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Forty Years of Telexistence —From Concept to TELESAR VI

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Abstract

Telexistence is a human-empowerment concept that enables a human in one location to virtually exist in another location and to act freely there. The term also refers to the system of science and technology that enables realization of the concept. The concept was originally proposed by the author in 1980, and its feasibility has been demonstrated through the construction of alter-ego robot systems such as TELESAR, TELESAR V, and TELESAR VI, which were developed under the national research and development projects "MITI Advanced Robot Technology in Hazardous Environments," the "CREST Haptic Telexistence Project," and the "ACCEL Embodied Media Project," respectively. Mutual telexistence systems, such as TELESAR II & IV, capable of generating the sensation of being in a remote place using a combination of alter-ego robotics and retro-reflective projection technology (RPT), have been developed, and the feasibility of mutual telexistence has been demonstrated. Forty years of telexistence development are historically reviewed in this keynote paper.

CCS Concepts • ***Human-centered computing***→ Mixed/augmented reality • ***Human-centered computing***→ Virtual reality • **Human-centered computing**→ Haptic devices • ***Human-centered computing***→Telexistence

1. INTRODUCTION

Telexistence technology enables a highly realistic sensation of existence in a remote location without any actual travel. The fundamental concept refers to the general technology that allows a human being to experience the real-time sensation of being in another place interacting with the remote environment, which may be real, virtual, or a combination of both [Tachi 2015b]. It also refers to an advanced type of teleoperation system that allows an operator at the controls to perform remote tasks dexterously with the feeling of being in a surrogate robot working in a remote environment. Telexistence in a real environment through a virtual environment is also possible.

Sutherland [Sutherland 1968] proposed the first head-mounted display system, which led to the birth of virtual reality in the late 1980s. This was the same concept as telexistence in computer-generated, virtual environments. However, it did not include the concept of telexistence in real, remote environments. The concept of providing an operator with a natural sensation of existence in order to facilitate dexterous remote robotic manipulation tasks was termed "telexistence" by Tachi [Tachi et al. 1980; Tachi et al. 1981] and "telepresence" by Minsky [Minsky 1980]. Telexistence and telepresence are very similar concepts proposed independently in Japan and the USA, respectively.

However, the concept of telexistence in virtual environments or in a real environment through a virtual environment is the unique feature of telexistence. Telepresence, in contrast, indicates remote presence only in the real world. In addition, telexistence uses even an autonomous robot as its avatar [Tachi et al. 1984], while telepresence uses only a teleoperated robot.

In this keynote paper, the development of telexistence technology and telexistence systems is historically reviewed from 1980 through 2019.

2. HISTORY OF TELEXISTENCE

Figure 1 illustrates the emergence and evolution of the concept of telexistence. Teleoperation emerged in Argonne National Laboratory soon after World War II to manipulate radioactive materials [Goertz 1952]. In order to work directly in the environment rather than work remotely, an exoskeleton human amplifier was invented in the 1960s. In the late 1960s, a research and development program was planned to develop a powered exoskeleton that an operator could wear like a garment. The concept for the Hardiman exoskeleton was proposed by General Electric Co.; an operator wearing the Hardiman exoskeleton would be able to command a set of

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mechanical muscles that could multiply his strength by a factor of 25; yet, in this union of a man and a machine, the man would feel the object and forces almost as though he is in direct contact with the object [Mosher 1967].

However, the program was unsuccessful for the following reasons: (1) wearing the powered exoskeleton was potentially quite dangerous for a human operator in the event of a machine malfunction; and (2) it was difficult to achieve autonomous mode, and every task had to be performed by the human operator. Thus, the design proved impractical in its original form. The concept of supervisory control was proposed in the 1970s to add autonomy to the human operations [Sheridan and Ferrell 1974]. In the 1980s, the exoskeleton human amplifier evolved into telexistence, i.e., into the virtual exoskeleton human amplifier [Tachi and Komoriya 1982].

