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Networked Telexistence: Real-time Remote Robotics with a Sensation of Presence

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Abstract: Telexistence (tel-existence) is fundamentally an advanced type of telerobotics system that enables an operator at the control to perform remote tasks dexterously with the feeling that he or she exists in a surrogate robot that is working in the remote environment. It is also a concept named for the technology which enables a human being to have a real time sensation of being at the place other than the place where he or she actually exists, and is able to interact with the remote and/or virtual environment. It enables a human operator to have a sensation of being in a remote real environment where a surrogate robot exists, while being augmented by a virtual environment synthesized by a computer, whose structure is based on the sensor information on board the robot. The concept of telexistence, i.e., virtual existence in a remote or computer-generated environment, has developed into a national R&D scheme of R-Cubed (Real-time Remote Robotics) for the advanced and comfortable life of the 21st century network society. R-Cubed can be said to be the effort toward the networked telexistence. Based on the scheme of R-Cubed, in the fiscal year of 1998, Ministry of Economy, Trade and Industry (METI) of Japan launched a national five-year project called the Humanoid Robotics Project (HRP). This is an effort to integrate telerobotics, network technology and virtual reality into networked telexistence. This paper reviews how telexistence technology has been developed, and describes a newly developed telexistence cockpit for humanoid robot control, and shows a technical demonstration to evaluate the developed cockpit and the robot. A human operator controls the robot within the remote cockpit as if (s)he were inside the robot itself.

Keywords: telexistence, tele-existence, telepresence, virtual reality, master-slave manipulation, humanoid robots

1. Introduction

Technology of projecting ourselves in real time into remote environments by using surrogate robots, remote/local computers and cybernetic human interfaces is called telexistence (tel-existence). This concept has been expanded to include projection into computer-generated virtual environments, and also the use of a virtual environment for the augmentation of the real environment.

The concept of the telexistence was proposed by the author in 1980 and it played the role of the fundamental principle of the eight year Japanese National Large Scale Project of "Advanced Robot Technology in Hazardous Environment," which started in 1983 together with the concept of the Third Generation Robotics. Through this project theoretical consideration has been done and systematic design procedure has been established. Experimental hardware telexistence system has been made and the feasibility of the concept has been demonstrated.

In our first report [1], the principle of the telexistence sensory display was proposed, and its design procedure was explicitly defined. Experimental visual display hardware was built, and the feasibility of the visual display with a sensation of presence was demonstrated by psychophysical experiments using the test apparatus.
A method was also proposed to develop a mobile telexistence system, which can be remotely driven with the auditory and visual sensation of presence. A prototype mobile televehicle system was constructed and the feasibility of the method was evaluated [2].
The first prototype telexistence master slave system for remote manipulation experiments was designed and developed, and a preliminary evaluation experiment of telexistence was conducted. An experimental telexistence system for real and/or virtual environments was designed and developed, and by conducting an experiment comparing a telexistence master-slave system with conventional master-slave system, efficacy of the telexistence master-slave system and the superiority of the telexistence method were demonstrated experimentally (**Fig.1**) [3, 4, 5].

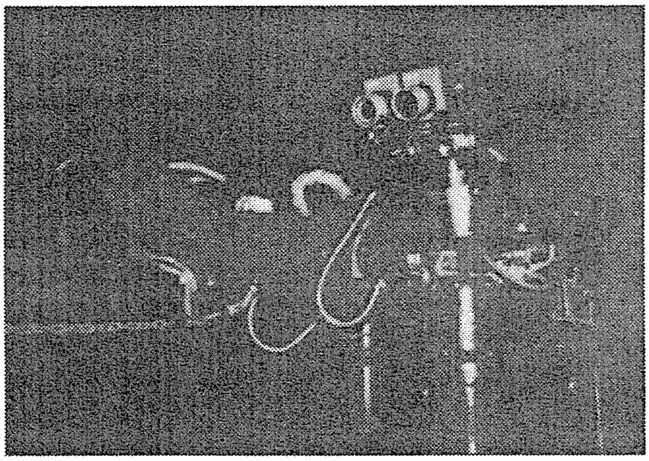

Fig. 1 Telexistence Surrogate Anthropomorphic Robot (TELESAR) at Work.

