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Robotics Research toward Next-Generation Human-Robot Networked Systems

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Abstract. Research on human-robot systems started as teleoperation and cybernetic prostheses in the 1940's. Teleoperation developed into telerobotics, networked robotics, and telexistence. Telexistence is fundamentally a concept named for the technology that enables a human being to have a real-time sensation of being at a place other than where he or she actually exists, and to interact with the remote environment, which may be real, virtual, or a combination of both. It also refers to an advanced type of teleoperation system that enables an operator at the control to perform remote tasks dexterously with the feeling of existing in a surrogate robot. Although conventional telexistence systems provide an operator the real-time sensation of being in a remote environment, persons in the remote environment have only the sensation that a surrogate robot is present, not the operator. Mutual telexistence aims to solve this problem so that the existence of the operator is apparent to persons in the remote environment by providing mutual sensations of presence. This enables humans to be seemingly everywhere at the same time, i.e., to be virtually ubiquitous. This paper reviews the generation of robots and the prospects of future networked robotics.

Keywords: generations of robots, networked robotics, real-time remote robotics (R-Cubed), humanoid robotics project (HRP), telexistence, mutual telexistence, telepresence, virtual reality, retro-reflective projection technology (RPT)

1. Introduction

One of humanity's most ancient dreams has been to have a substitute that can undertake those jobs that are dangerous, difficult or tedious. In primeval times, the dream was realized by utilizing animals, and unfortunately, by using fellowmen as slaves. In some countries, such conditions continued until nearly a hundred years ago.

With the advent of robotics and automation technology, and also the progress of computers and electronics in recent years, it has become possible to let automated machinery replace human labor. Robots are expected to replace human work as the only tolerable slave from a humanitarian point of view. The “Human Use of Human Beings” of N. Wiener will be truly realized only when humans make robots to replace them for adverse tasks, supporting an important end in the development and safety of our modern society.

The application fields are not limited only to ordinary manufacturing in secondary industry, but have been expanding gradually to mining, civil engineering and construction in the same secondary industry, as well as to agriculture, forestry and fisheries in primary industry.

They are expanding also to retailing, wholesaling, finance, insurance, real estate, warehousing, transportation, communications, nuclear power, space, and ocean development, to social work, such as medical treatment, welfare and sanitation, and to disaster control, leisure, household, and other tertiary industry-related fields.

Another dream of human beings has been to amplify human muscle power and sensing capability by using machines while reserving human dexterity with a sensation of direct operation. Also it has long been a desire of human beings to project themselves into a remote environment, that is, to have a sensation of being present or existing at the same time in a different place other than the place they really exist, i.e., to become virtually ubiquitous.

This dream is now on the way to accomplishment using robots as surrogates of ourselves over networks through technologies such as virtual reality, augmented reality, wearable systems and ubiquitous computing.

As this realization progresses our relations with the robot are becoming more and more important. These are called human-robot systems, human-robot interfaces, or human-robot communications, and are also referred to as teleoperation, telerobotics, networked robotics, r-cubed (real-time remote robotics) or telexistence when robots are remotely placed. These are some of the most undeveloped areas despite being among the most important in robot technology.

An example of the human-robot cooperation system, which will play an increasingly important role in the highly networked society of today and the future, as well as topics such as virtual reality and augmented realty for realizing such a system will be presented and intensively discussed.

2. Generations of Robots

Since the latter half of the 1960's, robots have been brought from the world of fiction to the practical world, and the development of the robot is characterized by generations, as in the case of the computer.

With the rapid progress of science and technology after World War II, the robot, which had been only a dream, came to realize some human or animal functions, although it had a different shape. Versatran and Unimate were the first robots made commercially available in 1960, and were introduced to Japan in 1967. They are called industrial robots and can be said to be the First Generation of robots finding practical use.

This is considered to have resulted from a combination of two large areas of development after World War II: hardware configuration and control technology for a remote operational type mechanical hand (or manipulator), which had been under research and development for use in the hot radioactive cell of a nuclear reactor, and automation technology for automated machinery or NC machine tools.