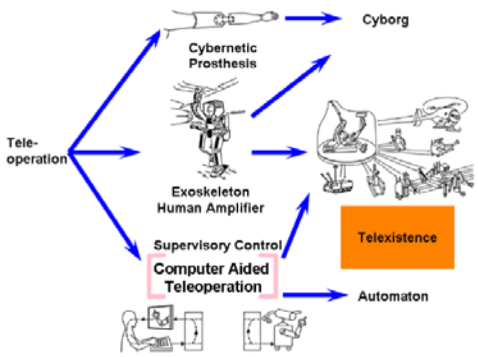

Figure 1: *Evolution of the concept of telexistence through Aufheben or sublation of contradictory concepts of exoskeleton human amplifier and supervisory control.*

In using a telexistence system, since it is not necessary for a human user to wear exoskeleton robot and be actually inside the robot, the human user can avoid the danger of crashing or exposure to hazardous environment in the case of a machine malfunction, and also make the robot work in its autonomous mode by controlling several robots in the supervisory control mode. Yet, when the robot is used in the telexistence mode, the human user feels as if he is inside the robot, and the system works virtually as an exoskeleton human amplifier, as shown in Fig. 2.

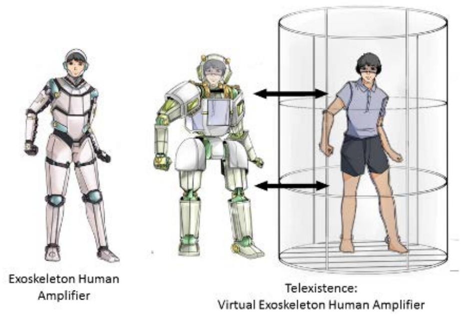

Figure 2: *Exoskeleton Human Amplifier (left), and telexistence virtual exoskeleton human amplifier (middle and right), i.e., a human user is effectively inside the robot as if wearing the robot body.*

Avatar robots can be autonomous and controlled by supervisory control mode while the supervisor can use one of the robots as his virtual exoskeleton human amplifier by using telexistence mode.

2.1 How Telexistence was Conceptualized and Developed

The author came up with the idea of telexistence while he was walking one morning in the corridor in the laboratory on September 19, 1980. He was suddenly reminded of the fact that human vision is based on light waves and that humans only use two images that are projected on the retina; they construct a three-dimensional world by actively perceiving how these images change with time. The robot would only need to provide humans, by measurement and control, with the same image on the retina as the one that would be perceived by human eyes. As he somewhat rediscovered this fact, all his problems dissipated and he started to tremble with excitement. He went back to his office immediately and wrote down what he had just discovered and all the ideas that sprang up following that discovery (Fig.3). Surprising enough, he simultaneously came up with the idea of how to design telexistence system and how to apply the technology to the evaluation of mobility aids for the blind [Tachi et al. 1980] and also to the dexterous remote manipulation with sensory feedbacks [Tachi et al. 1981].

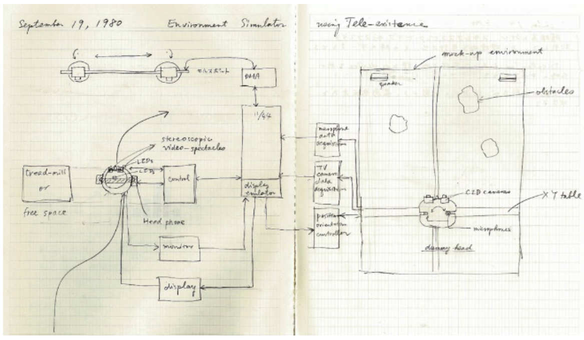

Figure 3: *Sketch of the idea when the author invented the concept of telexistence.*

2.2 Third Generation Robotics

The concept of telexistence was the fundamental principle behind the eight-year large-scale Japanese project entitled “Advanced Robot Technology in Hazardous Environments,” which was established in 1983 together with the concept of third-generation robotics. A typical potential use of a third-generation robot is as a substitute for humans in potentially hazardous working environments. These include, for example, work in nuclear power plants, underwater operations, and rescue operations in disaster areas. One type of robot system which can be used in these areas is a human-robot system consisting of several intelligent mobile robots, a supervisory control subsystem, a remote operator, and a communication subsystem linking the operator and the robots. Figure 4 shows the author’s concept of a human-intelligent robot system, which performs essential work in hazardous working environments [Tachi and Komoriya 1982].

