td>-5°</td>
<td>115°</td>
</tr>
<tr>
<td>J11</td>
<td>D7</td>
<td>-45°</td>
<td>90°</td>
</tr>
<tr>
<td>J12</td>
<td>D13</td>
<td>N/A</td>
<td>16°</td>
</tr>
<tr>
<td>J13</td>
<td>D10</td>
<td>-5°</td>
<td>115°</td>
</tr>
<tr>
<td>J14</td>
<td>D11</td>
<td>-45°</td>
<td>90°</td>
</tr>
<tr>
<td>J15</td>
<td>D14</td>
<td>-5°</td>
<td>115°</td>
</tr>
<tr>
<td>J16</td>
<td>D15</td>
<td>-45°</td>
<td>90°</td>
</tr>
</tbody>
</table>

have its own hardware servo motor control logic, thus it was not necessary to implement any special hardware in order to control the motors. PA10 uses a special network command set to communicate with a PC. The internal joint communication inside PA10 is carried out through a ARCNET Local Area Network (LAN based). Thus PA10 is directly connected to a compact PCI to ARNNET converter module (Model No: MHI PA-10A-CNT). Since there is no compact PCI slots in PC’s, we use a PCI to CompactPCI Interface board (Model No: PCI-852100). The last two joints (J8, J9) added for head motion is controlled manually via a 12bit DA / 12bit AD Interface board (Model No: PCI-3523).
3.5. Electrical System Architecture

Next, TELESAR V Arm and Hand uses all Brushless DC motors. Thus it is 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. In terms of speed this method is good, however dynamic changes to the control algorithm cannot be done on PC side, thus it has to re-program on the hardware level. Also to be able to use the system as a learning tool, the challenge was taken by doing closed loop control between a PC and Hardware Motor. This challenge was tricky when using Windows-based PCs as there are no accurate timing requirements for robotics applications.

3.5.1 Arm / Hand Controller Electrical Wiring Diagram

Current controlled PWM logic was used in order to control the current for each motor. 8 joints which have built-in encoders, however only potentiometers were used for all position measurements because it does not have to re-register at every run. Each potentiometer reading is sent to the PC as 16-bit value. Motor current is sensed at the motor driver chips using hall effect sensors and sent to the PC as current feedback. For communication between the PC and hardware, a special system called “TexART NCord” was used. It has both hardware and software C++ support to read and write data between hardware and PC.

As shown in Fig. 3.19, the brain of the hardware processing is two FPGA’s, one for arm (Xilinx Spartan-3 XC3S200) and another for hand (Xilinx Spartan-6 XC6SLX75). Thus the entire system (left/right) has 4 dedicated FPGA’s. These FPGA’s drives the individual motor drivers as well as read last current consumption using the hall effect sensors. This update loop is running at 8KHz parallel for each motor. There are 3 different motor driver chips used depending on the consumed current. Refer to Fig. 3.19 for more details. FPGA also monitors the last current consumption and controls via a closed loop between motor and FPGA. This is further referred to as “Hardware P Control”. It is possible to change the current control limits on the FPGA via a register value sent by the PC. However it is dangerous to control this directly because by any chance if the
Figure 3.19: TexART NCord Hardware for Arm / Hand Control
3.5. Electrical System Architecture

communication between PC and Robot is broken it will have an uncontrolled

current state. Thus, Hardware P control value is only set at the beginning of

the initialization routine.

In order to receive Target position and target current information for all motors

at an acceptable rate from the PC, it is necessary to communicate with the PC at

a higher speed. However if communicates with a serial protocol sending all motor

information it will be slow. Therefore, the motors were grouped (divide) in to

sections called Terminals. Each terminal can communicate up to maximum of 40

channels. Table. 3.9 shows the detailed channel assignment for each terminal.

“In Channels” means the input to the hardware. Thus it represents the drive

command by the PC. “Out Channels” represents the output from the terminal.

Thus it represents the potentiometer, encoder, current, force values as well as

force and thermal sensor values in the hand.

<table>
<thead>
<tr>
<th>Terminal</th>
<th>Assignment</th>
<th>In Channels</th>
<th>Out Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Jₐ₁-Jₐ₄ (R)</td>
<td>4 (16bit)</td>
<td>12 (16bit)</td>
</tr>
<tr>
<td>T2</td>
<td>Jₐ₅-Jₐ₇ (R)</td>
<td>3 (16bit)</td>
<td>9 (16bit)</td>
</tr>
<tr>
<td>T3</td>
<td>Jₐ₁-Jₐ₄ (L)</td>
<td>4 (16bit)</td>
<td>12 (16bit)</td>
</tr>
<tr>
<td>T4</td>
<td>Jₐ₅-Jₐ₇ (L)</td>
<td>3 (16bit)</td>
<td>9 (16bit)</td>
</tr>
<tr>
<td>T5</td>
<td>J₉₁-J₉₁₆ (R)</td>
<td>16 (16bit)</td>
<td>24 (16bit)</td>
</tr>
<tr>
<td>T6</td>
<td>J₉₁-J₉₁₆ (L)</td>
<td>16 (16bit)</td>
<td>24 (16bit)</td>
</tr>
</tbody>
</table>

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 readable

format, a RS485 to PCI-Express x1 converter board is used. Thus, when the

system is operating normally PC sends target information (motor current) at

every 1ms and retrieves the buffered position, current, sensor data at every 1ms.

The time between read/write data is 500us. In our setup the RS485 to PCI-

Express converter box is placed at the robot back. Since RS285 can operate up
to 5m we can successfully issue and retrieve commands at 1ms speed.
3.5. Electrical System Architecture

3.5.2 Arm Hybrid Control Logic Block

Fig. 3.20: Control Logic Block Diagram for 7 DOF Arm

Fig. 3.20 shows the control logic for Arm. As shown on Fig. 3.9 the arm outputs 7 channels of current data as well as the position information. Thus it is possible to model a control algorithm based on position + current based hybrid control. The advantage of using current control is that the manipulator arm can use it’s high currents when it moves up, and low currents when moving down similar to a gravity compensated model. The arm control in FPGA has a current controlled logic where it will maintain a desired torque at any given motion. However by default this is set to static and therefore the controlled current will be same for up motion as well as down motion. Initially this created a motion spikes in down motion when the PID is tuned for up motion. Therefore, a dynamic set current value was implemented, where the target current will be decided based on the present current consumption.

As can be seen in Fig. 3.20, when the motor is consuming more current, i.e it is moving up or lagging behind the target position, it will increase the set current dynamically. In this way a smooth motion on all joints were achieved regardless of if it was a up motion or down motion. However the disadvantage of this method is, if the manipulator is stuck on a position due to an obstacle, it will increase the current thinking that the end effector is lagging behind the target. In order to overcome this situation, a separate gravity compensated model and a force sense on the end effector will be implemented in our next development.
3.5.3 Hand Hybrid Control Logic Block

Fig. 3.21 shows the control logic for Hand. As shown on Fig. 3.9 the hand outputs 15 channels position and 8 channels of force information. Due to the higher number of motors per one terminal it was not possible to receive current information at the PC side. However the same P control at FPGA similar to Arm motors were available on the hardware. Thus, a current control model was able to implement based on a feed forward manner.

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 high torque. In order to avoid this situation, 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 lowest limiting torque where as 2, 3 joints have much more limiting torque. Joint 2, 3 torque limit was increased because to have a faster finger motion. 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 system because the operator can easily understand the fingers he see is not his own.

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 current TELESAR V system, those haptic inputs were used to reproduce the fingertip haptic sensation on the operators fingertip. However this content is out of the thesis bound. 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 fingertip joint bend. But due to the very low torque on fingertip joint, when the operator tries to pinch fingers, robot hand will naturally bend it’s finger tips due to J2, J3 torques being high enough. With this method the pinch finger gestures were naturally solved without modelling the opposite direction bend.

3.6 Robot Dynamics

The dynamics of TELESAR V should be able to provide not only accurate motion, but also how to accurately map the users posture at any motion path without breaking the visual-kinesthetic sensation. This goal can be addressed by mainly dividing it to two sub categories. First a mapping algorithm that can mimic any human movements and secondly a fast, accurate and reliable inverse kinematic solver.

Fig. 3.22, shows the overall kinematic configuration of the TELESAR V without hand. As can be seen two custom designed 7 DOF human sized anthropomorphic robot arms are fixed between $J_5(body)$ and $J_6(body)$ because it will be the best representation of human shoulder when seeing from the kinematic configuration. DH parameters for body can be found at Table. 3.4 and for arm at Table. 3.5.

3.6.1 Body / Arm Trajectory Generation Algorithms

As shown in Fig. 3.23, the most important condition in a teleoperation is to have the users eye-target vector mapped to slave robots eye-target ($T_{EYE} - T_{TARGET}$) all the time. The target can be his own hand when there is no object manipulations, where as it can be any objects during manipulation tasks. This way user will see the robot hand coordination same to your kinesthesia. But in TELESAR V, being able to move the torso at 6 DOF, Head 3 DOF and
Figure 3.22: Full upper body kinematic chain configuration of TELESAR V
3.6. Robot Dynamics

arms at 7 DOF the coordination between each motion provides even more great possibilities such as using natural spinal movements (extension, flexion, lateral flexion, and axial rotation), individual head rotations etc. Thus a rule based set of priority driven algorithms are used to obtain the final goal.

First, the users spinal vector \((T_{SP(u)} - T_{SH(u)})\) is calculated from the measurement system. Then a secondary tracker keeps tracking the head motion of the user and generates the users shoulder to head \((T_{SH(u)} - T_{EYE(u)})\) vector. Next, the users arms are tracked at the palm of each hand. From this calculated user vectors head/eye position \((T_{EYE(u)} - T_{TARGET(u)})\) will be determined and robots eye will exactly follow the users eye. Thus, any spinal or head movements that the user do will reflect in the robot’s head and spinal movements. This can result in slightly different spinal movements due to robot size and dexterity. However the arms are directly attached to the shoulders, thus a compensation is necessary to correct the error generated by the shoulder. To solve this issue, using the tracking data, \((T_{EYE(r)} - T_{SH(r)})\) was generated in real-time and shared with

\(^{1}\text{u - refers to User whereas r - refers to Robot in the equations above}\)
3.6. Robot Dynamics

In this step a calibration is necessary because the two coordinate systems and heights of the operator and user is different. First calibration step will measure the operator’s height (sitting posture) and map that height to the robot’s initial position. i.e (-390,0,1266). Secondly, since the \( T_{\text{EYE}(u)} - T_{\text{TARGET}(u)} \) should be equal to \( T_{\text{EYE}(r)} - T_{\text{TARGET}(r)} \), with the help of \( T_{\text{EYE}(r)} - T_{\text{SH}(r)} \), required robot vector \( T_{\text{SH}(r)} - T_{\text{TARGET}(r)} \) is generated. This will input to the arm kinematic solver. But there needs to be few more conditions to feel the actual visual-kinesthetic effect. Unlike other robots, TELESAR V not only focus on the accuracy of the end point, but also the posture where the user can see. Thus, the parts that user can see forearm arm, wrist should be with the same posture of the user’s. Thus, \( T_{\text{EL}} - T_{\text{WRIST}} \), \( T_{\text{WRIST}} - T_{\text{TARGET}} \) has to match with the users and robots. In order to do this, we use the remaining extra DOF of spine and upper arm to compensate for any error.

Figure 3.24: Expanding Field of view with Mobility in the upper body

In the above method explained for compensation, 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. This issue is solved 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. 3.24, 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. 3.24, such situation can be naturally resolved. With this setup, we have achieved a high level of dexterity and less complexity in object manipulation through this setup.

3.6.2 Inverse Kinematic Solver

In order to achieve the required accuracy and to maintain a higher stability of trajectory generation, 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. Also to concurrently solve the kinematics to avoid possible mechanical delays when reaching the goal, 2 closed form inverse kinematic models were used 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, the method of distance from a singular measure was considered 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. Also as performance criteria specially in the wrist, it is also have restricted the movements such as 60° ~ 105° (degrees) respectively and still satisfy the maximum possible according to human anatomy.

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 solver is tracked by control blocks for arm and hand which was explained in the previous sections.