The term "industrial robot" is said to have originated under the title "Programmed Article Transfer," which G. C. Devol applied for registration in 1954 and which was registered in 1961 in the United States. It has come into wide usage since the American Mental Market, a U.S. journal, used the expression in 1960. After passing through infancy in the latter half of the 1960's, the industrial robot reached the age of practical use in the 1970's.

Thus the robot entered an age of prevalence in anticipation of a rapid increase in demand. That is why 1980 is called "the first year of the prevalence of the industrial robot." From a technical point of view, however, the first generation robot that found wide use is a kind of repetition machine, which plays back repeatedly its position and posture instructed in an embedding process before commencement of operation.

In essence, it is a composite system of technology based on control techniques for various automated machines and NC machine tools, and design and control techniques of manipulators with multiple degrees of freedom. Naturally, the application area is limited. These robots can be most effectively used in manufacturing processes in secondary industry, especially in material handling, painting, spot welding, etc.

In other areas, such as arc welding and assembling, it is necessary to vary actions and to better understand human instructions by using not only knowledge from within, like for the First Generation Robot, but also to acquire external information with sensors. A device that could change its actions according to the situation using a sensor is the so-called Second-Generation sensor-based adaptive robot. It came to prevail gradually in the 1970's.

The non-manufacturing areas of primary industry (agriculture, fisheries, and forestry), secondary industry (mining and construction), and tertiary industry (security and inspection) had so far been excluded from mechanization and automatization, as the older type First and Second Generation robots could not operate in environments that were dangerous and unregulated or unstructured. However, harsh and hazardous environments such as nuclear power plants, deep oceans, and areas affected with natural disasters, are where robots are needed the most as substitutes to humans who risk their lives working there. The Third Generation Robot was proposed to answer these problems.

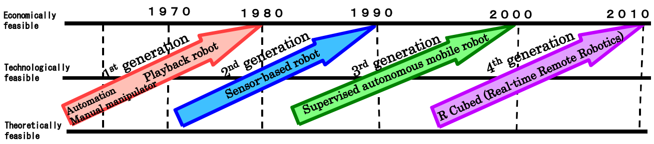
The key to the development of the Third Generation Robot was to figure out a way to enable the robot to work in an environment that was not maintained or structured. The First and Second Generation Robots possess the data of the maintained environment. This means that humans have a grasp of the entire scope of data concerning the environment. This is called the "structured environment." The factory where first and second generation robots work is an example of the structured environment. All the information concerning the structure of the factory, such as where passages are and how things are arranged, is clear. One can also change the environment to accommodate the robot. For example, objects can be rearranged to where the robot's sensor can recognize them easily.

However, there are structured environments that cannot be altered so easily. For example, it is not possible to change the environment in places such as the reactor of a nuclear power plant, objects in the ocean, and areas affected by disasters. Even with full knowledge about the environment, one cannot alter the environment to accommodate robots. In many cases, one cannot determine the vantage points and lighting. Furthermore, one can encounter an "unstructured environment" where humans do not possess accurate data. Nature is also full of environments where humans are totally disoriented.

In the development of the Third Generation Robot, one focused on the structuralization of the environment based on available information. Robots conduct their work automatically once the environment was structured, and worked under the direction of humans in an environment that was not structured. This system, called the supervisory controlled autonomous mobile robot system, was the major paradigm of the Third Generation Robot.

Thus the Third Generation Robot was able to work in places where humans possessed basic data of the environment but were unable to alter the environment. These robots are engaged in security maintenance in such uncontrollable environments, and could deal with unpredictable events with the help of humans.

In Japan, between 1983 and 1991, the Ministry of International Trade and Industry (now Ministry of Economy, Trade and Industry) promoted the research and development of a National Large-Scale Project under this paradigm called “Advanced Robot Technology in Hazardous Environments”. Telexistence played an important role in the paradigm of the Third Generation robots.