Planning, scheduling, and task sharing operations for several robots can be handled by a supervisory controller [Sheridan and Ferrell, 1974]. Each robot sends its work progress report to the supervisory controller in a consecutive manner. The reports are compiled and processed by the supervisory controller, and selected information is transmitted to the human operator through visual, auditory, and tactile channels. The operator issues macro commands to each of the robots via a voice recognition device.

When an intelligent robot is confronted with a task which is beyond its capabilities, the control mode is switched to a highly advanced type of teleoperation, namely telexistence. Telexistence attempts to enable a human operator at the controls to perform remote manipulation tasks dexterously with the feeling that he or she is present inside a remote anthropomorphic robot in a remote environment.

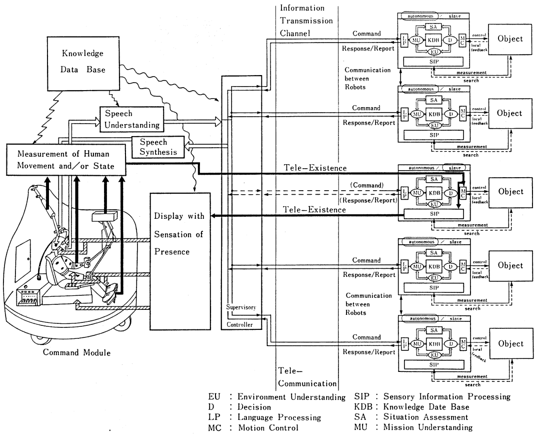

Figure 4: *Telexistence system architecture.*

2.3 First and Early Telexistence Hardware Systems

Our first report proposed the principle of a telexistence sensory display and explicitly defined its design procedure. The feasibility of a visual display providing a sensation of presence was demonstrated through psychophysical measurements performed by using an experimental visual telexistence apparatus. Figure 5 illustrates the first prototype telexistence visual display [Tachi and Abe 1982; Tachi and Komoriya 1982; Tachi et al. 1984].

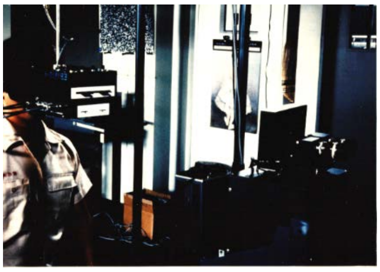

Figure 5: *First prototype telexistence visual display, which creates out-of-the-body sensation.*

In 1985, a method was also proposed for the development of a mobile telexistence system, which can be driven remotely with both an auditory and a visual sensation of presence. A prototype mobile televehicle system was constructed (Fig. 6), and the feasibility of the method was evaluated [Tachi et al.,1988].

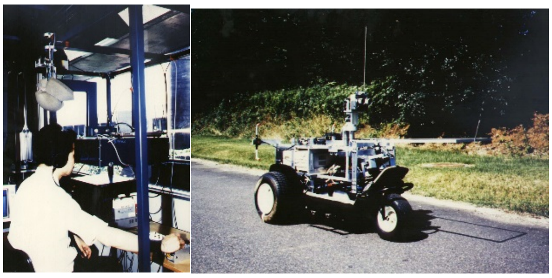

Figure 6: *Head-linked stereo display providing a sensation of driving a televehicle as if on borad the vehicle (left), and the mobile telexistence vehicle (right).*

2.4 Telexistence Surrogate Anthropomorphic Robot: TELESAR

The first prototype telexistence master-slave system for performing remote manipulation experiments was designed and developed, and a preliminary evaluation experiment of telexistence was conducted [Tachi et al. 1989].