2. Augmented Telexistence

Telexistence can be divided into two categories: telexistence in the real world that actually exists at a distance, and is connected via a robot to the place where the user is located; and telexistence in the virtual world that does not actually exist but is synthesized by a computer. The former can be called "transmitted reality," while the latter is "synthesized reality." The synthesized reality can be classified into two, i.e., a virtual environment as a model of the real world and a virtual environment of an imaginary world. Combination of transmitted reality and synthesized reality, which is called mixed reality, is also possible and has a great importance in real applications. This we call augmented telexistence to clarify the importance of harmonic combination of real and virtual worlds.
Augmented telexistence can be used in several situations. By takeing for instance, of controlling a slave robot in a poor visibility environment, an experimental augmented telexistence system using a virtual environment has been constructed. The environment model has also been constructed from the design data of the real environment. When augmented reality is used for controlling a slave robot, the modeling errors of the environment model must be calibrated. A model-based calibration system using image measurements has been proposed for matching the real environment and a virtual environment. The slave robot has impedance control mechanism for contact tasks and for compensating for the errors that remain even after the calibration. An experimental operation in a poor visibility environment was successfully conducted by using Telesar (Fig.1) and the virtual

Telesar (Fig.2). Figure 2 shows the virtual telexistence anthropomorphic robot used in the experiment and Fig. 3 shows how the real environment is augmented by the computer model [6,7].

Quantitative evaluation of the telexistence manipulation system was conducted through tracking tasks by using a telexistence master slave system designed and developed. Through these experimental studies, it has been demonstrated that a human being can telexist in a remote environment and/or a computer-generated environment by using the dedicated telexistence system [5].

However, it is still difficult for everyone to telexist freely through commercial networks like the Internet or the next generation worldwide networks.

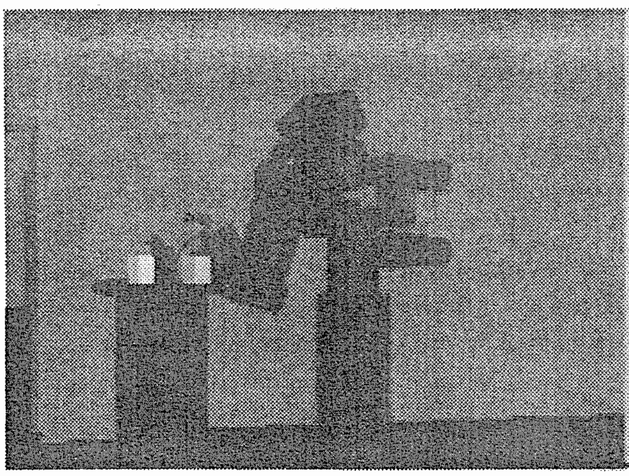

Fig. 2 An Experimental Augmented Reality.

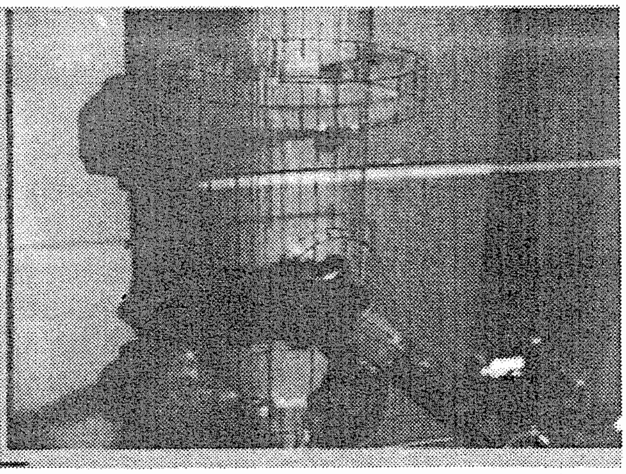

Fig. 3 Virtual TELESAR at Work.

3. R-Cubed (Real-time Remote Robotics) Scheme

In order to realize the society where everyone can freely telexist anywhere through network, Japanese Ministry of Economy, Trade and Industry (METI) together with the University of Tokyo proposed a long-range national R&D scheme, which is dubbed R-Cubed (Real-time Remote Robotics) in 1995 [8,9,10,11,12]. **Figure 4** shows an example of an artist's image of a future use of R-Cubed System. In this example, a handicapped person climbs a mountain with his friends using networked telexistence.