		1st generation	2nd generation	3rd generation	4th generation
Brain Function	Intelligence	A Priori [inborn] Play back	Adaptation Accommodation	Inference Problem Solving	A Posteriori [acquired] Learning, Neural Network
	Knowledge	Data	Data Base	Knowledge Base	Common Sense
Sensor Function	Internal Information	Exist	Exist	Exist	Exist
	External Information	None or Point	1-D, 2-D Structured Environment	3-D Unstructured Environment	3-D Natural Environment
	Communication	Unilateral (teaching, NC tape)	Interactive (robot language)	Bilateral Communication (supervisory control, telexistence)	Bilateral Communication (natural language, gesture, body language)
Effector Function	Manipulation	Position Control (Static)	Position Control (Dynamic)	Force Control	Cooperative Control
	Locomotion	1-D(guide cable)	2-D(plane, guided)	3-D(structured)	3-D (unstructured)
Application Fields		Secondary Industry (manufacturing) Material handling, Painting, Spot welding	Secondary Industry (manufacturing) Arc welding, Assembly	Secondary Industry (nonmanufacturing) Primary Industry Tertiary Industry (inspection, maintenance)	Secondary Industry (nonmanufacturing) Primary Industry Tertiary Industry (office, hospital, home, service)
Technical Feature		Internal Sensor + Servo Control Technology	External Sensor + Microprocessor System Technology	Knowledge Engineering + Man-Machine Interface Technology	Virtual Reality + Network Technology

Fig. 1 Generations of Robots.

3. Telexistence

Telexistence (tel-existence) is a technology that enables us to control remote objects and communicate with others in a remote environment with a real-time sensation of presence by using surrogate robots, remote / local computers and cybernetic human interfaces. This concept has been expanded to include the projection of ourselves into computer-generated virtual environments, and also the use of a virtual environment for the augmentation of the real environment.

The concept of telexistence was proposed and patented in Japan in 1980, and became the fundamental guiding principle of the eight-year Japanese National Large Scale Project called "Advanced Robot Technology in Hazardous Environments," which was initiated in 1983 together with the concept of Third Generation Robotics. Through this project, we made theoretical considerations, established systematic design procedures, developed experimental hardware telexistence systems, and demonstrated the feasibility of the concept.

Through the efforts of twenty years of research and development in the U.S., Europe and Japan [1-10], it has nearly become possible for humans to use a humanoid robot in a remote environment as if it was an other self, i.e., they are able to have the sensation of being just inside the robot in the remote environment.

Our first report [5,7] proposed the principle of the telexistence sensory display, and explicitly defined its design procedure. The feasibility of a visual display with a sensation of presence was demonstrated through psychophysical measurements using experimental visual telexistence apparatus. A method was also proposed to develop a mobile telexistence system that can be driven remotely with both an auditory and visual sensation of presence. A prototype mobile televehicle system was constructed and the feasibility of the method was evaluated.

In 1989, a preliminary evaluation experiment of telexistence was conducted with the first prototype telexistence master slave system for remote manipulation. An experimental telexistence system for real and/or virtual environments was designed and developed, and the efficacy and superiority of the telexistence master-slave system over conventional master-slave systems was demonstrated experimentally [11].

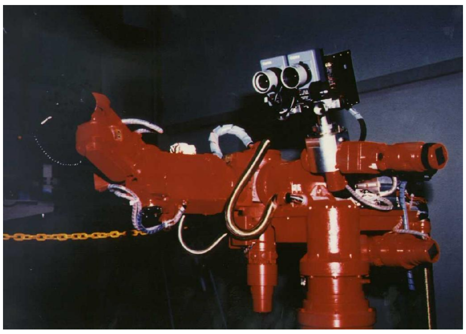


Fig. 2 Telexistence Surrogate Anthropomorphic Robot (TELESAR) at Work (1988).

Augmented telexistence can be effectively used in numerous situations. For instance, to control a slave robot in a poor visibility environment, an experimental augmented telexistence system was developed that uses a virtual environment model constructed from design data of the real environment. To use augmented reality in the control of a slave robot, a calibration system using image measurements was proposed for matching the real environment and the environment model [12].