The slave robot employs an impedance control mechanism for contact tasks and for compensating for errors that remain even after calibration. An experimental operation of block building was successfully conducted using a humanoid robot called TELExistence Surrogate Anthropomorphic Robot (TELESAR).

Experimental studies of the tracking tasks quantitatively demonstrated that a human being can telexist in a remote environment using a dedicated telexistence master-slave system [Tachi and Yasuda 1994]. Because measurements are performed using goniometers and potentiometers and all programs are written in C, the system is operated at an extremely high-speed cycle time of 3 ms, even when the operation is conducted as impedance control mode. Virtually, no delay is observed. Human operators perceive as though they were inside the robots. Figure 7 illustrates a telexistence master-slave manipulation system.

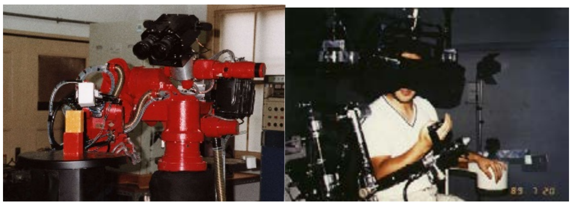

Figure 7: *TELESAR building blocks (left) and telexistence master system (right).*

2.5 Augmented Telexistence

Telexistence can be divided into two categories: telexistence in a real environment that actually exists at a distance and is connected via a robot to the place where the operator is located (transmitted reality), and telexistence in a virtual environment that does not actually exist, but is created by a computer (synthesized reality). Combining transmitted reality and synthesized reality, which is referred to as mixed reality, is also possible, and it has great significance for real applications. This is referred to as augmented telexistence, and it can be used in several situations, for instance, controlling a slave robot in an environment with poor visibility.

An experimental augmented telexistence system was constructed using mixed reality. An environment model was also constructed from the design data of the real environment. When augmented reality is used to control a slave robot, modeling errors of the environment model must be calibrated. A model-based calibration system using image measurements was proposed for matching the real environment with a virtual environment. An experimental operation in an environment with poor visibility was successfully conducted using TELESAR and its virtual dual. Figure 8 illustrates the virtual telexistence anthropomorphic robot used in the experiment [Yanagida and Tachi 1993].

Figure 8: *Virtual TELESAR at work.*

2.6 R-Cubed: Realtime Remote Robotics

In order to realize a society wherein everyone can freely telexist anywhere through a network, the Japanese Ministry of International Trade and Industry (MITI) and the University of Tokyo proposed a long-range national research and development program that was dubbed R-Cubed (R^{3}) in 1995. R^3 means real-time remote robotics. The concept of this program is the research and development of technologies that allow human operators to telexist freely by integrating robots, virtual reality, and network technology. Figure 9 illustrates an example of an R^3 robot system.

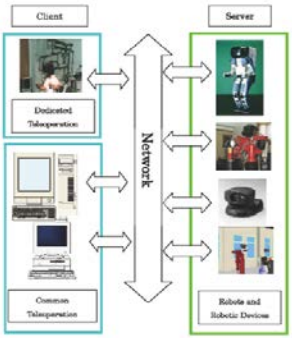

Figure 9: *Diagram for RCML and RCTP processes. Robots and control devices are placed virtually everywhere in the world and connected by Internet. Any user can use any robot when the robot is in use.*

Each robot site has a server as its local robot. The type of robot varies from a humanoid (high end) to a movable camera (low end). A virtual robot can also be a local controlled system. Each client has a teleoperation system. The system can be a control cockpit with master manipulators and a head-mounted display (HMD) or a CAVE Automatic Virtual Environment (CAVE) at the high end. It is also possible to use an ordinary personal computer system as a control system at the low end. In order to assist low-end operators with controlling remote robots through networks, R-Cubed Manipulation Language (RCML) and R-Cubed Transfer Protocol (RCTP) were developed [Tachi 1998].