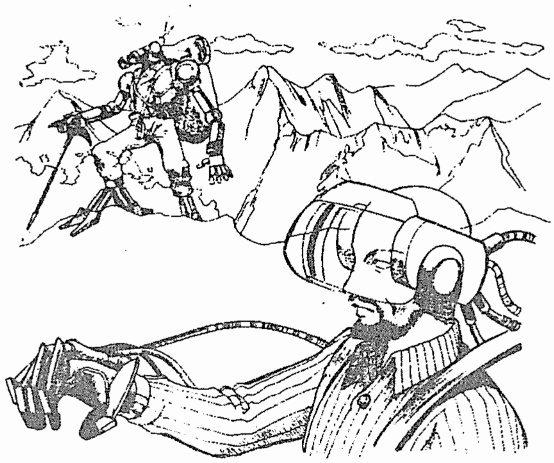

Fig. 4 Mountain Climbing using R-Cubed.

In an R-Cubed system, each robot site has its server of its local robot. The robot type varies from a humanoid (high end) to a movable camera (low end). A virtual robot can also be a controlled system to be telexisted.

Each client has its teleoperation system. It can be a control cockpit with master manipulators and a head mounted display (HMD) or CAVE Automatic Virtual Environment (CAVE) on the high end. It is also possible to use an ordinary personal computer system for its control system on the low end. In order to support the low end users to control remote robots through networks, RCML/RCTP (R-Cubed Manipulation Language / R-Cubed Transfer Protocol) is now under development [9].

To standardize the following control scheme, a language called RCML (http://www.rcml.org/), which describes a remote robot's features and its working environment, has been proposed. A communication protocol RCTP, which is designed to exchange control commands, status data, and sensory information between the robot and the user, has also been developed.

With Web browsers a user accesses a Web site describing information of a robot in the form of hypertext and icon graphics using WWW browser. Clicking on an icon downloads the description file, which is written in RCML format, to the user's computer and launches the RCML browser. The RCML browser parses the downloaded file to process the geometry information, including the arrangement of the degrees of freedom of the robot, controllable parameters, available motion ranges, sensor information, and other pertinent information. The browser decides what kind and how many devices are required to control the remote robot. It then generates a graphical user interface (GUI) panel to control the robot, plus a video window that displays the images "seen" by the robot and a monitor window that lets users observe the robot's status from outside the robot. If the user has a device, such as 6 degrees-of-freedom (DOF) position/orientation sensor, to indicate the robot-manipulator's endpoint, the user can employ that instead of the conventional GUI panel (**Fig.5**).

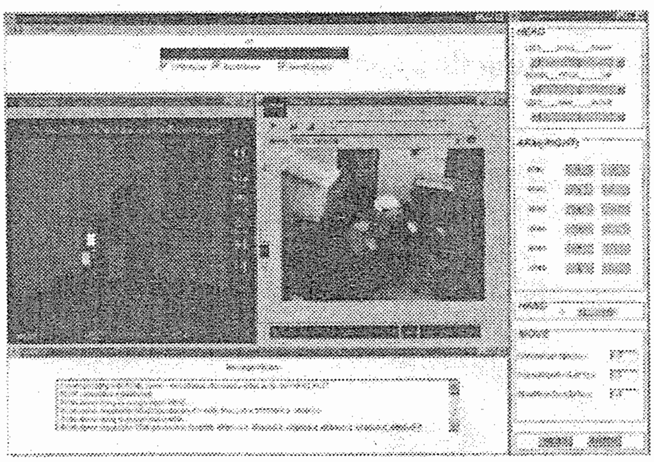

Fig. 5 An Example of an RCML Browser .

4. Humanoid Robotics Project (HRP)

A novel robot system capable of assisting and cooperating with people is necessary for any human-centered system to be used for activities such as the maintenance of plants or power stations, the operation of construction work, the supply of aid in case of emergency or disaster, and the care for elderly people. If we consider such systems from both a technical and a safety point of view, however, it is clearly intractable to develop a completely autonomous robot system for these objectives. The robot system should therefore be realized with the combination of autonomous control and teleoperated control. By introducing telexistence techniques, as an advanced type of teleoperated robot system, a human operator can be provided with information about the robot's remote site in the form of natural audio, visual, and force feedback, thus making him or her feel that he or she exists inside the robot itself [13,14,15].