The slave robot has an impedance control mechanism for contact tasks and to compensate for errors that remain even after calibration. An experimental operation in a poor visibility environment was successfully conducted by using a humanoid robot called TELESAR (TELExistence Surrogate Anthropomorphic Robot), shown in Figure 2, and its virtual dual. Figure 3 shows the virtual TELESAR used in the experiment, and Figure 4 shows the master system for the control of both real TELESAR and virtual TELESAR.

Experimental studies of tracking tasks demonstrated quantitatively that a human being can telexist in a remote and/or computer-generated environment by using the dedicated telexistence master slave system [11].

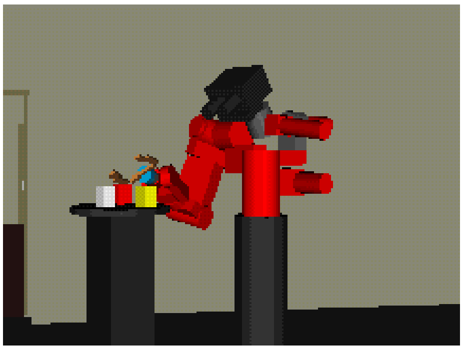


Fig. 3 Virtual TELESAR at Work (1993).

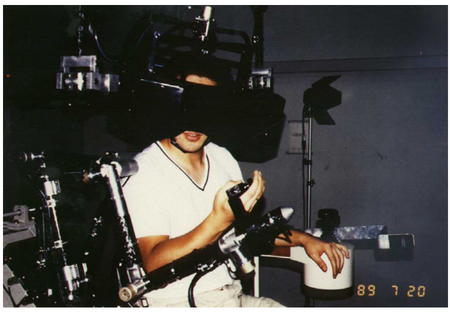


Fig. 4 Telexistence Master (1989).

4. R-Cubed

In order to realize a society where everyone can freely telexist anywhere through a network, the Japanese Ministry of Economy, Trade and Industry (METI) together with the University of Tokyo, proposed a long-range national research and development scheme in 1995 dubbed R-Cubed (Real-time Remote Robotics) [13].

Figure 5 shows an example of an artist's rendition of a future use of R-Cubed System. In this example, a handicapped person climbs a mountain with his friends using a networked telexistence system.

In an R-Cubed system, each robot site includes its local robot's server. The robot type varies from a mobile camera on the low end, to a humanoid on the high end. A virtual robot can also be a controlled system to be telexisted.

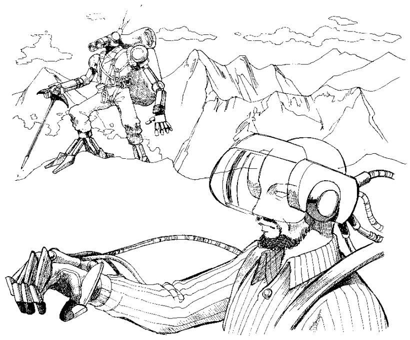


Fig. 5 Mountain Climbing using R-Cubed.

Each client has a teleoperation system called a cockpit, ranging from an ordinary personal computer system on the low end to a control cockpit with master manipulators and a Head Mounted Display (HMD), or a CAVE Automatic Virtual Environment (CAVE) on the high end. RCML/RCTP (R-Cubed Manipulation Language / R-Cubed Transfer Protocol) is now under development to support the lower end user's ability to control remote robots through a network [13].

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

5. Humanoid Robotics Project (HRP)

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

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 of 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 through 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 invoking the feeling of existing inside the robot itself [14,15].

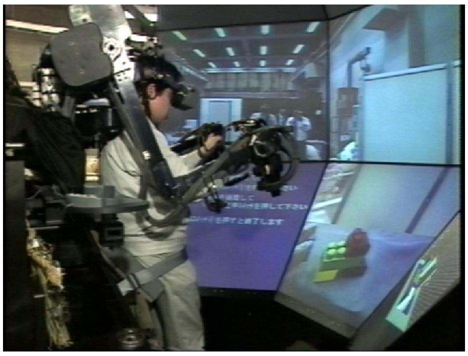


Fig. 6 Telexistence Cockpit for Humanoid Control (2000).