2.7 Humanoid Robotics Project (HRP)

On the basis of the R^3 program and after conducting a two-year feasibility study called Friendly Network Robotics (FNR) from April 1996 until March 1998, a National Applied Science & Technology Project called "Humanoid and Human Friendly Robotics," or "Humanoid Robotics Project (HRP)" was launched in 1998. This was a five-year project toward the realization of an R^3 Society by providing humanoids, control cockpits, and remote-control protocols.

In phase 1 of the project, a telexistence cockpit for humanoid control was developed, and the telexistence system was constructed using the developed humanoid platform. In order to evaluate the usability of the cockpit for HRP robots, an experiment was conducted where an operator was given the task to navigate the environment of a biped humanoid robot and manipulate objects by utilizing the robot as a surrogate. The operator navigated the robot as if he or she were inside the robot, and manipulated the robot's arms and hands to handle a stuffed animal, stack blocks, open and close a sliding glass door of a cupboard, pick up a can from inside the cupboard, place the can into a basket, and so forth. While the robot walked, real images captured by the multi-camera system for the wide field of view were displayed on four screens of the surround visual display. This provided the operator with a feeling as if he were inside the robot in the remote environment. Figure 10 presents the robot descending stairs. Since the series of real images presented on the visual display are integrated with the movement of the motion base, the operator experiences a real-time sensation of walking or stepping up and down.

This was the first experiment in the world which succeeded in controlling a humanoid biped robot by using telexistence [Tachi et al. 2003].

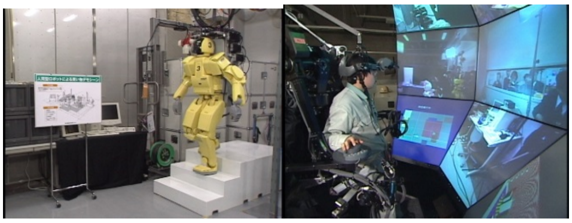

Figure 10: *HRP humanoid biped telexistence robot descending stairs (left), and a human operator at the telexistence cockpit feeling the sensation of stepping down (right).*

2.8 Mutual Telexistence Communication System: TELESAR II & IV

A method for mutual telexistence based on the projection of real-time images of the operator onto a surrogate robot using retroreflective projection technology (RPT) was first proposed in 1999 [Tachi, 1999], and the feasibility of this concept was demonstrated by the construction of experimental mutual telexistence systems using RPT in 2004 [Tachi et al., 2004]. In 2005, a mutual telexistence master-slave system called TELESAR II was constructed for the Aichi World Exposition. Nonverbal communication such as gestures and handshakes could be performed in addition to conventional verbal communication because a master-slave manipulation robot was used as the surrogate for a human [Tachi et al., 2008]. Moreover, a person who remotely visited the surrogate robot's location could be seen naturally and simultaneously by several people standing around the surrogate robot (Fig. 11).

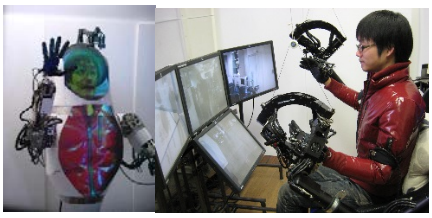

Figure 11: *Mutual telexistence surrogate robot TELESAR II (left), and an operator at the telexistence cockpit (right).*

The mobile mutual telexistence system, TELESAR IV, which is equipped with master-slave manipulation capability and an immersive omnidirectional autostereoscopic 3D display with a 360-degree field of view know as TWISTER, was developed in 2010 [Tachi et al., 2012]. It has a projection of the remote participant's image on the robot by RPT (Fig. 12).

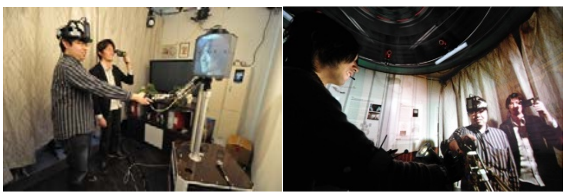

Figure 12: *Mobile telexistence surrogate robot TELESAR IV communicating with local participants (left), and a remote participant at the TWISTER cockpit (right).*

Face-to-face communication was also confirmed, as local participants at the event were able to see the remote participant's face and expressions in real time. It was further confirmed that the system allowed the remote participant to not only move freely about the venue by means of the surrogate robot, but also perform some manipulation tasks such as a handshake and several gestures.