### 3.6.3 Hand Trajectory Generation Algorithms

In this section, how the data conditioning is applied to get an accurate bend angle based on the normalized bend values were discussed. As explained in Eq. 3.2.3.3 the normalized bend data is sent to all PC’s. As shown in Table 3.8 the 2nd joint angle of each finger is limited to $0^\circ - 112^\circ$ and the 1st joint of each finger is limited to $-40^\circ - 85^\circ$. Doing Forward kinematics on index finger I quickly found that the entire trajectory of index finger and it can be shown as in Fig. 3.25. The black trajectory shows when 1st joint is bent at $85^\circ$ where as blue trajectory shows when 1st joint is bent in opposite direction (pinch) at $-40^\circ$. This proved that based on the limited trajectory that the fingers can move, it is impossible to get an inverse solution with just position data and therefore trigonometric based analytical Inverse approach was used to determine the joint angle.

![Index Finger Trajectory on xy with Simulated Theta](image.png)

**Figure 3.25: Index Finger Trajectory on xy with Simulated Theta**
3.6. Robot Dynamics

Based on Fig. 3.25, it also shows that no matter the operator bend his fingers the 2nd joint maximum bend on robot is limited to $112^\circ$. Thus, in other words the mapping between normalized data to bend angle should be accurate only within the range of $0^\circ - 112^\circ$. 1st Joint bend angle is derived using the 2nd joint bent angle as the first bending cannot be calculated using the current data glove. Considering the limited trajectory path of each finger this approach was not a problem at all.

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. 3.4. In this approach, it was found that the normalized bend values were not linear and thus the closest match was the ArcSin curve.

$$Bend_{modeled} = a + \arcsin(Bend_{normalized}) \cdot b$$  \hspace{1cm} (3.4)

Modeled joints vs. the ideal joints were plotted in order to understand the error of the modelling. As shown on Fig. 3.26 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 human’s finger length can be vary depending on the ethnicity, sex and even the characteristics of the person. This has been found quite a common occurrence in our operators and therefore we had to found a solution for this. The difference of finger lengths are measured as an index called “Digit Ratio”.

**Digit Ratio**

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 his 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 finger and the index index finger tend to be about the same length where as most men the index finger is usually the shorter of the two digits.

![Digit Ratio Pattern of Male and Female](image)

**Figure 3.27: Digit Ratio Pattern of Male and Female**

Fig. 3.27 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 we had to calibrate the fibers and bend angle for each finger.
The 15 DOF hand in TELESAR is made in a way that the Digit Ratio 2D:4D is 1. However out of the 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, first the best case on the robot hard where robot grasps a cylindrical can with its 5 fingers were modeled. As shown on Fig. 3.28 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 3.28: Finger Digit Ratio Calibration Method](image)

On the robot side, when index and thumb edges touches each other and it creates an approximate circle as shown in Fig. 3.28. If this this condition is satisfied when the user makes an “OK Sign” with his index and thumb finger it should be similar for other fingers. 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. 3.4. 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. 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.

3.7 Software Architecture and System Block Diagram

Most robotic applications are developed in Linux or Realtime OS environments. However in TELESAR V design, it was decided to use Windows environment for few reasons. First, to make TELESAR V as a telexistence platform for study purposed. To test various conditions, and wide range of software support was found in Windows platform. Next, some of the robotic arms (PA10) that used in TELESAR V does not have extended support on Linux or Realtime OS, thus had to use Windows only environment.

Even though it has great support for all our hardware, many problems were faced when using windows environment because Windows is not meant to process data at 1KHz speed. A typical windows applications refresh rate is 10ms and even the very common Sleep() function available on Windows environment is not accurate if the refresh cycle is less than 10ms. In TELESAR V, since the control logics are running on PC side, we desperately needed a 1KHz precise update rate for all PC’s. There are couple of high-resolution Timers available under windows. i.e

- Query Performance Counter (QPC)
- SetTimer - CPU Tick Count (TSC)
- Multimedia Timer

All these methods were tested, but however Multimedia Timer was the only success. First, Query Performance Counter is meant and released as a debug
3.7. Software Architecture and System Block Diagram

tool under windows which it can precisely measure time using a high resolution hardware timer. But this timer is based on for each die on the CPU (not cores) thus it does not have Multi Processor (CMP) support. So when QPC is used by one core, all other cores in the same die will have a great performance reduction. Also QPC uses a blocking timer which resulted in precise time, but other applications timing was effected. Next, the set timer or CPU tick count gives the number of counts on the CPU. Windows by native try to save CPU speed for performance and energy saving purposes and thus the CPU tick frequency is not static. This is a common problem in windows and it is impossible to make a constant CPU frequency all the time by changing a setting. Thus, when time is measured using TSC, over time it is different based on other application load on that CPU.

In order to have a precise timer, Multimedia Timer was used, which also widely used by encoding decoding applications to maintain 1KHz MIDI signals under windows. Also this high resolution timer is not directly based on the chip level, it supports Multi Processor (CMP). Multimedia Timer (MMTimer) can accurately measure intervals of 1ms. A custom call back handles were created based on Multimedia Timer so that multiple instances of the timer can be run in single application as well as several applications on single PC.

3.7.1 Shared Memory Agent

In TELESAR V, Arm Kinematics, Hand Kinematics, Data Transmission, Sensory and other services has to run parallel in order to attain a 1ms full cycle. Thus parallel processing of multiple applications distributed on multiple cores of the CPU is required. To transfer data between multiple software inside the PC with a higher speed without affecting any I/O performances there are mainly two common methods. i.e POSIX Message Queues or Shared Memory based access. In case of POSIX messages it is necessary to pass messages on to each process separately and this will be a tedious and non effective way when there are too many processes running parallel. Thus to use a shared memory access method was decide so that there is a shared memory creator on each PC and all other processes will read/write to the desired memory locations. Since shared
memory is based on non-volatile memory on the PC, it has the highest access speed compared to disk access or POSIX Queues.

Fig. 3.29 shows one portion of the custom shared memory structure created for TELESAR V. We use a custom prefix for all our shared memory storage and use a heap size of 0x1900. For each read or write access we set the head size as 0x100. These shared memory heap is then synchronized with a LAN network at 1ms so that the data is available on any PC. The details of the network structure is discussed on the next section. Out of the memory heap joints, sensors and status structures are fully synchronized among all PC’s. The rest of the structures are limited to local access only and being used to pass data between services within one PC. All the data has been stored and sent as floats so that it has the maximum resolution.

The glove structure is send from the master PC to the server PC. Also the hardware structure is send from the hardware PC to server PC which contains all real time robot information. Once all the data is gathered on the server
3.7. Software Architecture and System Block Diagram

PC, the processed joint and sensor data is sent to all PC’s. Furthermore each intermediate values such as current robot, user position, orientation is updated on the target structure. This Target structure is used to log data on the system and the required log data can be easily changeable.

The shared memory method helps individual application developer in a way that they do not have to consider about the network issues, but can read/write to the common shared data and reduces the overloading the server network load. The data cycle speed is limited to 1KHz just to preserve the bandwidth when doing real-time operations, but there is no design limitations to increase this speed. Previous research shows that 1KHz is more than enough to produce a sense of presence in terms of visual-kinesthetic effect.

3.7.2 Software Block Diagram

Fig. 3.30 shows the combined software diagram of TELESAR V. As explained in the previous section, inter-application communication is achieved using creating a shared memory space and synchronized through network.

Master workstation captures all the operator posture data, finger bending and sends to the server workstation. In the server workstation all mathematical calculations are performed and joint data space is sent back to all its clients at a rate of 1 KHz. One client act as the hardware driver for body, head, arm and hands and the same clients runs a simulated telexistence environment. The hardware driver client receives robot’s sensor data such as position, torque, current, haptic sensory and sends back to the server. Server encapsulates these data into the multicast datagram and sends back to its all clients. Haptic information is built in to the TELESAR V software framework and being used in the current system. However the haptic transmission system does not have any relationship to this thesis.

The distributed PC network was helpful when development phase as communication is handled by the com Agent. Also for example, when the driver PC have a problem, and needed to reboot, by just rebooting that PC will preserve all the states and recover faster. During public demonstrations this feature was helpful.
3.7. Software Architecture and System Block Diagram

Figure 3.30: Software and Network Block Diagram
Similarly when one section is not in use (Haptics) it is possible to shutdown the entire section and minimize the hardware load. The simulator is placed on the same PC as hardware so that it confirms the same data is sent to the hardware drivers. The system can fully operate in virtual environment, physical or a combination of both. A separate second Simulator is running on a different PC in order to provide instruction wizard to guide the operator on calibration steps, the procedure etc. This will be explained detailed in the next section under state machine.

Master PC and the Haptic PC runs on Windows 7, 64bit environment since the processing should be fast enough to capture data at a higher rate. Ideally it’s better to run app applications at 64bit, but however there are driver limitations for body and arm hardware controllers which restrict us to use 32bit processing. Thus Hardware and Server PC runs on Windows 7, 32bit environment. The shared memory approach and network synchronisation allowed us to use different environments on different PC’s but still keep everything under 1KHz processing. For the development environment, Microsoft Visual Studio 2000 C++ was used and all the services and applications are written in win32 console mode in order to get the highest speed. The simulator is operating at Visual C++ for obvious reasons that needed to visualize data.

3.7.3 Data Delivery Media

A Telexistence operation can happen between two remote locations or at a same physical location isolated from each other. The data communication and processing architecture is designed such that the master and slave systems are connected through a LAN network and can be located in two different places. Ideally this will require only 2 workstations, but due to the hardware compatibility and performance issues 4 workstations were used.

As shown in Fig. 3.31 all these workstations are connected via a LAN network and a common shared memory location is synchronized over LAN with the speed of 1 KHz. The distributed High Performance Computing (HPC) environment allows the workstations to independently carry out the assigned tasks while in background network layer keeps the data network updated.
As explained in the shared memory section each PC creates a shared memory space and using UDP Multicast this shared memory space is synchronized. But to synchronize this data effectively over network a the size of the heap was very big. In order to effectively transmit the entire structures of the shared memory content, Object Serialization was used which the process of translating data structures or object state into a format that can be transmitted across a network connection and resurrected later in the same or another computer environment. When the resulting series of bits is reread according to the serialization format, it can be used to create a semantically identical clone of the original object. In order to decode the data on the other side of the network I use standard deserialization techniques in C++. Using serialization it was able to get a very stable synchronization with minimum error correction and to reduce the network traffic significantly compared to direct implementations of UDP usage.

All data except for the HD Video link / Robot Binaural Audio and scanned tactile PCM audio is transmitted over a closed wired LAN network. Video and audio data is currently 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 latency which was sufficient for Telexistence operations.
3.7.4 State Machine

In order to perform a remote manipulation by an operator there needs to perform several steps such as finger calibration, body posture calibration, confirmation of correct calibration and finally the connecting to the remote environment. To make this simple, TELESAR V includes a State Machine mechanism. Fig. 3.32 shows the state machine used in the system. The state machine starts with state 0 which is the “DISCONNECT” state. Once the operator is ready to connect with a remote environment, he first need to wear the gloves, tracking vest and finally put the HMD. When the operator wear the HMD he will be guided with visual and narrative instructions on what to do next. Underlying this instructions, this state machine is running.

![State Diagram of TELESAR V](image)

Figure 3.32: State Diagram of TELESAR V

In order to confirm the states or go to the next state operator is given a foot switch as shown on Fig. 3.33(Right). This foot switch has two inputs such as a ordinary tap and a long tap (more than 3s). After starting with “DISCON-
NECT” state, when the operator is ready to go to the next step he will be asked to do a ordinary tap. This will advance to the next state “HOME” which the robot will move to it’s original posture. When this step is done, operator will be asked to do another tap when he is ready to calibrate the fibers. In this “FIBER CALIBRATION” step the maximum bend and minimum bend is recorded and the raw fiber data will be normalized and sent to the bend data to angle calculation block. There are several steps in order to capture all fibers bending as the placement of the fibers are different for each finger depending on the sensors type such as Flexion/Extension, Adduction/Abduction or Opposition. However the exact steps that needed to perform for finger calibration is provided as a video so that the operator has to follow the exact same sequence. Once he has completed all the steps he will be asked to tag again and the fiber calibration step will be finished.