In order to address the problem of narrow fields of view associated with HMD's, a surround visual display using immersive projection technology (as adopted in the CAVE), has recently been developed (Fig. 6). 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.

Various teleoperation experiments using the developed telexistence master system confirmed that kinesthetic presentation by the master system through visual imagery greatly improves both the operator's sensation of walking, and dexterity at manipulating objects.

If the operator issued a command to move the robot, the robot actually walked to the goal. As the robot walked around, real images captured by a wide field of view multi-camera system were displayed on four screens of the surrounded visual display. This made the operator feel as if he or she was inside the robot, walking around the robot site (Fig. 7).

A CG model of the robot in the virtual environment was represented and updated according to the current location and orientation received from sensors on the real robot. The model was displayed on the bottom-right screen of the surround visual display, and by augmenting 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 stepping up and down.

This was the first experiment and success of controlling a humanoid biped robot using telexistence [15].

Fig. 7 HRP Humanoid Robot at Work (2000).

6. Mutual Telexistence using RPT

By using a telexistence system, persons can control the robot by simply moving their bodies naturally, without using verbal commands. The robot conforms to the person’s motion, and through sensors on board the robot the human can see, hear and feel as if they sensed the remote environment directly. Persons can virtually exist in the remote environment without actually being there.

For observers in the remote environment, however, the situation is quite different: they see only the robot moving and speaking. Although they can hear the voice and witness the behaviour of the human operator through the robot, it does not actually look like him or her. This means that the telexistence is not yet mutual. In order to realize mutual telexistence, we have been pursuing the use of projection technology with retro-reflective material as a surface, which we call Retro-reflective Projection Technology (RPT) [16,17,18,19].

RPT is a new approach to augmented reality (AR) combining the versatility of projection technology with the tangibility of physical objects. By using RPT in conjunction with an HMP, the mutual telexistence problem can be solved as shown in Figure 8: suppose a human user *A* uses his telexistence robot *A′* at the remote site where another human user *B* is present. The user *B* in turn uses another telexistence robot *B′*, which exists in the site where the user *A* works. 3-D images of the remote scenery are captured by cameras on board both robots *A′* and *B′*, and are sent to the HMP's of human users *A* and *B* respectively, both with a sensation of presence. Both telexistence robots *A′* and *B′* are seen as if they were their respective human users by projecting the real image of the users onto their respective robots. The first demonstration of RPT together with an HMP was made at SIGGRAPH98, followed by demonstrations at SIGGRAPH99 and SIGGRAPH2000.

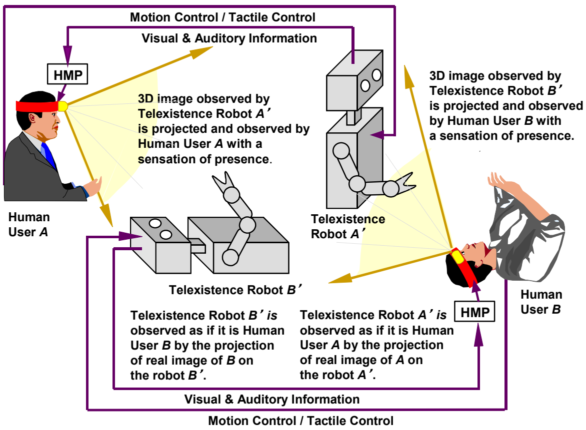


Fig. 8 Concept of Robotic Mutual Telexistence (adopted from [16]).

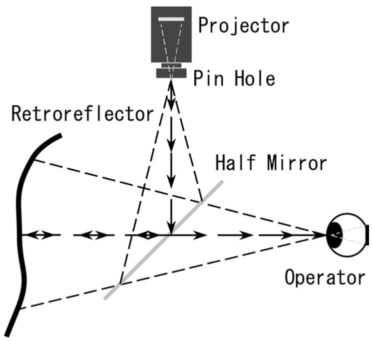


Fig. 9 Principle of Retro-reflective Projection Technology (RPT).