Based on R-Cubed Scheme and after two-year feasibility study called Human Friendly Network Robot (FNR), which was conducted from April 1996 till March 1998, National Applied Science & Technology Project, "Humanoid and Human Friendly Robotics (HRP)," was launced oin 1998. It is a five-year project toward the realization of so-called R-Cubed Society by providing humanoids, control cockpits and remote control protocols.

For METI's national five year HRP, as shown in **Fig.6**, we have applied telexistence technology to a new type of cockpit system for controlling a humanoid biped robot

The telexistence cockpit that has been developed in this project (**Fig.7**) consists of three main subsystems: a audio/visual display subsystem, a teleoperation master subsystem and a communication subsystem between the cockpit and the humanoid robot (**Fig.8**).

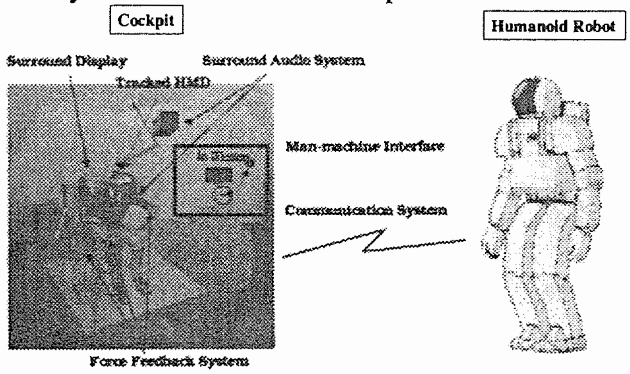

Fig.6 Telexistence Control of Humanoid Robot.

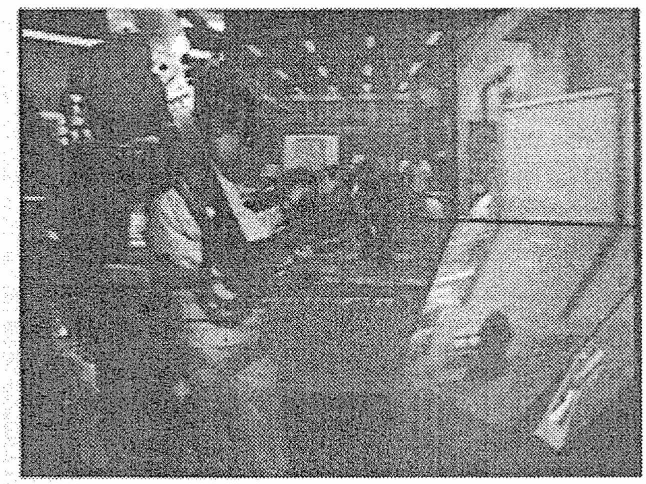

Fig.7 Telexistece Cockpit for Humanoid Control.

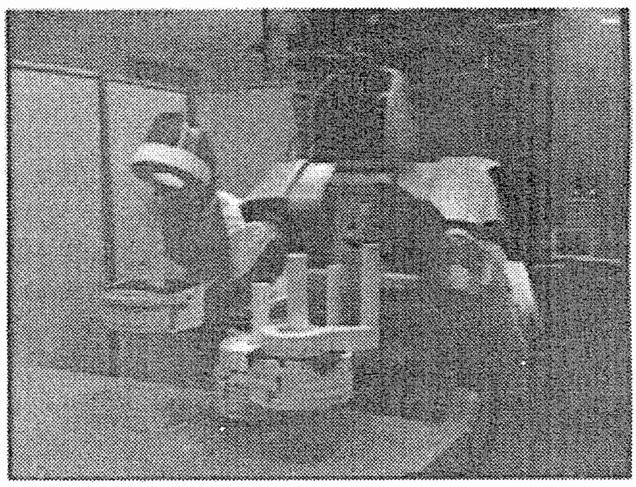

Fig.8 HRP Humanoid Robot at Work.