Next, depending on the users finger size, length it is necessary to calibrate. The operator is asked to pose for “OK SIGN” with all fingers and when he is ready a tap is necessary to confirm the calibration. The detailed instructions will be provided in a video to the user at the same time. Once the “FINGER CALIBRATION” state is done, next the operator will be asked to go in to straight pose, put his two hands on the knees and to do another tap for confirmation. Up on the tap “POSTURE CALIBRATION” step will be completed and he will be ready to connect to the robot. When he is ready to connect he will be asked to perform another tap and he will be connected to the robot which is called the “CONNECT” state.

When the user is connected to the remote side, the instruction wizard video is faded to the robot live view and the operator will be able to see the remote side. When the operator needs to disconnect or pause the manipulation, he can tap again. This step will go back to the “DISCONNECT” state. Since the fiber calibration data is saved, the operator does not have to perform fiber calibration and it will be skipped to the “FINGER CALIBRATION” state. However if the user prefers to do the fiber calibration again, he can do a long press (3s) and it will go to the “RESET” state and performs a full reset.
3.8 TELESAR V Simulator

This entire operation can be guided by another person (Backyard Helper) using a 10-key operation. Fig. 3.33(Left) shows the 10-key used to control the entire operation of TELESAR V. Using the 10-key the state machine can be advanced from any state to another state at any time. For example if the Backyard Helper thinks that the finger calibration is not necessary, he can skip that step and directly connect to the remote side. 10-key operation has more advanced options such as recording data to a log file, Force actuator test, Thermal actuator test etc.

3.8 TELESAR V Simulator

In order to visualize the data, give experience of Virtual Telexistence and to guide operator with real time feedback steps a custom built Simulator [66] was used in TELESAR V. The simulator uses NVidia PhysX for physics and rendering runs completely on GPU. Simulator can output 2 separate DVI channels each rendering at $1600 \times 1200$. In order to switch the video channels from Virtual Telexistence environment to Robot, a small DVI Switcher Hardware was built and which can switch DVI channels via a USB interface. This USB interface is integrated with the comAgent software and it can be controlled by the server PC commands.
Currently TELESAR V system uses two instances of the simulator on completely different PC’s. The first instance is on the hardware PC which shows the exact data that is sent to the hardware drivers. Second instance is used to provide the Virtual Telexistence environment as well as the help wizard and this is connected to the DVI switcher. Thus when the user first put the HMD, he will see the help wizard and the virtual telesar until he connects to the remote environment.

3.8.1 Realtime Data Visualization

To understand the latencies, and also to show what is the real time status of the robot, the real-time data was superimposed on the target data. If the data is shown all the time it will be hard to understand, thus when the joint target and robot angle difference exceeds 3 degrees the real-time data was shown. When there is an offset of nth joint it will affect the position error of adjacent joints. Therefore the following joints and the overall position shift is shown in red color super imposed on the target posture.

![TELESAR V Simulator Real-time Data vs. Target Data Visualization](image)

Figure 3.34: TELESAR V Simulator Real-time Data vs. Target Data Visualization

Fig. 3.34 shows the data visualization using TELESAR V Simulator. As can be seen, in this specific time, the robot position is lagging the target values and the real robot posture is shown in RED color. Since this error shows that an
3.8. **TELESAR V Simulator**

entire shift of the robot, it can be easily reason out that the lag is happening at J1 of the body. This feature is helpful to understand the mechanical issues of the robot and to resolve them quickly. Simulator also helped us greatly when in development because we did not have to use the real robot hardware when we test new algorithms. Finally this real time robot information can be used as a feedback to the robot, when teleoperations are carried out with time delays. Since the rendering can happen at any place and only the joint data is necessary, we do not have to send the video and audio in realtime. Instead the operator can look at the simulated environment and perform manipulations.
Chapter 4

Technical Evaluation

The system “TELESAR V” was designed and implemented based on various custom hardware components, software blocks, and thus the expected performance could be far away from the ideal expectation. Therefore, it is necessary to evaluate each section of the system to find out the limitations and specifications of the current system. In addition, the results of the technical evaluation chapter will lead to possible future enhancements to the system and the direction of the research.

The initial milestone of the technical evaluation was to find out the limitations body schema transfer system based on manipulation types of inspection, reaching and grasping. As defined in the Chapter 2, these parts can be evaluated based on the accuracy, speed, perception errors etc. Therefore, the overall limitations and the specifications of the system can be list up as below.

1. Visual inspection accuracy
   - Operator vs. robot eye tracking accuracy, latency and performance measurements.
   - Operator’s perspective parameters vs. actual parameters

2. Reaching accuracy
   - Operator vs. robot eye-to-hand vector tracking accuracy, latency and performance measurements.

3. Grasping accuracy
   - Operator vs. robots fingers posture tracking accuracy, latency and performance measurements.
4.1 Visual Inspection Accuracy

There has been past research on about display technologies of telexistence and they have been verified with Helmoholtz horopters [52, 67–71] as measures of visual space and visual space observed indirectly though the telexistence display systems. With the experiments, the important parameters necessary to have the same distance and size perception has been found. Thus, the vision system of TRELESAR V was built according to these specifications. However, the TELESAR V system was not evaluated before and the accuracy of perceiving distance and size has to be found. In addition, the position errors and velocity limitations might cause invalid operator’s eye to robot eye vector during high speed motion. Thus, it will result in giving a wrong perception with over time.

4.1.1 Operator vs. Robot Eye Tracking Accuracy

In order to obtain visual inspection accuracy first, the operator vs. robot eye tracking accuracy, latency and performance measurements was found. If the operator only changes the head orientation, it was found that the speed of 3DOF head was enough to follow the trajectory. But when the user moves his upper body (spinal movements) there will be multiple joints used and therefore it was expected to be increasing the delay. In this evaluation, the goal was to find out the maximum speed that the operator can move his head where no significant motion lag can be felt.

First, the slave robots head and body was tracked with a pre-programmed trajectory which represents a half circle of 100mm radius where z (height) is kept static at the robot’s home position. The center of the circle was programmed to be the location of (-390,0,1266) coordinates. Fig. 4.1 shows the target eye trajectory (half circle) vs. robot real time trajectory. According to the robot body specification, the theoretical speed limit was found to be $15\text{cms}^{-1}$ when drawing a circle of 100mm radius. However, when the speed is increased over time, a lag started to occur and it got increased over time. Fig. 4.1 shows a $0.11\text{ms}^{-1}$ speed tracking accuracy where a 200ms lag was induced. However, at this speed there was a 200ms delay. As an concluding, it was found that in order to track the operators eye without any delays the maximum body motion speed
4.2 Reaching Accuracy

With visual inspection accuracy satisfied, next the reaching accuracy has to be satisfied in order to have an accurate reaching motion. In this step, it is important to track the operators arm with a certain position accuracy and to keep a very low latency to provide the sensation of one’s own hand during teleoperation. A simple test was carried out and tracking accuracy, mechanical latencies, maximum velocity was found.

4.2.1 Operator vs. Robot Eye-to-Hand Tracking Accuracy

A compass like apparatus was given to the operator to draw a perfect circle on the work space. The radius was fixed at 150mm and the circle was drawn on
4.2. Reaching Accuracy

x-y plane. Fig. 4.2 top shows the data logged on x-y plane and operators head, right hand, target head, hand position (kinematic solver) and robot head, hand (robot) position data in absolute coordinates. Bottom graph shows the same information when seeing from x-z plane. Operator was asked to move with three speeds slow, medium and fast. Fig. 4.2 (top) shows the speed that resulted a lag in the trajectory. At this point, the operator was drawing the circle at a speed of $20 \text{cms}^{-1}$.

As can be seen from the graphs, operators head was slightly moved. However, user was able to draw a perfect circle on x-y plane with a radius of 150mm. Note that the graph was shrink to fit the page so that it is not visible as a circle. As can be seen on Fig. 4.2 top, the target circle is little bit wider on one side. This is due to the tracking marker installation placement. For example, right hand marker was placed outside the hand and the coordinate frame is shifted 67mm (-x) back and 20mm (-y) before fetching to the kinematic solver. However, the data logged in this evaluation does not contain the coordinate frame shift and it was shown as a circular shift.
4.2. Reaching Accuracy

Theoretically if there was no mechanical latencies and position errors, target trajectory should match robot trajectory. However in Fig. 4.2, it can be seen that there is a noticeable tracking error on x and z-axis. Table. 4.1 shows the exact error analysis results of the right arm.

Table 4.1: X, Y, Z Axis Position Error for Right Arm

<table>
<thead>
<tr>
<th>Axis</th>
<th>Avg(mm)</th>
<th>PMax(mm)</th>
<th>NMax(mm)</th>
<th>SD(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>-7.40</td>
<td>43.09</td>
<td>-64.71</td>
<td>26.68</td>
</tr>
<tr>
<td>Y</td>
<td>-1.86</td>
<td>46.77</td>
<td>-61.85</td>
<td>29.74</td>
</tr>
<tr>
<td>Z</td>
<td>6.87</td>
<td>110.04</td>
<td>-50.08</td>
<td>43.84</td>
</tr>
</tbody>
</table>

According to the Table. 4.1, y-axis has the minimum average error where as z-axis has the maximum positive error. It was important to understand what causes this error on the x and z-axis. In addition, the cause of the error and the detailed analysis could be used in the next iterations of the robot development to improve the position error. Therefore, a further investigation was carried out.

Position Error vs. Time

In the previous experiment it was found that there was a 110mm positional error at a speed of $20\,cms^{-1}$. However, this experiment was done on x-y plane and z axis was kept static. However, in ordinary manipulations, operator uses ll 3 planes. Therefore, in order to understand the exact error, a common trajectory which involves movements in all 3 axis was chosen. The operator was asked to draw a square trajectory on x-z plane which is about $30^\circ$ tilted.

Fig. 4.3 shows the generated target trajectory based on the user arbitrary drawn trajectory vs. robot real-time trajectory. As can be seen on Fig. 4.3 when moving up and down the tracking creates a considerable position error and also a time lag. However, with 3D representation of the trajectory it is difficult to understand the cause of error. Therefore, the same trajectory was plotted in x-y and x-z planes as below.

As shown in Fig. 4.4 top there is a 48mm lag in z axis when moving at the speed
4.2. Reaching Accuracy

Figure 4.3: Trajectory on x-z plane with $30^\circ$ tilt

Figure 4.4: x-y plane and x-z plane view, Drawing a Square
4.2. Reaching Accuracy

of 20\(\text{cms}^{-1}\) up. Also as seen on the bottom figure there is a small lag on the x-axis as well. The large error cause in z-axis causes the entire trajectory to shift. Therefore, to identify the exact error values in z-axis, the trajectory as seen from z-axis over time was plotted.

![Figure 4.5](https://example.com/figure4.5.png)

**Figure 4.5: Z axis Error vs. Time**

As shown in Fig. 4.5 trajectory over z-axis is lagging 180ms. As can be seen from Fig. 4.5 bottom, the error increases when the trajectory moves on z-axis either up or down. This seems like an issue with shoulder joint which moves mostly to compensate position errors caused in z-axis. For further analysis each axis with time vs. error was plotted.

As shown in Fig. 4.6, average errors on each axis can be seen minimum on y-axis. x, and z axis error mostly seems considerable level. However, if compared to Fig. 4.6 there were much error on y and z axis compared to x axis. In addition, the standard deviation of error on x is 10.12mm which is considerably very low. Axis y and z has maximum positive errors of 38.57mm and 36.82mm and negative maximum errors of -47.98mm and -42.87mm respectively. As can
4.2. Reaching Accuracy

be seen on Table. 4.2 the highest standard deviation error was on z-axis. It is also noticed that when the speed is increasing the z-axis error becomes higher where as other two axis seems fairly low increments. Thus a 20\(cms^{-1}\) speed is the highest speed that can consider to be tracking the target with the accuracy of nearly 40mm error on z-axis.