Fig. 10 Head-Mounted Projector.

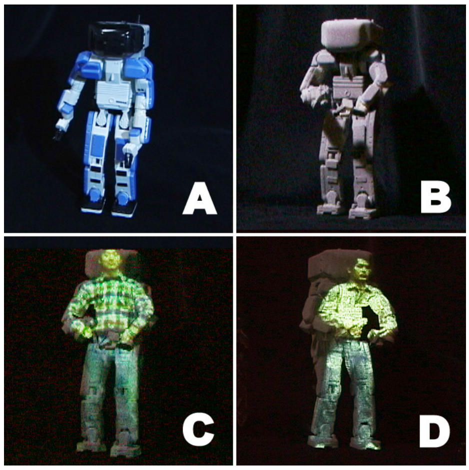


Fig. 11 (A) Miniature of the HONDA Humanoid Robot, (B) Painted with Retro-reflective Material, (C) and (D) Examples of Projecting a Human onto it. (adopted from [16]).

Figure 9 shows the principle of Retro-reflective Projection Technology (RPT) and Figure 10 shows a Head-Mounted Projector (HMP) constructed according to RPT [17,18,19].

Figure 11 presents an example of how mutual telexistence can be achieved through the use of RPT. Figure 11(A) shows a miniature of the HONDA Humanoid Robot, while Figure 11(B) shows the robot painted with retro-reflective material. Figures 11 (C) and (D) show how they appear to a human wearing an HMP. The telexisted robot looks just like the human operator of the robot, and mutual telexistence can be naturally performed [16]. However, this preliminary experiment was conducted off-line, and real-time experiments are yet to be conducted by constructing and using a mutual telexistence hardware system.

7. Toward the Future

There are two major styles or ways of thinking in designing robots. An important point to note here is that these ways of thinking have nothing to do with the forms of robots, such as the distinction between humanoid robots or those with special forms. Other distinctions include those that perform general or specific functions, and those in the shapes of animals or those that are not. These distinctions are indeed important especially when the robots are applied to practical use, and must be considered in practical situations.

However, the distinction that is discussed here concerns the philosophy toward robot design per se. The two different ways of thinking concern the question of whether to make "robots as independent beings" or "robots as extensions of humans". Robots as independent beings will ultimately have a will of their own, although that is far off from the stage of development today. Accordingly, commands toward the robots are made through language, such as spoken words, written manuals, or computer instructions.

On the other hand, robots as extensions of humans do not have a will of their own. Robots are a part of the humans who command them, and humans are the only ones who possess will. Commands are made automatically according to human movements and internal states, and not through language. Robots move according to the human will.

A prime example of robots as extensions of humans is a prosthetic upper-limb or an artificial arm, which substitutes lost arms. Humans move artificial arms as though they moved their own arms. What if one gained an artificial arm as a third arm, in addition to the existing two arms? The artificial arm would move according to the human will and function as an extra arm extending the human ability. The artificial arm, or, a robot as an extension of human, could physically be separate from the human body; it would still move according to the human will without receiving lingual commands. The robot would not have its own will and function as part of the human, even though the robot is physically separated from the human body. This is what can be called "one's other-self-robot". There may be multiple other-self-robots.

It is also possible to create an environment where humans feel as if they are inside one's other-self-robots, thereby the human cognizes the environment through the sense organs of the robot and then operates the robot using its effect organs. This technology is known as telexistence. Telexistence enables humans to transcend time and space, and allow them to be virtually ubiquitous.

Robots as independent beings must have the intelligence that pre-empts any attempt of the robots to harm humans. That is to say, "safety intelligence" is the number one priority in this type of robot. Isaac Asimov's three laws of robotics, for example, are quite relevant in designing this type of robot. It is crucial to find a solution to make sure that machines would never harm humans by any means.

