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Original Research

Developing a Telepresence Robot for Interpersonal Communication with the Elderly in a Home Environment

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ABSTRACT

"Telepresence" is an interesting field that includes virtual reality implementations with human–system interfaces, communication technologies, and robotics. This paper describes the development of a telepresence robot called *Telepresence Robot for Interpersonal Communication (TRIC)* for the purpose of interpersonal communication with the elderly in a home environment. The main aim behind *TRIC*'s development is to allow elderly populations to remain in their home environments, while loved ones and caregivers are able to maintain a higher level of communication and monitoring than via traditional methods. *TRIC* aims to be a low-cost, lightweight robot, which can be easily implemented in the home environment. Under this goal, decisions on the design elements included are discussed. In particular, the implementation of key autonomous behaviors in *TRIC* to increase the user's capability of projection of self and operation of the telepresence robot, in addition to increasing the interactive capability of the participant as a dialogist are emphasized. The technical development and integration of the modules in *TRIC*, as well as human factors considerations are then described. Preliminary functional tests show that new users were able to effectively navigate *TRIC* and easily locate visual targets. Finally the future developments of *TRIC*, especially the possibility of using *TRIC* for home tele-health monitoring and tele-homecare visits are discussed.

INTRODUCTION

TELEPRESENCE IS AN INTERESTING FIELD that includes virtual reality implementations with human–system interfaces, communication technologies, and robotics. The earliest research in telepresence dates back to the 1960s. Goertz, in 1965, and Chatten, in 1972, showed that when a video display is fixed relative to the operator's head and the head's own pan-and-tilt drive the camera's pan-and-tilt functions, the operator feels as if she were physically present at the location of the camera, however remote it is.[1]

Sheridan defines telepresence as: " . . . visual, kinesthetic, tactile or other sensory feedback from the teleoperator to the human operator that is sufficient and properly displayed such

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that the human feels that he is present at the remote site, and that the teleoperator is an extension of his own body."[1,2] Whereas Akin et al.[3] describe telepresence such that, "At the worksite, the manipulators have the dexterity to allow the operator to perform normal human functions. At the control station, the operator receives sufficient quantity and quality of sensory feedback to provide a feeling of actual presence at the worksite." These two definitions emphasize control and sensory feedback between the human operator and the "teleoperator" or the "manipulator at the worksite."

Draper[4] discerns three definitions of telepresence: the simple, the cybernetic, and the experiential. In the simple definition, telepresence refers to the ability to operate in a computer-mediated environment. In the cybernetic definition, telepresence is an index of the quality of the human–machine interface. In the experiential definition, telepresence is a mental state in which a user feels physically present within the computer-mediated environment.

Schloerb defines telepresence from the point of view of an "observer," "a person is objectively present in a real environment that is physically separated from the person in space."[5] He uses three types of specifications to make the definitions more precise: (1) a set of tasks, (2) a transformation imposed on the human operator's control output and sensory input, and (3) a transformation of the region of presence. The degree of objective telepresence is equal to the probability of successfully completing a specified task. Schloerb also proposed that perfect telepresence occurs when the operator cannot discriminate virtual from reality.

To summarize, telepresence provides a connection between a user (or the "operator" as defined by Sheridan and Akin) and a distant participant or an environment (real world or computer-generated world), to perform social interactions (user–participant interactions) or specific tasks (user–environment interactions). In this research, we are interested in the application of a telepresence robot for communicating and interacting between the "user" and the "participant" in a remote site. In such applications, the remote participant is not only an "observer" as in Schloerb's definition, but also a "dialogist" in the interpersonal communication.

Following this framework, there are two views in telepresence application for interpersonal communication: the user's view and the participant's view, as depicted in Figure 1. From the user's view, telepresence enables the user to project herself/himself to another place by controlling the telepresence robot or system. In the meantime, the user perceives immersion from the sensory feedback from the remote environment created by telepresence.