Table 4.2: X, Y, Z Axis Position Error for Eye-Hand Vector

<table>
<thead>
<tr>
<th>Axis</th>
<th>Avg(mm)</th>
<th>PMax(mm)</th>
<th>NMax(mm)</th>
<th>SD(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>7.52</td>
<td>28.74</td>
<td>-11.82</td>
<td>10.12</td>
</tr>
<tr>
<td>Y</td>
<td>0.84</td>
<td>38.57</td>
<td>-47.98</td>
<td>17.69</td>
</tr>
<tr>
<td>Z</td>
<td>-3.84</td>
<td>36.82</td>
<td>-42.87</td>
<td>19.40</td>
</tr>
</tbody>
</table>
4.2. Reaching Accuracy

4.2.2 Tracking Velocity vs. Time

The same trajectory was plotted for velocity. Fig. 4.7 shows the generated target velocity curve vs. tracked robot velocity. Note that this velocity is the end effector velocity. Target velocity is shown in black whereas tracked robot velocity is shown in red color. It is clearly visible that the robot is following the target velocity curve with a time lag. Furthermore, it can be seen that the z-axis target velocity cannot be reached by the robot. Thus, it was confirmed that the velocity limit was the main cause to have the position error on z-axis and lag between the target and robot trajectories.

![Graphs showing target vs. robot end effector average velocity](image)

Figure 4.7: Target vs. Robot End Effector Average Velocity

Based on the data above, the maximum, minimum and average velocities were calculated that can be produced by the robot arm. However, it has to be noted that the maximum and minimum velocities calculated here are based on the instantaneous velocity produced on each cycle so that it does not represent the resultant velocity of the end effector.

Table 4.3 shows the target and robot instantaneous velocity over the square
4.2. Reaching Accuracy

Table 4.3: X, Y, Z Target and Robot Average, Instantaneous Velocity

<table>
<thead>
<tr>
<th>Axis</th>
<th>Avg($ms^{-1}$)</th>
<th>PMax($ms^{-1}$)</th>
<th>NMax($ms^{-1}$)</th>
<th>SD($ms^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-Target</td>
<td>0.02</td>
<td>1.49</td>
<td>-1.74</td>
<td>0.11</td>
</tr>
<tr>
<td>Y-Target</td>
<td>-0.03</td>
<td>4.64</td>
<td>-3.96</td>
<td>0.39</td>
</tr>
<tr>
<td>Z-Target</td>
<td>0.02</td>
<td>6.09</td>
<td>-6.57</td>
<td>0.43</td>
</tr>
<tr>
<td>X-Robot</td>
<td>0.02</td>
<td>2.26</td>
<td>-3.09</td>
<td>0.18</td>
</tr>
<tr>
<td>Y-Robot</td>
<td>-0.02</td>
<td>4.91</td>
<td>-4.92</td>
<td>0.47</td>
</tr>
<tr>
<td>Z-Robot</td>
<td>0.01</td>
<td>4.95</td>
<td>-4.83</td>
<td>0.45</td>
</tr>
</tbody>
</table>

drawing trajectory. This table shows that the operator is moving at an average speed of $20cms^{-1}$ on x-axis, $30cms^{-1}$ on y-axis and $20cms^{-1}$ on z-axis. However, the robot only can follow the x and y axis where z-axis seems to be $10cms^{-1}$ is the maximum. It can also see the maximum instantaneous velocity produced by the robot arm does not permit to reach the target speed due to the hardware limitations.

4.2.3 Operators vs. Robot Eye-to-Hand Error, Joint Space

TELESAR V arm was built with different configuration DC motors in order to make the mechanical design closely equal to the size of an ordinary human. In contrast stiffness, friction, coefficients are different from each joint. Position errors can happen due to joint errors or setting time delays. But it is necessary to have a smaller settling time for the entire trajectory for a given target. Thus, joint space was further analyzed to find out what joint(s) are causing error and to measure the joint specifications.

Target vs. Robot Joint Angle

In this analysis, the same free space drawn square trajectory (Fig. 4.3) with an average speed of $20cms^{-1}$ was used. Furthermore, joint torques were plotted together with joint tracking as well.

Fig. 4.8 shows the target angle vs. robot angle on the joints J1 to J6. Even
though there are 7 joints, for clarity, only first 6 joints were plotted. However, the joint analysis was carried out on all 7 joints and a summary of results can be found later in the section. As can be seen on Fig. 4.8, except for J1 and J4, all other joints were stable and following the target joint angle. J1 has a 200ms delay on some positions of the trajectory.

It was found that the mechanical delay caused in J1 was due to having high harmonic drive gear ratio. In addition, J4 was directly driven and it is over driven from 9V to 12V in order to get the speed. However, since it is direct driven and consumes much torque, it seems like during the required speed it will overshoot a lot. This caused the error or J4.

J1 resulted an average angle error of $0.82^\circ$ (degrees) where as J4 resulted a $1.81^\circ$ (degrees). However, the maximum error reported on J1 was $4.37^\circ$ (degrees) where as J4 reported an error or $6.33^\circ$ (degrees). Highest standard deviation error joint was J4 which resulted $2.4^\circ$ (degrees). J5, J6 and J7 resulted very low error and standard deviation was less than $1^\circ$ (degrees). Summary of Joint

![Figure 4.8: J1 - J6 Joint Space Tracking Error vs. Time](image-url)
4.2. Reaching Accuracy

analysis results can be found on Table 4.4

![Graphs showing joint errors and torques over time.](image)

*Figure 4.9: J1 - J5 Individual Joint Error, Joint Torques vs. Time*

To further understand if the joint space errors were occurring due to insufficient motor torques or joint friction, joint torques were examined. Fig. 4.9 shows the joint space and torques for the first 5 joints as last two joints do not have much error to consider. Theoretically according to the specification, J1 can provide 46.8mNm stall torque which will result in a maximum 23.4mNm torque. Considering the efficiency of harmonic drive gears and other friction (efficiency of 85%) practical maximum torque will be 19.89mNm. However, according to Fig. 4.9 J1 goes to a maximum of 15mNm but it cannot recover the joint error. This shows that J1 is almost driving at it’s maximum power. But the generated angular velocity is not sufficient to keep the tracking where the velocity is more than $10\text{cm/s}^{-1}$. This can be further seen on Fig. 4.9 J1 graph where the error becomes very low when J1 is working at higher torques. But simply when the velocity increases it is not possible to provide the necessary angular velocity.

In case of J4, Torque increases when the error becomes higher. i.e J4 tries to
4.2. Reaching Accuracy

Stabilize over time due to higher joint angle error, but again the motor cannot provide the speed. However, the maximum torque output by J4 seems to be less than the maximum stall torque. Thus, it seems like the motor current limits can be further increased. However, when the drive currents was increased J4 became more unstable due to direct driven mechanism. In future this issue could be addressed with a different current control algorithm where it will consider the joint velocity to determine the output current.

Table 4.4: Target vs. Robot Joint Angle Error

<table>
<thead>
<tr>
<th>Joint</th>
<th>Avg(° Deg)</th>
<th>PMax(° Deg)</th>
<th>NMax(° Deg)</th>
<th>SD(° Deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>-0.82°</td>
<td>4.37°</td>
<td>-3.35°</td>
<td>1.33°</td>
</tr>
<tr>
<td>J2</td>
<td>0.13°</td>
<td>3.01°</td>
<td>-2.90°</td>
<td>1.62°</td>
</tr>
<tr>
<td>J3</td>
<td>0.07°</td>
<td>2.11°</td>
<td>-2.44°</td>
<td>1.05°</td>
</tr>
<tr>
<td>J4</td>
<td>1.81°</td>
<td>6.33°</td>
<td>-4.19°</td>
<td>2.40°</td>
</tr>
<tr>
<td>J5</td>
<td>0.29°</td>
<td>1.22°</td>
<td>-0.56°</td>
<td>0.35°</td>
</tr>
<tr>
<td>J6</td>
<td>-0.001°</td>
<td>2.90°</td>
<td>-2.09°</td>
<td>0.83°</td>
</tr>
<tr>
<td>J7</td>
<td>-0.001°</td>
<td>1.79°</td>
<td>-1.37°</td>
<td>0.62°</td>
</tr>
</tbody>
</table>

The kinematic solver can produce a valid target trajectory at a rate of 1KHz. This will be transferred to the hardware PC via a network and still it provides a 1KHz update rate over the network. Thus any lag would happen in the robot dynamics. As the conclusion, TELESAR V can maintain a position accuracy of 7.52mm when the body and arm is independently moving at a rate of 10cms$^{-1}$. This position accuracy is more than enough to not detected by a human when using in a remote teleoperation. The main cause of the delay is due to J1 high gear ration and J4 being consuming higher torque compared to the limited current. Since J1 being the first link joint of a 720mm arm, even a slight joint angle error on J1 will create a big end effector position error. For example 1° error on J1 will result a 12mm position error at the end effector.
4.3 Grasping Accuracy

4.3.1 Operators vs. Robots Fingers Posture Tracking Accuracy

With 14 DOF master glove and 15 DOF slave hand it is possible to mimic the human hand in various ways. In order to find out the effectiveness of the finger mapping algorithm on multiple users’ hand, a random grasping test with 4 users were carried out.

Fig. 4.10 shows 9 counting examples that the operator hand is 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. 4.10, 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 and all open fingers can be performed. These gestures are quite common on existing robots with pre-programmed trajectories. However the ability to perform repeated gestures in a dynamic manner was very helpful in telexistence manipulations as dexterity of hand will help the operator to perform manipulations much easily.

Figure 4.10: Counting Examples of TELESAR V Hand
Next, the finger calibration algorithm accuracy over different length finger was examined over the same users. A finger-finger pinch task was used to evaluate the correct fingertip position mapping. As for the first step, user was calibrated before connecting to the robot. He was then asked to check the thumb and index finger pinch position. Some users initial trial was not accurate as the calibration was not successfully performed. Therefore the finger calibration was performed while connected to the robot and test again. Approximately with 3 calibrations users were able to pinch with thumb and index finger and position estimation algorithm results were promising.

![Figure 4.11: 2 Finger, 3 Finger Pinching, Rolling Examples of TELESAR V Hand](image)

Next, with the same calibration, user was asked to do middle to thumb pinch. As shown in Fig. 4.11 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, thus this was negligible. For each finger combination, 10 repetitions was performed and the accuracy was acceptable.

During the previous experiment, it is also found that the operator even can roll his 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. 4.12. 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. 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 tasks as he wish.

Figure 4.12: 2 Finger, 3 Finger Grasping, Rolling Examples of TELESAR V Hand

4.4 Reaching and Grasping with Eyes Closed

4.4.1 Visual Inspection, Reaching Success vs. Grasping Success

It was found that in TELESAR V, if the operator is moving at the speed of \(10 \text{cm/s}^{-1}\) or less it is possible to maintain tracking accuracy without any lag. In other words, it is possible to have a correct visual inspection, reaching and grasping accuracy within this speed limits. The specification of the visual system was made according to the previous findings and should perceive a correct distance. However, in TELESAR V the perception accuracy, reaching and grasping accuracy when using real objects was unknown.

An experiment with 9 subjects (6 male, 3 female) was conducted to test the perception accuracy, reaching and grasping accuracy for the first time users. 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. but however only 7 subjects have had used HMD’s. 3 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 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 step was repeated (max 3 times) until the correct posture is mapped. As shown on Fig. 4.13 red rectangle an object (125mm × 100mm) on the remote side was placed exactly 500mm apart from the subjects body, and 200mm down the eye level. Then subjects were given a training period so that they can adjust to the dynamics of the robot body via their body schema. This step was repeated until they could successfully reach, grasp and lift the object up from their right hand. Next,
4.4. Reaching and Grasping with Eyes Closed

subjects were asked to position their head (roll, pitch, yaw) so that they can see the whole object clearly and in a comfortable manner. They were restricted for going closer, or back as well as sides. 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.

Next the same steps was carried out, but they were allowed to move their body in x-axis. i.e going closer or far apart and 3 trials were carried out. Finally, they were not restricted to any posture, and were asked to go in to any posture and perform the same steps. The trajectories were logged and plotted. Fig. 4.13 shows 4 random posture samples from the subjects where Black circle denotes the robot head, red rectangle denotes the object placed in (0, 500) coordinates. Initial position of the robot head should be (0,0), and the subjects different postures various arm reach trajectories can be seen on Fig. 4.13.