The safety intelligence requires high technology and its innovation will not an easy task. The intelligence must be perfect, as a partially successful safety intelligence would be totally useless. The robots need to possess safety intelligence that even exceeds human intelligence. As Alan M. Turing has argued, this idea was still not relevant in the twentieth century, when autonomous robots could not have true intelligence as humans have. However, inventing the safety intelligence is the most important mission in the twenty-first century as robots are about to enter the everyday lives of humans.

On the other hand, there is an alternate approach to this problem. One could argue that the "one's other-self-robots" rather than the "independent robots" should be the priority in development. The other-self-robots are analogous to automobiles. The robots are machines and tools to be used by humans; robots are extensions of humans both intellectually and physically.

This approach pre-empts the problem of robots having their own rights, as they remain extensions of humans. Humans therefore need not to be threatened by robots, as the robots remain subordinate to humans. One's other-self-robot therefore is a promising path that humans can follow.

Take nursing for example. It is not desirable for a nursing robot that takes care of you to be an independent being. We can protect the patient's privacy the most when it is the patient who is taking care of himself. Accordingly, it is more appropriate if the nursing robot is the other-self-robot, an extension of oneself. The other-self-robot can either help himself or other people. The other-self-robot is more secure than the robot as an independent being, as the rights and the responsibilities associated with the robot are evident in the former type. The right and the responsibility of the robot belong to the humans who own the robot as their other self. Robots cannot claim their own rights or responsibilities.

One can nurse himself not only by using his own other-self-robot but also by asking family members and professional nurses to take care of him by using robots. These people, who may live far away from the patient, can use telexistence technology to personify the robot near the patient to help him. One important consideration in using this technology is that through the robot the patient needs to feel as though a person he knows, rather than an impersonal robot, is taking care of him. It is essential that the robot have a "face": a clear marker of who personifies it.

The analogy with the automobile is effective in considering the importance of clarifying who is using the robot. Just as the driver of a car, as opposed to the car itself, is responsible for the consequences of the car, so is the person using the robot is responsible for the robot's conduct. When you interact with a robot controlled by someone else, you need to know who is using the robot. I call this concept a robot's "anti-anonymity". To put it simply, the concept refers to the visibility of the face and figure of the robot's user.

In general, there are two major uses of one's other-self-robots: one is to transcend time and space by expanding one's existence, and the other is to supplement and extend human abilities by using the robot as part of oneself, as exemplified by artificial arms and seeing-eye dog robots [20]. Furthermore, the ultimate use of the other-self-robot would be to make an appreciator of oneself. It is a copy of oneself, including its intelligence. The robot would memorize the intelligence and the behavioral patterns of its user by being used through telexistence. The robot becomes, so to speak, the replica of its user.

Computers can imitate language and memory; however, only robots can imitate behaviors. One's other-self-robot spends its daily life with its user as the other-self or a companion, thereby recording that human individual's behaviour. The robot can exist after the user's death, serving as the remnant of the deceased person, together with his photos, recorded voice, videotaped images, writings, paintings, and music compositions that the person leaves behind. The other self-robot therefore has a more extended use than the robot as an independent being.

Thus "one's other-self," "anti-anonymity," and "safety intelligence" will be the three pillars of technical elements that are essential to future robots. As previously noted, the other self must be part of oneself even though it is physically separated, as the self and the other self share their lives. Accordingly, the other-selfness is the key to robots working in daily life space. Research on this topic must take the concept of the human body into consideration.

Anti-anonymity means visibility of the user's face and figures. The robot must indicate its user every time it is in use through telexistence via a network. One needs not explain how dangerous the world would be without a system that enables this visibility of the user. In addition, the importance of safety intelligence is evident for one's other-self robots as well.

A paradigm shift is essential in this research in the sense that the research of intelligence should not be focused on finding out and replicating the working of human intelligence; the safety intelligence is a far more important and pressing topic for research. Pursuit of research concerning these three elements are essential to future technology as a whole, and will lead to the realization of twenty-first century robotics, i.e., Next-Generation Human-Robot Networked Systems.

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