Face-to-face telexistence communication has been developed using TWISTER booths. The following systems were added to the original TWISTER's omnidirectional 3D autostereoscopic display: a 3D facial image acquisition system that captures expressions and line of sight, and a user motion acquisition system that captures information about arm and hand position and orientation. An integrated system has been constructed whereby communication takes place via an avatar in a virtual environment.

The results of having two participants engage in TWISTER-to-TWISTER telecommunication verified that participants can engage in telecommunication in the shared virtual environment under mutually equivalent conditions as is shown in Fig. 13 [Watanabe et al. 2012].

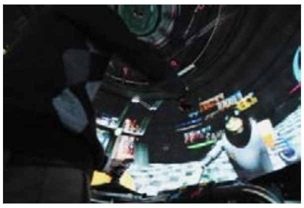

Figure 13: *TWISTER to TWISTER mutual telexistence.*

2.9 Telexistence Avatar Robot System: TELESAR III and TELESAR V

In telexistence, an operator can feel his/her slave robot as an expansion of his/her bodily consciousness and has the ability to move freely and control the slave robot in a similar way to his/her body movement. In order to certify this concept in telexistence, the TORSO (TELESAR III) system, which can acquire visual information in a more natural and comfortable manner by accurately tracking a person's head motion with 6 DOF, was constructed [Tachi et al. 2004].

TELESAR V, a master-slave robot system for performing body movements including 6-DOF head movement such as that of TORSO, was developed in 2011 (Fig. 14) [Tachi et al. 2011]. In addition, an operator can feel the fingertip tactile and thermal sensations when touching objects remotely. The TELESAR V system satisfies the following functions [Fernando et al. 2012].

(1) The operator can freely and independently move his/her head, upper body, and both arms and hands. In contrast, the slave robot's arms and hands follow similar movements with 53 DOF while maintaining 6-DOF arm endpoint accuracy.

(2) The operator can have a clear wide-angle stereo view of the remote site with 6-DOF point-of-view robot vision accuracy. The operator also has the ability to perform binaural, bi-directional verbal communication.

(3) The operator can grasp and manipulate objects in a similar manner to a human hand.

(4) The operator feels fingertip tactile and thermal sensations when touching objects remotely.

In July, 2012, it was successfully demonstrated that the TELESAR V master-slave system can transmit fine haptic sensations, such as the texture and temperature of material, from an avatar robot's fingers to the human user's fingers.

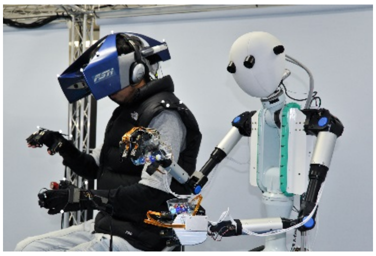

Figure 14: *TELESAR V transferring small balls from one cup to another cup.*

3. Toward a "Telexistence Society" [Tachi 2016]

Working at home remotely to date has been limited to communications and/or paperwork that transmit audio-visual information and data, as well as conversations. It was impossible to carry out the physical work at factories or operations at places such as construction sites, healthcare facilities, or hospitals; that cannot be accomplished unless the person in question is actually on site. Telexistence is a technology that departs from the conventional range of remote communications that transmit only the five senses, and it realizes an innovative method that transmits all the physical functions of human beings and enables the engagement of remote work accompanying labor and operations that was impossible until now.