In order to address the problem of narrow fields of view associated with HMD's (Head Mounted Display), a surround visual display, using immersive projection technology (as adopted in the CAVE), has recently been developed. The surround visual display panoramically presents real images captured by a stereo multi-camera system for a wide field of view mounted on the robot, which allows the operator to have the feeling of on board motion when he or she uses the robot to walk around. In addition, when the human operator uses the robot to manipulate an object at a robot site, he or she needs an image precisely coordinated with his/her head motion, so an HMD system with a head-tracking function has been developed to meet these needs. Since a binocular camera platform is originally installed, the real right and left images captured by the binocular camera are presented on the HMD as the camera precisely follows the operator's head motion in real time. Also, an augmented reality technique is utilized to support the manipulation of the operator, and a virtual environment is supplemented to the real environment images captured by the robot camera. A surround audio display system consists of eight speakers mounted on the robot and headphones worn by the human operator. A three-dimensional microphone system mounted on the robot detects sound signals around the robot, which are displayed on the eight speakers and the headphones.

The surround visual display, shown in Figure 7, is composed of nine screens, each 60 inches along the diagonal. Two projectors are located on the backside of each screen to display polarized right-eye and left-eye images. The operator wears polarizing glasses to assemble a stereo image.

The stereo multi-camera system for the wide field of view mounted on the robot consists of two sets of four small cameras: one set for each eye, separated by a distance of 65mm. Each camera corresponds to one screen. The real images captured by the multi-camera system are presented on the four screens of the surround visual display: left, right, center and bottom. Thus, the field of vision is set at 150 degrees in the horizontal, 19 degrees in the upper vertical, and 58 degrees in the lower vertical directions.

If a visual user interface provides only a camera image during teleoperation of the robot, it is possible for the operator to get disoriented, and therefore unable to navigate the robot's location or orientation. This is because the operator has to perceive and assess the robot's situation based on local information provided from the camera. In order to help the operator assess a situation and decide an appropriate control action for the robot, (s)he should be provided with not only local information from the camera but also global information. Thus, we have introduced the novel system of augmenting camera images with global information that supports the operator's navigation of the robot. Here, we have constructed a computer graphics (CG) model of the humanoid robot operating in the virtual environment (VE), using VRML (Virtual Reality Modeling Language). We have both the CG model in the VE and camera images presented on the surround visual display.

The telexistence teleoperation master system, shown in Fig.7, consists of left and right master arms each with a gripping operation device, a motion-base, and a three- dimensional mouse. When using the teleoperation master system, a human operator leans on a seat on the motion base, attaches the gripping operation device, and grips the master-arm. Through the master arm and the gripping operation device, the operator can remotely manipulate the robot arms with hands. The motion base can display vibration, shock, and acceleration acting on the robot, as well as the relative displacement of the robot's upper body from a reference position based on the inclination of the operator.

Each master arm is designed as an exoskeleton type and has seven degrees of freedom (DOF). This redundancy in the DOF allows the operator to execute multiple postures of a slave arm directly using elbow posture, the motion of which is tracked by a joint motor on each master arm, and measured by optical sensors located on the lower links. The other joint motors generate appropriate force (up to 10 N) based on the feedback force from the slave arm, so the operator feels force and moment naturally.

Each master arm has a recently developed gripping device, with which an operator can easily operate open-close motion by feeling the gripping force of the slave robot. In order to realize small and lightweight mechanisms as well as a wide operation space for the thumb and index finger, a wire tension mechanism with a passive DOF is used to facilitate the thumb's radial abduction and ulnar adduction.

The developed motion base system allows the operator to experience locomotion of a humanoid robot with a sensation of reality by representing its acceleration, posture, and motion. The motion

base provides the operator with a sensation of walking, displacement, and upper body inclination by driving the seat position under the operator's standing posture. In order to minimize the displacement of an operator's focal point, the motion base system limits locomotive motion to a 3 DOF translation: back and forth (surge), left and right (sway), and up and down (heave).
We carried out various teleoperation tests by using the developed telexistence master system, and the results show that kinesthetic presentation by using the master system with visual image greatly improves both the operator's sensation of walking, and dexterity at manipulating objects.

The communication system between the cockpit and the robot consists of two main subsystems: one for communicating audio/visual information, and the other for control information. The audio and visual information is transmitted through an analogue communication module. The control information is exchanged and shared through a shared memory module called a Reflective Memory module, which is shared and accessed by the audio/visual display subsystem, the telexistence master subsystem, and the control system of the robot itself.