Figure 4.14: Reaching Success vs. Grasping Success of 9 Subjects

As shown in Fig. 4.14(left) the experiment results for head (roll, pitch, yaw) freedom. The reaching accuracy was found as 89% and grasping success of 63%. Fig. 4.14(middle) shows when the subjects were given freedom in head, closeup/far-apart and reaching accuracy was found as 96% and grasping success of 74%. When full upper body freedom was given, as shown as in Fig. 4.14(right), reaching accuracy was found as 93% and grasping success of 63%. Overall results
4.5 Network Performance

proved 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 the go closer the grasping accuracy was increased. However when they were given full freedom, some subjects were unable to perceive the size of the object because they were too close. It can further say that even the body posture is correctly represented, there might be differences in the fingers when the posture changes and since there is no feedback mechanism they were unable to confirm the reach when no visual is provided. As the conclusion, 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.

4.5 Network Performance

Network infrastructure and the performance measurements are not directly associate with the body schema transfer model. However, as described in the data delivery section in the Implementation Chapter, TELESAR V uses closed LAN network for transferring data between PC’s. Therefore the overall system latency depends on the network performance and thus it affects the tracking performances of head, body, arm and hand.

4.5.1 Node vs. Network Load over Time

TELESAR V, system consists of 3 network node types. i.e Master, Server, Client. Master will capture all the body movements, finger movements. Server will take the captured data and generate joint space, and also retrieve the robot real time information, sensor information and distribute among all clients. Clients are only receiving data and is used on the hardware PC, Simulator PC, Help Wizard PC etc. Every network communication is carried out at a constant speed of 1KHz and the sending and receiving speeds were verified in the implementation stage. A typical network data packet consists of approximately 650 Bytes of data.
4.5. Network Performance

All intra-communications were done in UDP Multicast datagrams so when the clients joined the multicast group, network load is handled by the network layer without burdening the CPU usage. To test the performance we conducted a network data rate analysis when the clients are incremented gradually. We measured the server to clients data rate (joint data, sensor data, status data) and the results showed that the server has a steady transmit data rate of 653.23 KB/s and a steady receive rate of 903.02 KB/s during the clients were increased from 1 to 4.

![Network Load Graph](image)

Figure 4.15: Master, Server and Client Network Load over Time

Next the required network throughput between master, client and slave workstations were examined. Average data rate for 2s periods were logged on master and slave side for 60s. As shown in Fig. 4.15(a) transmit and receive data rates were measured on the master side. Master side is sending the posture data (body, arms, hands, fingers) at a steady rate of 206.98 KB/s and at the same time it receives processed joint data, status messages and real-time information from all other clients at a rate of 652.98 KB/s. Next as shown on Fig. 4.15(b), server receives the posture data from the master as well as the realtime joint data from the robot hardware through hardware client at a rate of 903.02 KB/s. After
4.5. Network Performance

processing, joint data and sensor data is sent to all clients at a rate of 653.23 KB/s. Finally as shown on Fig. 4.15(c) clients will only listen to the multicast data. It contains target joint, robot joint data, sensor data, and status messages sent internally to other PC’s. Clients will receive data at a rate of 653.02 KB/s.

Table 4.5: Master, Client and Server Network Throughput Summary

<table>
<thead>
<tr>
<th>Axis</th>
<th>Average (KB/s)</th>
<th>Max (KB/s)</th>
<th>Min (KB/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master Tx</td>
<td>206.98</td>
<td>207.02</td>
<td>206.90</td>
</tr>
<tr>
<td>Master Rx</td>
<td>652.98</td>
<td>653.03</td>
<td>652.80</td>
</tr>
<tr>
<td>Server Tx</td>
<td>653.23</td>
<td>653.97</td>
<td>653.05</td>
</tr>
<tr>
<td>Server Rx</td>
<td>903.02</td>
<td>903.40</td>
<td>902.83</td>
</tr>
<tr>
<td>Client Tx</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Client Rx</td>
<td>653.02</td>
<td>653.03</td>
<td>653.01</td>
</tr>
</tbody>
</table>

According to Table 4.5 it shows that in order to isolate this system over Internet it will require a minimum bandwidth of 653.23/206.98 (TX/RX) KB/s assuming that the server processing is done on the robot side locally. This shows that the system can operate with the same performance over the Internet if the bandwidth is about 1MB/s up/down link. Having a 1MB/s Internet connection is not rare these days. However currently audio and video is transmitted locally from the slave to user side without using network connection. Typically this will take the most bandwidth out.
Chapter 5

Evaluation of Body Schema, Results

5.1 Body Schema Experience in TELESAR V

The body schema transfer system “TELESAR V” was technically evaluated in the previous Chapter. Based on the technical evaluation, speed and velocity limitations, position error, accuracy, and other specifications of the system was found. Furthermore, with 9 participants (first timers) system’s visual perception, reaching and grasping accuracy was found. In addition, most subjects found that the size and shape of the object is easy to perceive and an accurate reaching and grasping can be achieved when the object was placed between 400mm - 500mm from eye. Humans naturally feel some quality of body schema due to the visual-kinesthetic coherent relationship when when they manipulate their body directly. However, it is unknown that what will be the quality of body schema experience in telexistence manipulations.

When non-expert users manipulate tools, it requires some time to practise. Once he or she has practised, the training will remain in their body schema so that the subsequent usage of that tool is seamless. Thus, body schema is a illusion of one’s full body representation in space. Ideally, if the body schema was transferred to the robot, a user should be able to manipulate their body in remote place without any practise. This experience of your body in space is actually the most simple and fundamental experience for feeling to be someone else at somewhere else.

If the quality of full upper body visual-kinesthetic coherent correlation provided by telexistence systems and other general teleoperation robots can be compared
under a standard index, the advantages of telexistence systems and the multi DOF dexterity can be evaluated. The multi DOF (53) synchronized in Telexistence allows the operator to pose in any posture and frees him from any limitations. This allows him/her to represent the same body schema in the remote space and therefore it will significantly increase the performance over any other teleoperated robots. Secondly, if the body schema is matched correctly, users will be able to perform tasks even without vision. For example, when using a hammer or tennis racket, user does not concentrate on the tool position, or how it is connected to the body. Instead, he can feel an extended body schema and therefore can use the internal body schema to position with accuracy.

Two approaches have been taken to prove the above. First, an objective evaluation method with two experiments is used to prove that the TELESAR V system’s higher DOF advantage over existing robots. Secondly, easiness to transfer the body schema, time taken and the error rate when transferring body schema was evaluated. Next, the effectiveness of body schema to teleoperations and quality of body schema experience was further discussed through qualitative observations, questionnaires and some unique tasks that the robot can perform. With some case studies, how the subjects perform manipulations without prior training, eye-hand coordination and effectiveness of different subjects with various backgrounds was studied and discussed.

5.2 Objective Evaluation

The advantages of multi DOF synchronization for flexible postures, maintaining correct eye-to-hand coordination was evaluated under the objective evaluation. Furthermore, with a psychological experiment the quality of the body schema transfer experience and the body schema transfer error was evaluated. To find out the advantage of multi DOF synchronization, initially the full upper body was considered. However, it is obvious that most robots have more than 6 DOF arms and 3 DOF head. In addition, unlike most teleoperated robots TELESAR V has it’s unique spinal movements and this allows the operator to move into any posture with full upper body. There are higher dexterity hands in teleoperation robots. However, they are not fully controlled in a tele-manipulation
5.2. Objective Evaluation

manner, but vision and hard coded algorithms were used for correct reach angles and grasping. Therefore, the multi DOF hands synchronized with same hand postures of the operator in TELESAR V is an advantage over other existing teleoperation robots.

To compare the performance of teleoperated robots and standard telexistence robots a standard “Peg-in-Hole” test also referred to as “PiH” was conducted. According to previous research findings [72–78], it is known that the force feedback gives significant performance increment for teleoperation manipulations. Therefore, a standard PiH test could be used as a way to compare telexistence robots with state-of-the art teleoperation robots and prove that if there is a significant performance increment in telexistence systems such as TELESAR V.

5.2.1 High Precision Peg-in-Hole Insertion Task for Telexistence Performance Evaluation

The goal was to find out a performance index for TELESAR V telexistence robot and compare with existing teleoperated robots. Hannaford. et al. [72] has used the telemanipulator of NASA JPL Teleoperation Laboratory to prove that their system has a significant performance increment over previous work [73–76] when using force feedback. Therefore, if the TELESAR V system can be compared only with Hannaford. et al. work [72] it is the resultant of comparing all previous works. Therefore, the previous work [72] is being used as a reference to the experiment done for telexistence robots in this thesis. Notations of “Teleoperation-FFB” and “Teleoperation-NFFB” were used to represent the referred teleoperation systems with force feedback and non force feedback hereafter.

To compare the results of TELESAR V PiH to teleoperation-FFB and teleoperation-NFFB it is necessary to follow the standard PiH experiment with the same experimental conditions of the previous work. Table 5.1 shows the comparison of PiH parameters used by referenced work [72–76]. Therefore, TELESAR V PiH parameters were carefully chosen so that it matches with the previous references, and also it can be defined as High Precision Peg-in-Hole insertion task to so that it can be compared with teleoperation-FFB and teleoperation-NFFB previous
5.2. Objective Evaluation

Table 5.1: PiH Parameter Comparison of Referenced Work [72]

<table>
<thead>
<tr>
<th>Reference</th>
<th>Hole Size (mm)</th>
<th>Peg Size (mm)</th>
<th>Clearance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>[73]</td>
<td>50.8</td>
<td>25.4 - 50.6984</td>
<td>0.335</td>
</tr>
<tr>
<td>[74]</td>
<td>25.4</td>
<td>6.35 - 24.9936</td>
<td>0.621</td>
</tr>
<tr>
<td>[75]</td>
<td>64.77 - 318.516</td>
<td>64.516</td>
<td>1.970</td>
</tr>
<tr>
<td>[76]</td>
<td>29.5 - 38.6</td>
<td>25.4</td>
<td>0.341</td>
</tr>
<tr>
<td>Referred [72]</td>
<td>25.4762 - 25.4152</td>
<td>25.3492</td>
<td>0.004</td>
</tr>
<tr>
<td>TELESAR V</td>
<td>22.0 - 23.0</td>
<td>21.5</td>
<td>0.047</td>
</tr>
</tbody>
</table>

works. Furthermore, TELEESAR V system’s H - Hole Size, P - Peg Size and CR - Clearance Ratio can be seen as shown in the Table. 5.1.

4 subjects with average age of 27 took part in this experiment and the performance was evaluated based on the completion time of the High Precision Peg-in-Hole insertion task. In the referenced work all subjects were given at least 100 hours of training and therefore with same conditions 3 subjects were chosen with at least 100 hours training. In addition, to understand the learning curve for a first time operator, 1 subject was selected with 0 training hours.

**Experiment Procedure**

A PiH matrix panel was created with similar conditions as teleoperation-FFB and teleoperation-NFFB experiment and mounted in front of the subject as shown in Fig. 5.1. The matrix follows the same saw tooth hole increment and the constant translations of 100mm. The holes were 22mm, 22.5mm and 23mm and the depth of each hole was set at 10mm. The peg is 240mm long, which of 120mm is the handle. The tip of the Peg has marked 50mm in RED and this is used to give instructions to the user on how deep to peg-in. The subject was instructed to insert the peg until the RED mark becomes invisible. The position and the plane of the PiH Matrix panel is decided based on the working plane of TELESAR V where it has average dexterity to reach all holes. The holes were given names from H1 - H9, positioning H1 at top left, H4 at middle right, H7 at
5.2. Objective Evaluation

Figure 5.1: Peg-in-Hole Experiment Setup with TELESAR V

left bottom and the pattern follows up to H9 at right bottom. To have similar translations in all movements, H6 hole was used as the default home position and the user was asked to wait at home position before the experiment starts.