If a telexistence society that can delegate physical functions were realized, the relationship between people and industry and the nature of society would be fundamentally changed. The problems of the working environment would be resolved, and it would no longer be necessary to work in adverse environments. No matter where a factory is located, workers would be assembled from the entire country or the entire world, so the conditions for locating factories will see revolutionary changes compared to the past, and population concentration in the metropolitan area can be avoided. Since foreign workers would also be able to attend work remotely, the myriad problems accompanying immigration as a mere labor force, separate from humanitarian immigration, can be eliminated. Moreover, it will be possible to ensure a 24-hour labor force at multiple overseas hubs by making use of time differences, rendering the night shift unnecessary. Both men and women will be able to participate in labor while raising children, and this will help to create a society in which it is easier to raise children.

The time-related costs due to travel in global business will be reduced. Commuting-related travel will become unnecessary, and transportation problems can be alleviated. It is predicted that it will no longer be necessary to have a home near one's workplace, the concentration of population in the metropolis will be alleviated, the work-life balance will be improved, and the people concerned will be able to live where they wish and lead fulfilling lives.

In addition, owing to additional functions of an avatar robot, which is the body of the virtual self, even the elderly and handicapped will not be at a disadvantage physically compared to young people, since they can augment and enhance their physical functions to surpass their original bodies, and thus they can participate in work that gives full play to the abundant experience amassed over a lifetime. The quality of labor will rise greatly, thereby reinvigorating Japan. The hiring of such specialists as technicians and physicians with world-class skills will also be facilitated, and optimal placement of human resources according to competence can also be achieved.

With a view to the future, it will be possible to respond instantly from a safe place during disasters and emergencies, and this technology can also be used routinely to dispatch medical services, caregivers, physicians, and other experts to remote areas. In addition, owing to the creation of new industries such as tourism, travel, shopping, and leisure, it will greatly improve convenience and motivation in the lives of citizens, and it is anticipated that a healthy and pleasant lifestyle will be realized in a clean and energy-conserving society (Fig.15).

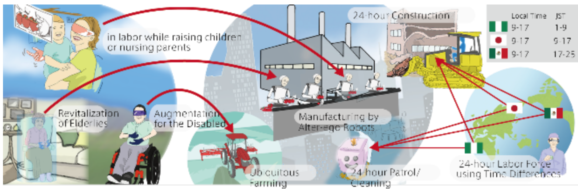

Figure 15: *Telexistence Society.*

4. Avatar XPRIZE

On August 3, 2016, XPRIZE Foundation's Visioneers Prize Design team visited the Tachi Laboratory at Miraikan (the National Museum of Emerging Science and Innovation) located in Odaiba. The XPRIZE Foundation was founded in 1995 by Peter H. Diamandis, selected as one of the world's 50 Great Leaders in 2014, who is regarded as a charismatic persona in the world of innovation. So far, the Foundation has helmed a number of large-scale projects, such as a manned ballistic spaceflight contest, and cleanup of seawater surface oil. Like Charles Lindbergh's solo nonstop transatlantic flight, which has explosively expanded new areas of human travel and tourism, the attempt to create a new industry through a global prize competition and the creation of the current private space industry are considered to be the results of the XPRIZE.

In one room of the Tachi Laboratory in a private research building, those who have experienced TELESAR V wore a head mount display, and at the second they put the gloves on and move, collectively exclaimed, “Yes, this is exactly what I was looking for!” About 2 months later, the XPRIZE Foundation opened the Summit. About 300 mentors in various fields: investors, scholars, businessmen, philanthropists, artists, and engineers gathered over 2 days to judge the 9 nominated themes for the next prize competition. Here, TELESARV, which was developed by the author and his team, was invited by the foundation to give a demonstration (Fig.16). Because of this, it was decided that the theme for the next prize competition is ANA AVATAR XPRIZE. After that, details of the development goals and evaluation were solidified by the XPRIZE Foundation, and a formal opening of the competition was declared on March 12, 2018 at the SXSW Hall in Austin, Texas, USA. The plan is to accept entries from around the world until the end of September 2019, narrow down the teams to 150 by February 2020 through a proposal document screening, open the qualifying tournament in May 2021, and select 20 teams; the main battle will be held in January 2022. In the preliminaries, the physical examination of the man-machine synergy telexistence system is carried out; during the main competition, candidates will perform tasks in the fields of welfare, disaster response, and laboratory environment and they will compete in terms of degree of achievement.