In order to evaluate the usability of the cockpit for HRP robots, we carried out an experiment that had an operator walk around and manipulate objects by utilizing a humanoid robot as his/her surrogate (Fig.8). To demonstrate the possibility of using the developed system in the field of service robots, we built a mockup shopping zone in a real environment 3.5x6.0m in size. We set a humanoid robot inside the mockup, and a human operator in the telexistence cockpit in the remote site to control the robot with a sensation of presence. The operator navigated the robot as if (s)he were inside the robot, and manipulated the robot's arms and hands to handle a stuffed animal, stack blocks, open and close a glass window, pick up a can from the inside, place the can into a basket, etc.

When the operator controlled the robot to walk around, (s)he wore polarizing glasses and leaned on the sheet of the motion base. On the bottom-left screen of the surrounded visual display, an operational menu appeared. The menu included a 2D map of the environment, and a series of operational commands to the robot. The operator uses the 3D mouse to indicate on the map an objective location and orientation for the robot to reach, and the menu system automatically generated a path to reach the goal. If the operator issued a command to move the robot, the robot actually walked to the goal. While the robot walked around, the real images captured by the multi-camera system for the wide field of view were displayed on four screens of the surrounded visual display. This made the operator feel as if he were inside the robot, walking around the robot site. A CG model of the robot in the virtual environment was represented and updated according to the current location and orientation received from the real robot. It was displayed on the bottom-right screen of the surround visual display and when augmented to the real images captured by the camera system, it supported the operator's navigation of the robot.

Since the series of real images presented on the visual display are integrated with the movement of the motion base, the operator feels the real time sensation of walking, or stepping up and down.

Figure 9 shows a photograph of picking up a can as an example. The operator observed the binocular camera images on the HMD, and captured a can with the arms and hands of the robot by operating the master arms and hands, while (s)he felt a force feedback received from the robot hands shown in **Fig. 10**. **Figure 11** illustrates the robot handing over the can to a child.

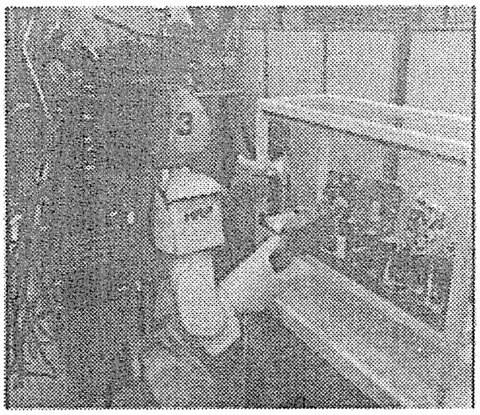

Fig.9 HRP Robot picking up a Can.

5. Conclusion

One of the most promising technologies today is the integration of virtual realty and robotics on the network. It is called networked robotics in general and R-Cubed (Real-time Remote Robotics) in particular. R-Cubed is a Japanese national R&D scheme toward the realization of the next generation telexistence through various kinds of networks including the Internet. METI launched the 5-year Project "Humanoid and Human Friendly Robotics (HRP)" in April 1998. This is the first step toward the realization of R-Cubed, i.e, the next generation telexistence.

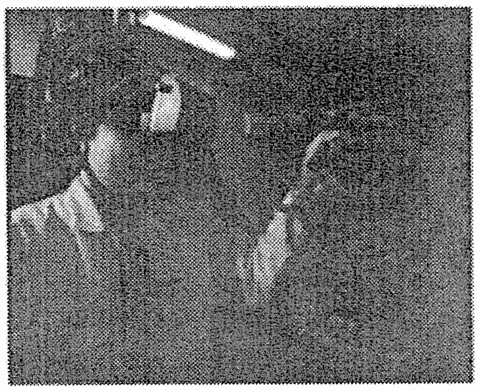

Fig.10 Operator in Telexistence Cockpit.

Fig11 Robot handing over a Can to a Child.

A human operator in the telexistence cockpit we developed can navigate and manipulate the humanoid robot as his surrogate as if he were inside the robot itself, and can also expand his visual, audio and tactile abilities through the augmentation of visual, audio and force feedback.

RCML (R-Cubed Manipulation Language) and RCTP (R-Cubed Transfer Protocol) were implemented so that the cockpit can be used as a server for the control of HRP robot through the Internet by using an RCML browser.

Telexistence cockpit will be used as a human tool for the augmentation of human ability, especially in expanding the limits of space and time.

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