Figure 5.2: Peg-in-Hole Matrix Panel

Fig. 5.2 shows a close up of the PiH matrix panel and the insertion step by a subject. The subject was briefed about the task before he sits on the master cockpit. A tracking vest, right hand glove and the HMD was given to the user.
5.2. Objective Evaluation

The correct placement of the HMD, glove and the finger fibers were confirmed before the next step. After the initial fiber, finger and body calibration, subject was connected with the robot and asked to confirm the finger calibration by pinching the thumb-index and thumb-middle fingers. Any errors in calibration was fixed at this step.

The subject was given a peg with correct orientation (peg tip pointing downwards) and ask to wait at the default home until the start cue was received. They were further instructed to peg-in, peg-out and follow next hole sequence as fast as possible keeping the peg to matrix contact at minimum. Subjects were given a preliminary trial from insertions H1 to H9 to confirm if the experiment conditions were correctly understood. Once the understanding was confirmed the experiment trial 1 was started with telexistence manipulation mode. Experiment was video logged and time coded to calculate the time between deepest insertion point from one hole to another. The telexistence mode experiment was done with 3 trials for each user, while the peg was removed and handed back at every trial. Once the 3 trials were finished, the same steps were continued with direct manipulation without using the robot. This was used as the controlled data set in the experiment.

Results

Fig. 5.3 shows the average completion time (CT) of each subject 3 trials. As can be seen, the 100 hours experienced subjects S1, S2 and S3 completion time was smaller compared to first time user S4 at the beginning. This is common as he had 0 telexistence manipulation experience and needs to adjust to the dynamics of the robot, practise etc. It is also noted that S1, S2, S3 users do have a decaying completion time curve over time from H1 → H9. But S4 has a much more decaying curve compared to experienced subjects. Besides that H3 → H4 being the saw-tooth drop from 23mm → 22mm all subjects find it as the most difficult. The second drop at H6 → H7 also shows a significant difficulty for all subjects. The H6 → H7 difficulty was improved on all subjects after they got trained during the first trial. More over if the same difficulty of holes were compared for each users, it can be seen as a learning factor.
5.2. Objective Evaluation

Fig. 5.4 shows the PiH average completion time compared with direct, telexistence, teleoperation-FFB and teleoperation-NFFB manipulations. It’s clearly shown that the average completion time of telexistence manipulation is less compared to the teleoperation. It also shows the subjects follows exactly same completion time curve in direct and telexistence manipulation. Furthermore, they go through a learning/training phase in both direct and telexistence modes. It also clear that the same difficulty hole completion time, and standard deviation (STD) had gradually decreased over time.

Being experiment conditions such as peg size, hole size, translation distance and the robot dynamics different, it was not possible to conclude that the completion time as a performance measurement. However, it can be seen that the hole vs. average completion time follows the same difficulty profile for all the test conditions and it proves that the difficulty of the tests were the same. Furthermore, it can be seen that the subjects undergoes a learning over time, while the pattern of difficulty is the same. The same experiment with direct manipulation has obviously the highest performance. It is interesting to find that the telex-
Objective Evaluation

Existence manipulation without any force feedback completion time was 4 times than direct manipulations where as teleoperation with feedback was 40 times and teleoperations without force feedback was 73 times. Therefore, the results had a significant trend for telexistence systems to perform better compared to traditional teleoperation systems.

![Graph showing Direct, Telexistence, and Teleoperation PiH Average Completion Time](image)

Figure 5.4: Direct, Telexistence and Teleoperation PiH Average Completion Time (Error Bars indicates STD)

To calculate a performance index which normalizes the effects of peg size, hole size, translation distance and the robot dynamics, a standard index “Fitts Measure Index” [74, 76] was used.

\[
I_f = \frac{1}{T} \cdot \log_2 \left( \frac{2A}{H - P} \right)
\]  

(5.1)

To compare the results of different systems, as shown in Eq. 5.1 Fitts Measure Index \((I_f)\) was calculated for direct, telexistence, teleoperation-FFB and teleoperation-NFFB manipulations. The notations of T, A, H and P repre-
5.2. **Objective Evaluation**

...sents the average completion time, translation distance, hole sizes and, peg size. Furthermore, in the referred manipulation experiments the maximum speed of 15\(cms^{-1}\) robot was used where as in TELESAR V it was 10\(cms^{-1}\). However, the average completion time of the referred experiment shows average completion task time to be 40s - 50s, where as in TELESAR V the average completion time was 4s - 6s. These differences might be due to the performance of tele-operators actual teleoperation manipulation speed being very slow due to other limitations of the system. However, the time difference is incorporated in Eq. 5.1 normalizing and calculating the Fitts Measure Index \((I_f)\).

![Graph](image.png)

**Figure 5.5: Fitts Measure Index for Direct, Telexistence and Teleoperation Manipulations**

Fig. 5.5 shows the comparison between calculated Fitts Performance Index for direct, telexistence and teleoperation manipulations. Note that according to Eq. 5.1 when the average completion time is less, the performance index is high. Thus, higher the fitts index results in a performance system. Fig. 5.5 shows that ultimate performance can be achieved with direct manipulations where as...
5.2. Objective Evaluation

teleoperation-NFFB has the lowest performance and as teleoperation-FFB has a small performance increment. It was also noted that the teleoperation-FFB → telexistence manipulations, there is a significant performance increment even though any force feedback mechanism is used in telexistence manipulations.

To conclude the results of the PiH experiment, the average completion time shows that telexistence systems has a faster, close to ideal speed when compared to the teleoperation manipulation task where as direct manipulations have the minimum completion time. However, this can be due the differences in peg size, hole size, translation distance and the robot dynamics of different systems. Thus, a performance index that normalizes the effects of those variables were used and “Fitts Measure Index (I_f)” was calculated.

The results of $I_f$ shows that the overall performance from H1 → H9 insertion can be compared if the direct manipulation is considered as 100% performance. In addition, telexistence manipulations have a performance measure of 27.9% and teleoperation-FFB of 2.1% and teleoperation-NFFB of 1.1% respectively. It can also said that telexistence manipulations have 13 times performance increment over teleoperation-FFB. Based on the results of this experiment, it was found that the method described here can be used to compare any telexistence system with different configurations.

5.2.2 Body Schema Transfer Error in Telexistence

From the previous PiH insertion task experiment it was found that the higher dexterity was important to transfer body schema experience in full upper body. Also it was found that the multi-DOF synchronization from master to slave greatly increases the remote manipulation performance. Even though the users can feel the quality of body schema, it can be due to the natural error correction when the users were provided with vision feedback. However, if the posture is exactly mapped and the perceived distance size is correct, the vision will be not important to feel the quality of body schema transfer experience. Thus, if there is no vision, it is unknown that if the users can re-calibrate their body in telexistence manipulations. In addition, if there is an error during the body schema transferring it is unknown that the amount of error and how significant it
is for teleoperations. Moreover, even with a high quality of body schema transfer experience when the manipulation object becomes smaller it is hard to perceive the size and distance information. For example, an non-expert users might touch the two fists while eyes closed. But, it will be hard to touch the two index fingers together with eyes closed.

A psychological experiment was conducted to find out the quality of the body schema and how it is perceived in human brain as explained below. The experiment was done in two conditions, direct manipulation (controlled) and telexistence manipulation and the results were further analyzed to calculate error, accuracy and perception error measurements. 4 subjects took part in this experiment and the performance was evaluated based on the position accuracy of the arm in space, ability to understand the size and different shapes when grasping and visual perception distance to remote objects.

**Experiment Procedure**

As shown in Fig. 5.6 two styrofoam cylinders (red and blue) with two different circumference sizes (65mm and 45mm) were used in this experiment. Two base stands were created to easily mount the same cylinders in user space and robot space at the same absolute position. The absolute position of the cylinder on the two spaces was confirmed at the end of the experiment by placing two cylinders (same size) on two spaces and ask the subject to grasp it. All 4 subjects were able to grasp the object at the same place synchronized in robot space as well as the user space. However, this step was performed to confirm the position of
two spaces but not as an experimental step.

The experiment started with briefing the subjects about the task before he sits on the master cockpit. The tracking west and right hand glove was given to the user. No HMD was provided at the initial step. Glove and the fibers were checked and initial fiber and finger calibration was completed by confirming with the simulator.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Direct</th>
<th>Vision</th>
<th>No Vision</th>
<th>Telexistence</th>
<th>Vision</th>
<th>No Vision</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>RED 65mm</td>
<td></td>
<td>-</td>
<td>RED 65mm</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Haptics</td>
<td>No Haptics</td>
<td></td>
<td>No Haptics</td>
<td>No Haptics</td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>Blue 45mm</td>
<td></td>
<td>-</td>
<td>Blue 45mm</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Haptics</td>
<td>No Haptics</td>
<td></td>
<td>No Haptics</td>
<td>No Haptics</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2 shows the summary of experimental conditions for the above experiment. First step of the experiment was started by placing the RED (65mm) cylinder 500mm in front and 860mm from ground. Subject was asked to grasp the cylinder with full hand. In the first trial it was confirmed that if the subject understood the rules of the experiment and was repeated until they do it correctly. Except for one user everyone understood by the explanation and no repetitions were necessary. Next, the subject was asked to close eyes while the object was removed from the space. He was further asked to imagine the object in space and grasp it with eyes closed. The above two steps were repeated with 3 trials (w/ vision - 3 trials, w/o vision - 3 trials). Next, the same steps were repeated with the Blue (45mm) cylinder. The bending data of the subject was recorded at both trials with eyes open and closed.

Next, the apparatus from the user side was removed and a HMD was provided. The body posture was calibrated and connected with the robot and asked to confirm the finger calibration by pinching the thumb-index and thumb-middle fingers. Any errors in calibration was fixed at this step until the user is satisfied.
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with the calibration. The same steps with RED and Blue cylinders were carried out in telexistence manipulation mode. Fig. 5.6(a) shows the subjects grasp the RED cylinder with vision, where as Fig. 5.6(b) shows the consecutive trial without vision and the object. The RED line shows the perception drift in z axis, and green line shows how that perception drift will be affected in the robot.

A LCD display was placed on the experiment setup and the subject’s right eye was duplicated. This was used to confirm if the vision is ON or OFF during the experiment. A black screen was posted to the subject when the remote vision is OFF. The transition time from black screen to remote vision is about 1s.

Results

The arm position and finger-to-finger distance (diameter of the object) was calculated based on the logged data and it was used to measure the perception distance and diameter. Furthermore, the object in space and the perceived diameter and shape was further analyzed to understand the respective perception errors when same task was carried out in direct manipulations and telexistence manipulations. The error was calculated based on the understanding of no error during eyes open.

![Graphs showing arm position and finger-to-finger distance](image)

Figure 5.7: 65mm - Red Cylinder Position and Diameter Perspective Error

Fig. 5.7(left) shows where exactly the subjects perceive the 65mm - RED cylinder in space when eyes closed. The object position in space was shown as a circle as seen from the x-y plane (top view) and for clarity the drift of center point was plotted for all 4 subjects. Fig. 5.7(middle) shows the same results when
5.2. Objective Evaluation

seeing from x-z plane (side view). At last, Fig. 5.7(right) shows the diameter error perceived when eyes closed. The actual size of the object was shown as seen from the top view. However, the x-axis does not represent the x-axis but the diameter perceived. It was found that most users have a “-” position error in y-axis, and “+” error in z-axis. x-axis error had a balanced distribution. Furthermore, the results shows that the x-y plane position error is same in direct and telexistence mode where as z-axis (height) perception has an average 50mm shift in telexistence mode. Furthermore, users did not have much errors in diameter perception in direct manipulation where as they perceive the object to be much bigger (15mm) than the actual.

![Graph Image](image-url)

**Figure 5.8: 45mm - Blue Cylinder Position and Diameter Perspective Error**

Fig. 5.8(left), Fig. 5.8(middle), and Fig. 5.8(right) shows where exactly the subjects perceive the 45mm - Blue cylinder in space when eyes closed under the same conditions as previous. It was again found that most users have a “-” position error in y-axis, and “+” error in z-axis. x-axis error had a balanced distribution. Thus these results were not changed when the size of the object is changed. Results also showed that most users did not have much errors in diameter perception in direct manipulation where as they perceive the object to be much bigger (20mm) than the actual. Thus becoming the object smaller resulted in diameter perception error propagation from 15mm → 20mm. Therefore it was confirmed that when the target size becomes smaller, the body schema transfer error from direct to telexistence mode will increase.