This competition uses cutting-edge technology such as virtual reality, robotics, AI, and network technologies. The aim is to industrialize telexistence technology where human beings can exist in a number of different places by using the robot's body to physically touch objects and work with them. Thus, AVATAR XPRIZE will lead the way to the Telexistence Society.

Figure 16: *Demonstration of TELESAR V at the XPRIZE Visioneers Summit 2016.*

5. TELESAR VI

TELESAR VI (TELExistence Surrogate Anthropomorphic Robot VI) is a newly developed telexistence platform for the ACCEL Embodied Media Project. It was designed and implemented with a full body mechanically unconstrained master cockpit and a 67 degrees-of-freedom (DOF) anthropomorphic slave robot. The system provides a full-body experience of our extended “body schema,” which allows a human to maintain up-to-date representation in space of the positions of his/her various body parts, including his/her head, torso, arms, hands, and legs. Body schema can be used to understand the posture of the remote body and to perform actions with the belief that the remote body is the user’s own body. With this experience, users can perform tasks dexterously and feel the robot’s body as their own, through visual, auditory, and haptic sensations, which provide the most simple and fundamental experience of a remote existence.

Figure 17: *General view of TELESAR VI avatar robot.*

The TELESAR VI system consists of a master (local) and physical avatar (remote). As shown in Fig.17, the 67-DOF dexterous robot was developed with a 6-DOF torso, a 3-DOF head, two 7-DOF arms, two 16-DOF hands, and two 6-DOF legs. Its torso has 2 DOF for its chest motion, 1 DOF for its spine’s telescopic motion, and 3 DOF for its waist motion. Each arm has 3 DOF for its shoulder, 1 DOF for the elbow, and 3 DOF for the wrist. Each hand has a 5-DOF thumb, a 3-DOF forefinger, a 3-DOF middle finger, a 2-DOF ring finger, a 2-DOF little finger, and 1-DOF abduction of four fingers. Each leg has 3 DOF for its hip, 1 DOF for its knee, and 2 DOF for its ankle. The hands are custom designed, human-sized, anthropomorphic robotic hands, which have a similar number of joints as real human hands. The robotic fingers of each hand are driven by 16 individual DC motors, and dynamically coupled wires and a pulley-driven mechanism connect the remaining joints that are not directly attached to a motor. All of the DC motors are connected to the custom-made DC motor driver with a combination of optical encoders and potentiometer readings as position measurements. Furthermore, voltage and current consumption are monitored at each motor, and torque at the motor shaft is calculated.

The robot has two cameras (See3CAM CU135), two microphones (AT9912), and a speaker (SoundCore Boost). Cameras for capturing wide-angle stereo vision, and stereo microphones are situated on the robot's ears for capturing audio information from the remote site. The operator's voice is transferred to the remote site and outputted through a small speaker installed in the robot's body area for conventional, verbal, bidirectional communication.

On the master side, the operator's movements are captured with a motion capturing system (OptiTrack) and sent to the kinematic generator PC. Finger postures are captured to an accuracy of 16 DOF using IGS-Cobra gloves with OptiTrack active markers.

6. Conclusions

Telexistence was conceptualized in 1980 and has been developed through several research and development projects. Recently, as start-ups specializing in telexistence have been established, momentum has built toward the industrialization of telexistence and its application to a variety of industrial fields. Contributing to this trend, the XPRIZE Foundation has launched the ANA Avatar XPRIZE as its next challenge. Intense worldwide competition within the emerging telexistence industry, which integrates AI, robotics, VR, and networking, has just begun. In this keynote, forty years of research on telexistence was overviewed and cutting-edge technologies of telexistence were explained. We also discussed several problems to be solved to attain a telexistence society and foresee the future that telexistence will develop and create.

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