As discussed earlier, the "participant" may have two roles in telepresence application in interpersonal communication: as an observer and a dialogist. From the participant's view as an observer, telepresence provides necessary elements to the user and the telepresence robot, so that the participant recognizes the telepresence robot as a representation of the user. From the participant's view as a dialogist, telepres-

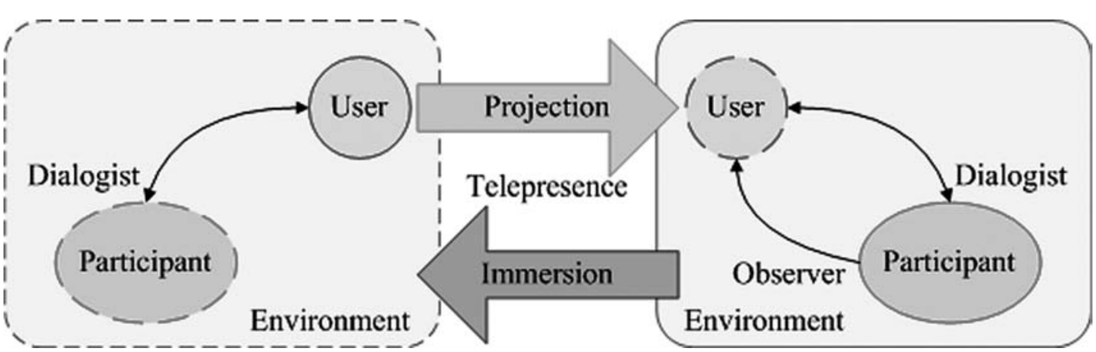

FIG. 1. The framework of projection-immersion and observer-dialogist.

ence also enables dialogue between the participant and the user by transmitting audio, video, gestures, physical movements, and other environmental information between the participant and the user, which are helpful for effective communication.

For interpersonal communication, telepresence differs from traditional video conferencing by establishing a true sense of shared space among geographically remote persons. By duplicating the three-dimensional human experience via actual face-to-face encounters, telepresence is a stunningly different way to telecommunicate.

Applying robotic technology for homecare of the elderly

Many developed countries are facing the problems associated with an increasing elderly population. The need of healthcare for the elderly, both physiologically and psychologically, is an urgent issue. In particular, many elderly people desire to stay in their own private residences for as long as possible, and thus methods are needed to allow them to do so safely and at a reasonable cost. Development of service robots to assist elderly people in activities of daily living (ADL) or to improve their quality of life (QOL) in a home environment is an important research field.

Prassler et al.[6] developed the robotic wheelchair Mobility Aid for Elderly and Disabled People (MAid) to support and transport elderly people with limited motion skills and to provide them with a certain amount of autonomy and independence. Kiguchi et al.[7] developed robotic exoskeletons to assist the mobility of physically weak persons such as the elderly, the disabled, and the injured. The control of the robotic exoskeleton is based on electromyography (EMG) signals, as EMG signals are imperative signals to understand how the user intends to move.

Robots are not only used for physiological assistance but also can provide psychological consolations for elderly people. Wada et al.[8] tested a seal-type animal robot "Paro" at a daycare service center to investigate its effects on the elderly. After interaction with Paro, the face scale scores of elderly people were classified as "good," and their vigor scores in the questionnaires were considered high, confirming that Paro improved the mood of elderly people and made them more vigorous. Kanamori et al.[9] also examined the usefulness of pet-type robots named AIBO among elderly patients and handicapped persons in nursing homes or in home environments via biochemical markers, self-assessment, or health-related QOL questionnaires.

In slight contrast, Pollack et al.[10] developed "Autominder," an intelligent cognitive orthotic system intended to help older adults adapt to cognitive decline and continue satisfactory performance of routine activities, thereby potentially enabling them to remain in their own homes longer. Lytle[11] presented a robotic care bear whose purpose was to watch over the elderly residents in a hi-tech retirement center. The Teddy-like bear could record how long the residents spent performing various tasks and assisted in monitoring the residents' response times to spoken questions, before relaying conclusions to staff or altering them of unexpected changes.

In telepresence research, there have been few examples in the field of medical care, emphasizing the use and application of telepresence robots as a tool for interpersonal communication. "Physician-Robot" is a telepresence robot developed by Intouch-health Company in cooperation with Johns Hopkins University for physicians to easily and more frequently visit with hospitalized patients.[12] Physicians operate the robot with a swiveling video camera and computer screen mounted on a mechanical base by guiding it through patients' rooms via a remote-control joystick. By communicating through the hospital's virtual private network (VPN) and an 802.11b wireless network, doctors at home or out of town can teleconference with and examine patients. Physician-Robot is not expected to replace visits from real physicians, but is to act as an extension of physician–patient contact. In the evaluation at the Johns Hopkins University Hospital, patients are more satisfied because physicians spend more time with them.