Fig. 5.9 and Fig. 5.10 shows the consolidated position perception error when
### 5.2. Objective Evaluation

#### Figure 5.9: Error Propagation from Direct to Telexistence Manipulation

Seeing from x, y, and z axis for direct and telexistence modes as well as two different target sizes (65mm, 45mm). It was shown above that the position perception error in x-axis is increasing in telexistence manipulations. However the error propagation compared to the direct manipulation was approximately 4.9 times. The perception error in x-axis is distributed evenly so that there is no bias. It was also found that when the target becomes smaller, the error in x-axis sightly increased in direct manipulation as well as in telexistence manipulation. This can be considered as a training and body schema re-registering as the position was not changed in x-axis for different target size.

It was also found that the position perception error in y-axis was increased approximately 1.6 times in telexistence manipulations. When the target size was changed, the error became more lower up to 1.2 times. When the target size is reduced the error in telexistence manipulation was increased. This can be also the training effect. However, it was interesting to find that unlike x-axis, the perception error was biased towards a “-” error in both direct and telexistence manipulation modes. Since this bias is common for direct and telexistence manipulations it is not considered as a body schema transfer error, but rather a body schema building error.

It was also found that the position perception error in z-axis was higher similar to x-axis. The position perception error was increasing in telexistence manipulations approximately 3.6 times and when the target becomes smaller the error was
5.2. Objective Evaluation

The average position perception error for direct manipulation on each axis was found to be x-axis -4mm, y-axis -11mm and z-axis as 6mm where telexistence manipulation resulted in x-axis -24mm, y-axis -15mm and z-axis as 44mm. The “-” error in y-axis showed that the users were reluctant to push towards the object and they always stop before it reaches the target. This might be due to not having haptic feedback to confirm the object touch. The “+” shift in z-axis was due to the low vertical field of view. It was found that, even when in direct manipulations, when the subject was asked to hold the arm and look down, their arm naturally moves a bit up. This is due to not having a reference
5.2. Objective Evaluation

in space at that point. Furthermore, if the subject was asked to use two hands and look down, due to the reference hand this shift does not occur. Therefore, being the HMD FOV less than ordinary human vertical FOV, subjects tend to look more down to look at the same place in remote environment. Thus, to re-calibrate their body schema, the head tilt was important factor as well. Thus the results of this experiment can be concluded as the operators body schema can be transferred with an certain accuracy which the error is not so significant for real world manipulations.
## 5.3 Subjective Evaluation

### 5.3.1 Qualitative Observations

The advantage of body schema transfer model can also be evaluated subjectively. Up to date the system was tried with more than 100 individual first time users during demonstrations, lab visits, press releases and also television coverage events which is listed under the Appendix A. To try and operate an ordinary robot requires practise. However, the users who tried the system was able to use the TELESAR V system with 2 or 3 minutes of training. This also confirms that the effectiveness of this method is useful to reduce the training time.

In addition, it was interesting to find that subjects who had physical training (sports) can adjust to the system with much lesser time and for any first timer manipulating tools was a easy task. However, there were some subjects having trouble sensing the correct perspective distance and unable to manipulate tools until they get used to the environment. But the majority of the first timers had success manipulating tools in their first time.

<table>
<thead>
<tr>
<th>Question</th>
<th>Variable</th>
<th>Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>mybody</td>
<td>I felt as if the arms I saw in the virtual world were my arms.</td>
</tr>
<tr>
<td>Q2</td>
<td>mybody</td>
<td>I felt as if the hands I saw in the virtual world were my hands</td>
</tr>
<tr>
<td>Q3</td>
<td>control</td>
<td>I felt like I controlled the avatar robot as if it was my own body.</td>
</tr>
<tr>
<td>Q4</td>
<td>notime</td>
<td>I felt like the avatar robot was not me.</td>
</tr>
<tr>
<td>Q5</td>
<td>liked</td>
<td>I liked being able to control the movements of the avatar robot.</td>
</tr>
<tr>
<td>Q6</td>
<td>wanted</td>
<td>I wanted to touch objects as I saw them.</td>
</tr>
</tbody>
</table>

A cup pouring manipulation where subject was asked to pour the glass balls
from one cup to another was conducted with 9 subjects (6 male, 3 female). The average age was 26 (STD = 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. 3 Of them have controlled robots in the past and 8 of them had no experience of TELESAR V system. However, one subject had experience manipulating TELESAR V for a small period of time.

As shown in Table. 5.3, 6 subjective questions were asked to evaluate the body schema experience state that they had during the robot control. A 0 to 7 Scale was used for marking. The results showed that subjects agreed 78% to Q1, 76% to Q2 respectively showing that they strongly believe that the body that they control was felt as their own body. Subjects agreed 78% to Q3, showing that they strongly believe that they were controlling the robot. As a counter question with notime, only 32% subjects agreed to Q4. With a 92%, most subjects liked that they could control the robot limbs using their own limbs. Finally, with 92% agree to Q6, subjects wanted to touch the objects that they saw. The results of the evaluation showed that a deep relationship was built when they were given to do simple manipulation task during telexistence mapping.

### 5.3.2 Advanced Manipulation Tasks in Controlled Environments

![Figure 5.11: Academic Conference Demonstrations](image)

To understand the advantage of natural body motion, natural spinal movements (extending reach, stroking) and thinking in the brain and acting on the robot, few lab experiments were conducted with experienced operators. In addition,
5.3. Subjective Evaluation

TELESAR V system has been demonstrated internationally and locally for general public several times in various locations and the feedback got from the users indicated that it was very easy task to operate the robot for first timers. Not only experiencing the robot from inside, Fig. 5.11 shows that the first time operators can mimic any gesture when interacting with remote participants as well as perform complex tasks without even have to practise.

Remote glass ball pouring and stacking bricks

A remote glass ball pouring and stacking bricks experiment was conducted to understand the limitations of body schema use in general use. As shown in Fig. 5.12(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.

![Figure 5.12: (a) Ball pouring, (b) stacking up bricks vertically](image)

Next, 3 cubes were placed (Fig. 5.12(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 extend his arm using the spinal rotation and therefore he was able to grab it without any mistake.
5.3. Subjective Evaluation

Writing Japanese Calligraphy using a brush and ink

Figure 5.13: (a) Japanese Calligraphy, (b) Completed Calligraphy

Writing characters involves thinking in the brain and output the thoughts to the pen or a brush. Humans can perform this with their built in body schema. However, it is difficult to write characters using ordinary teleoperation robots due to not having the dexterity of the upper body. In TELESAR V, with the full upper body dexterity, the operator should be able to write calligraphy. To find out the efficiency of writing characters, an experiment was conducted where the 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. 5.13(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 use of spinal rotation he could extended his body and reach the ink tank which was placed far to dip the brush with ink. Fig. 5.13(b) shows the completed calligraphy.

Manipulating small objects in denser environment

Most teleoperation robots are over sized compared to human scale. Therefore, it is sometimes impossible to manipulate tools which is build for humans. In this experiment, operator was given a Japanese Chess board (Shogi) where he has to participate in a chess game with a remote participant. The board
5.3. Subjective Evaluation

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. 5.14(a), operator was able to pick and place shogi pieces up to middle size. The second experiment as shown in Fig. 5.14(b), operator was given a pile of sticks diameter ranging from φ4mm to φ8mm. In this experiment, operator was able to use fine finger movements to grab the sticks and able to control the applied force so that the stick will not flip around during grasping.

Figure 5.14: (a) playing Japanese chess (shogi), (b) picking thin sticks

Stroking

Figure 5.15: (a) playing Japanese chess (shogi), (b) picking thin sticks

TELESAR V system was build to have haptic sensation during telexistence manipulation. However, haptics was not discussed in this thesis. Conventional teleoperation robots can stroke precisely, but the roughness of the manipulators and the rigid motion does not allow to perform a smooth stroking motion when used with manual mapping. These robots uses complex algorithms to perform
smooth stroking. But, there cannot have a body schema experience because the operator is not controlling the robot. To stroke cloths in telexistence, the robot arm, hand, and fingers should provide constant forces while the position accuracy of the stroke should be good enough not to force the cloth to smudge. As shown in Fig. 5.15, the operator was given 2 kinds of cloths, a rough and a smooth cloth. Smooth stroking was achieved in TELESAR V due to the force controlled arm and fingers, where keeping the position accuracy at a considerable range to not to smudge the cloth. Even though the tactile sensation is out of the this thesis bound, with the haptic transmission system operator was able to feel the stroking sensation and even to feel what kind of cloth is being touched.
Chapter 6

Conclusion, Limitation and Future Directions

6.1 Summary of Significant Contributions

Artificial sense of presence has been studied in the past within virtual reality technology such as teleoperations. Since then, there are systems built that can provide artificial sense of presence and they can be subcategorized as telepresence and telexistence technologies where the operator was provided with an immersive stereoscopic display, auditory feedback and the ability to move arms hands and head according to his postural changes. Similarly, in the field of psychology and neurology the concept “Body Schema”, that allows the operator to keep an up-to-date representation of the positions of different body parts in space were studied. By combining the two functional elements of body schema and teleoperations, a new experience can be defined where humans can perform remote actions with the awareness of one’s body position at any given moment.

In Chapter 1, existing technologies that provides the body schema experience is discussed. Telepresence and Telexistence robots allow having some body schema transfer experience during manipulation. However, a full upper body representation of this experience was not achieved in current systems. Moreover, it is limited to body parts such as head and arms only. Since, modelling body schema for full upper body is a complex task, a base model can be used to study the artificial body schema. In addition, depends on the complexity of the remote manipulation what sensations are needed, what body parts are needed and what are the advantages of body schema in teleoperations were not known.

In Chapter 2, body schema in context to teleoperations was defined and how
6.1. Summary of Significant Contributions

to build artificial body schema is discussed based on the body parts involved in the specific teleoperation types. For example, if only viewing, operator does not arms. However he might need spinal movements and the quality of visual and the motion lag is important. Based on the required parameters, “Body Schema Transfer Model” was defined where it can be used to model the body schema depending on the teleoperation type, what body parts involved etc.

Next, with the decided sensations how to model the cross modal perception sensation to achieve desired body schema transfer experience was discussed. Furthermore, the model is extended to model any type of teleoperation based on the sensors used and the body parts involved. By applying the above body schema transfer model, a telexistence master-slave robot system was designed.

Chapter 3 explains implementation of “TELESAR V”, a telexistence master-slave robot system to transfer body schema experience. The implementation steps, specific technical novelties, algorithms used, and a technical evaluation to find out the specifications, limitations and performance counts in the TELESAR V system was discussed.

Significant technical novelties implemented in the system can be listed as:

1. Design and development of a high speed, robust, full upper body, mechanically unconstrained operator’s posture re-construction master cockpit with inverse kinematics algorithms at a posture update rate of 167Hz (6ms)
   
   (a) Development of robust, 2 closed form numerical inverse kinematic algorithms for head, body, arm posture re-construction with 5 tracking points of the body and 14 camera based open air motion tracking system.

   (b) Development of a robust, novel 15 DOF hand posture reconstruction algorithm for reproducing the complex hand gestures and postures.

2. A scalable, network distributed and high performance robust software framework for telexistence under Windows.

   (a) State driven architecture for software developers that can be used to easily integrate different modules.
(b) High speed, hardware I/O independent, inter application message passing protocol using dynamic shared memory allocation.

(c) Network scalable, node independent, data mirroring communicator back end with update rate of 1KHz over LAN networks.

(d) Selective and effective data delivery over Internet at 1Khz update rate with minimum bandwidth using object serialization and deserialization techniques.

(e) Precise timer routines at 1KHz.

3. Design and development of 7 DOF anthropomorphic robot arm software controller with an master-slave end effector tracking accuracy of 20mm, and an error rate of \(20\text{cms}^{-1}\) during random motion trajectory.

(a) 6 DOF arm position + torque hybrid controller at 1KHz update.

(b) 7 DOF arm windows control driver with motion fading, manual joint control, joint angle tuning and many more features.

4. Design and development of 15 DOF anthropomorphic robot hand software controller to map master hand postures and slave robot hand.

(a) 15 DOF hand position + torque hybrid controller at 1KHz update.

(b) Novel hand posture mapping algorithm with custom sensors for opposition and thumb roll detection.

(c) Robot hand’s proximal and distal phalanx natural back drivability with position feedback controlled selective torque control.

Chapter 4 shows the technical evaluation results based on the visual inspection accuracy, reaching accuracy, and grasping accuracy. Thus, the speed and position accuracy, limitations, and specifications of the system were found. With 9 first time subjects system’s reaching and grasping accuracy was found. Overall results proved that the reaching accuracy was increased when the subjects were given the freedom to move with their body. Furthermore, it was found that the perception of the remote object size was accurate when the object to eye distance was in the range of 400mm - 500mm. Understanding the speed limitations,
reaching, grasping capabilities described in Chapter 4 was not sufficient to prove that the system is capable of transferring body schema in Telexistence.

In Chapter 5, to prove the effectiveness of “Body Schema Transfer Model” two conditions were considered. The multi DOF (53) synchronized in telexistence may allow the operator to pose in any posture and frees him from any limitations. Therefore the multi DOF dexterity may increase the performance of telexistence systems compared to traditional teleoperation systems. Next, the quality of the body schema that the operator feels during direct manipulations and telexistence manipulations can be different. Thus, what correlations exists in terms of quality of the body schema experience over direct and telexistence manipulations can be known. Furthermore, the body schema transfer error and the required training can be found.

Conducting a High Precision Peg-in-Hole insertion task and comparing with a standard data set, it was evidenced that the higher dexterity in telexistence systems with no force feedback will have a significant performance increment compared to conventional teleoperated robots with force feedback. This method can also be used to compare any telexistence system built with different dynamics under a common index. Furthermore, the results of PiH for telexistence experiment concluded that telexistence systems have an overall performance increment compared to teleoperated robots. If the direct manipulation is considered as 100% performances, telexistence robots have a performance measure of 28% and teleoperation-FFB of 2% and teleoperation-NFFB of 1% respectively. It can also be said that telexistence manipulations have 13 times performance increment over teleoperation manipulations with force feedback mechanisms. Even though there is a clear trend that shows a significant performance increment when using the full body synchronous motion and the correct eye-hand coordination, it should be noted that this results cannot be used as a generalized conclusion due to few subjects being used. In the future, a follow up study should be conducted with large amount of subjects and to generalize the results. Furthermore, the method here described can be used to compare any telexistence system with other systems and also different configurations.
By conducting a second experiment it was found that, non-expert subjects natural body schema error shows significant coherent relationship to telexistence mode body schema error. The body schema transfer error experiment results conclude that the operators body schema can be transferred with the accuracy of position perception error of x-axis -24mm, y-axis -15mm and z-axis as 44mm in telexistence manipulations where as the same values in direct manipulations will be -4mm, y-axis -11mm and z-axis as 6mm. The “-” error in y-axis showed that the users were reluctant to push towards the object and they always stop before it reaches the target. This might be due to not having haptic feedback to confirm the object position. The “+” shift in z-axis was due to the low vertical field of view. Thus, to re-calibrate their body schema; the head tilt is important factor as well. Thus the results of this experiment can be concluded as the operator’s body schema can be transferred with a certain accuracy, which the error is not so significant for real world manipulations. However, it should be noted that the number of subjects used in this experiments is not sufficient to normalize the 4 variables used in the experiment. Therefore, a more wide subject group should be considered as a follow up study in order to generalize the conclusion.

Up to date the system was tried with more than 100 first time users during demonstrations, lab visits, press releases, and media coverage events. The effectiveness of body schema to teleoperations and quality of body schema experience was further discussed through qualitative observations, questionnaires and some unique tasks that the robot can perform. With some case studies, how the subjects perform manipulations without prior training, eye-hand coordination and effectiveness of different subjects with various backgrounds was studied and discussed. This experience of your body in space is actually the most simple and fundamental experience for feeling to be someone somewhere.
6.2 Limitations

The effectiveness of “Body Schema Transfer Model” in teleoperation was proved in Chapter 5. However, there are several limitations from the ideal system that was proposed in Chapter 2.

First, the operator should be able to move at any speed and the robot should be able to track the operator’s body, arms, and hands at any speed. However, as found on Chapter 4, the maximum speed that the operator can move is limited to $10\text{ cms}^{-1}$. This limitation is due to two reasons. First, using the industrial manipulator PA-10 as the will normalize the motion to match the dynamics of the robot. As shown on Fig. 4.1, to accurately track the robot head and body the operator’s maximum speed should be less than $10\text{ cms}^{-1}$. Apart from the robot body, it has been found that the arm can move along its x-axis and y-axis at a speed of $20\text{ cms}^{-1}$. However, the z-axis speed is limited to $10\text{ cms}^{-1}$. This z-axis speed limit is due to the arm’s joint J1 couldn’t reach the desired angular velocity due to higher harmonic gear ratio. Currently, a mechanical upgrade is in progress to reduce the gear ratio and increase the speed on z-axis up to $30\text{ cms}^{-1}$. Therefore, in the future the operator would be able to move at much higher speeds.

Next, the finger calibration sometimes needed to be done several times to get an accurate fingertip-to-tip pinch. This is due to some users being not able to make a circle or “OK” sign with their thumb and index fingers. The algorithms could exclude the step to make a circle, but then the calibration steps will be increased. In the future, a different approach should be used to calibrate fingers.

When using the arms, hands, and body in a remote manipulation the operator was able to move his body and limbs without any mechanical constrain acting on his body. However, the dynamics of the robot body and operator is not matched and in this study it was ignored and taken a different approach of making the robot dynamics fast enough to match the operator. Faster operator movements were achieved in this work compared to previous studies. However, it is not the ultimate speed that the operator would not feel a mechanical lag. It is impossible to speed up the arm movements close to ordinary humans speed. Therefore,
counter pseudo haptics based feedback systems could be one approach to match the robot impedance to the operator impedance.

When the user grasps objects and to feel the realistic haptic sensation there should be haptic feedback. The TELESAR V system does have haptic transmission system, which provides the operator with force, tactile and thermal sensation. However, the feedback quality of the haptic in terms of building body schema was not sufficient in the current implementation. Thus, building visual-haptic and kinesthetic-haptic cross modalities was omitted in the discussion. In the future, the body schema transfer model should be evaluated with these cross modalities in order to prove the consistency of the model theory.

Operator’s vision is currently limited to a field of vision (FOV) of $H \times V (61 \times 40)^\circ$ (degrees). However, this is far below the human vision system. Recent development shows that some commercial HMD systems “Oculus Rift” provides FOV of $H \times V (110 \times 90)^\circ$ (degrees) but do not provide HD vision. Therefore in the future, TELESAR V system should include a HD and wider FOV HMD so that the operator could clearly see the remote environment and have a much more immersive experience close to reality.

Even though the TELESAR V system is capable of transferring the operator’s full upper body schema, there are several operations that require slight training. Moreover, it is not the ultimate body schema transfer experience where the operator can do any task that he did in the past by just logging in to the robot system for the first time. In this thesis the concept, advantage and the proof with implementation was provided. It was proved that the body schema experience can be provided with limitations. Therefore, in the future, a higher dexterity robot can be used to reduce the body schema transfer error.
6.3 Future Direction

“Body Schema Transfer Experience” in teleoperations enable the operator to have new experiences of perceiving the robot arms, head and fingers as his own. This will allow the user to use his muscle memories, previous learning and react to un-excepted behaviors. The outcome of this research can benefit many fields of research and industries in the near future. For example, it can be used to model teleoperation systems that requires body awareness experience based on the available sensations such as remote manipulations in hazardous sites, remote surgery, sightseeing without spending much time on travelling, micro manipulation such as biotechnology, microsurgery, micro assembly, etc.

Providing “Body Schema Transfer Experience” with a virtual environment will enable the current teleoperations to operate under time delays. There are lots of implementations to overcome time delays in teleoperations. However, knowing how to model the body schema transfer experience, the remote environment can be virtually rebuilt on the operator side. The time delays can be buffered and simulated while the real manipulation will occur with a time delay, but the operator can have a real-time sensation of manipulating in the buffered virtual environment. With a well-defined model, the real world objects and the surroundings can be virtually built, transferred to the operator so that the operator will only see and interact with the virtual environment. However with the time shifted operation will happen actually in the remote environment and based on the real-time situation the virtual scene will be updated. The operator will be able to feel that he is performing manipulations in real-time.

The contents of this thesis, “Body Schema Transfer Model” can be used as a framework to build new systems that provides new experiences and raising aesthetic qualities and operating environments. “Body Schema Transfer Experience” can be used in other disciplinary outside teleoperation giving new experience of controlling devices on personal space, games, next generation computing etc. The ultimate proposal of this dissertation aims towards creating a new type of experience where users are not afraid of interacting with personal space and feel that what they see, hear, and feel is real regardless of the provided stimuli.
6.3. Future Direction

With the new experience, people will feel engaged in activities and the enjoyment that they will have might allow them to embed the remote space to their body.
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Appendix A

List of Publications

Significant amount of materials, ideas, and results from this dissertation have previously appeared in the following peer-reviewed publications.

A.1 Journal and Conference Papers

A.1.1 International Conferences


A.2. Awards


A.1.2 Domestic Conferences


A.2 Awards

1. IROS2012, Best Student Paper Award Finalist.

2. IROS2012-ICROS, Best Application Paper Award Finalist.
A.3  Demonstrations

TELESAR V has been demonstrated at the following academic venues and more than 200 people have experienced the system.

2. JST CREST Haptic Media Symposium jointly with IVRC 2011.
5. IEEE RAS Telerobotics Summer School (IEEE/RAS Summer 2013).

A.4  Press Releases, Magazine and Newspapers

A.4.1  Press Releases

2. Telexistence Robot Avatar Transmits Sight, Hearing and Touch - TELE-SAR V. DigInfo, 2011.11.6
3. Japan Scientist Makes 'Avatar' Robot, AFP, 2012.2.11

A.4.2  Magazine Articles

2. Life and Future seen from Virtual Reality, Milsil Volume 5 No.5, p.3, 2012.9 on sale (In Japanese)
3. Feel what the Robot Touched on your Fingers, Newton 32nd volume No.13 p.13, 2012.11.7 on sale (In Japanese)


### A.4.3 International Newspapers

1. New Robot Offers up Tasks of Avatar, *The Japan Times*, 2012.2.11

### A.5 Television and Web Articles

#### A.5.1 International Television


3. Japan Created a Robot "Avatar" *POCCNR, Russian State Television*, 2012.2.17

4. TELESAR V Coverage *Jornal Nacional*, Brazil TV, 2012.3.9

#### A.5.2 International Web Articles

1. Telesar V: Telexistence Robot Avatar *Ubergizmo*, 2011.7.11

2. Telesar V: Your Next Telepresence Robot Avatar *technabob*, 2011.11.7


4. TELESAR V Wants To Be Your Robotic Avatar. *Medgadget*, 2011.11.8


7. Electric Avatar: Japanese Robot Works Like a Hi-Tech ‘Puppet’ Controlled via a Virtual Reality Suit (Telesar5) mailOnline, 2012.2.6


9. TELESAR V, Un Robot al Estilo Avatar Desarrollado en Japon alt1040, Spain, 2012.2.10

10. The Week’s Best Robot Videos: AlphaDog, Avatars, and a Death Star, Slate, 2012.2.10

11. Robo TELESAR V Quer Trazer filme Avatar Para a Realidade, TECH-MUNOO, Brazil, 2012.2.13

12. TELESAR V: Robot Antropomorfo Teledirigido robodosis, Spain, 2012.2.14


14. Telesar V: Controlez un Robot a Distance, ici Japan, France, 2012.2.16


A.6 University Research Gallery Articles and Interviews

1. Man Driving His Telexistence Robot Avatar “TELESAR V” Special Interview. ElectricTV, 2012.10.3

2. NHK TV “Manabi-ya -Learning and Living Abroad in Japan-” Special Interview. Ministry of Education, Culture, Sports, Science and Technology, GLOBAL30 Project, 2013.07.10