Providing Education By Bringing Learning Environments to Students (PEBBLES), a telepresence system, is developed to unite medically fragile children who are hospitalized for prolonged periods with their regular school site. PEBBLES was developed in Canada by a private company called Telbotics, in cooperation with Ryerson University and the University of Toronto. A PEBBLES system consists of two child-sized robots capable of transmitting video, audio, and documents to each other. One unit is placed with the hospitalized child and the other unit is located in the child's regular classroom. The units are connected via a high-speed communications link. The classroom unit has a swiveling monitor that duplicates human head movement and a hand that serves as an attention-getting device. PEBBLES creates a virtual presence for the remote child in the classroom. The presence is so real that in the many evaluation cases teachers and fellow students come to react to the school unit as if it were the hospitalized child.[13]

Telepresence robot for interpersonal communication

Aging is associated with an increased risk for isolation. However, social interaction can delay the deterioration and associated health problems of elderly people.[14] This paper describes the development of a telepresence robot called *Telepresence Robot for Interpersonal Communication (TRIC)* for interpersonal communication with the elderly in a home environment. The main aim behind *TRIC*'s development is to allow elderly populations to remain in their home environments, while loved ones and caregivers are able to maintain a higher level of communication and monitoring via traditional methods.

TRIC is positioned as a low-cost, lightweight robot, which can be easily implemented in the home environment. Actually the *TRIC* robot is intended to be used as often and as easily as a home appliance. It is expected that *TRIC* not only provides a convenient interactive communication device for family members and caregivers to communicate with and express care to elderly people, but also a tool for tele-homecare visits by doctors or nurses, and a tool for home tele-health monitoring tasks such as measuring vital signs (blood pressure, glucose, etc.), and monitoring ADL.

Section 2 of this paper reviews the recent and relevant research literature in the field of telepresence, with an emphasis on the various design elements used throughout. Decisions on the design elements included are discussed in Section 3. In particular, the implementation of key autonomous behaviors in *TRIC* to increase the user's capability of projection of self and operation of the telepresence robot, in addition to increasing the interactive capability of the participant as a dialogist are emphasized. Section 4 describes *TRIC*'s hardware design. Focus then shifts to human factors considerations and interface design in Section 5. Section 6 describes preliminary evaluations of *TRIC*, followed by the concluding remarks in Section 7. Future developments of *TRIC*, especially the possibility of using *TRIC* for home telehealth monitoring and tele-homecare visits are discussed.

Design elements in telepresence systems

This section surveys the application-oriented telepresence literature which describes the development of a telepresence system. The design elements emphasized in these studies are extracted and summarized in Table 1. A discussion of these design elements as they fit into the framework of projection-immersion and

TABLE 1. DESIGN ELEMENTS AND RELATED TECHNOLOGICAL KEYWORDS FOR TELEPRESENCE

Design elements	*Related technological keywords*
Data transmission	RF and Internet transmission, time-delay improved algorithm
Teleoperation	Simultaneous operation, robotic design
Supersensory	Dexterous mechanism
Anthropomorphic elements	Humanoid mechanism and expression
Stereoscopic elements	Binocular and panoramic vision, image processing
Stereophonic elements	Head-related transfer function, stereo audio
Eye contact	Camera and screen with specific placement
Autonomous behaviors	Environmental map establishment, self-maintenance capability

observer-dialogist illustrated in Figure 1 in the previous section is given below.

Data transmission. Data transmission, the transmission of control commands and sensory feedback, is a basic design element for the connection between the user and the remote telepresence robot or system. Wireless radio frequency and Internet are used in most telepresence applications, and dedicated lines are used in specific applications (such as operation in space and deep sea).

From the user's view, timing of data transmission is important. Time delays would degrade the telepresence performance in both projection and immersion of the user. From the participant's view, the time delays also affect the participant's impression as an observer and interactive capability as a dialogist. Therefore, past telepresence research in data transmission focused on the development of a control scheme to deal with time delays for promoting performance.[15,16]

Teleoperation. Many studies in telepresence emphasize on enabling the user to modify the remote environment[17–19] that is, projecting the user to the teleoperator. A teleoperator is a machine that extends the user's sensing and/or manipulating capability to a location remote from that user. Teleoperation refers to direct and continuous human control of the teleoperator.

NASA's Full-Immersion Telepresence Testbed (FITT), which combines a wearable interface integrating human perception, cognition and eye–hand coordination skills with a robot's physical abilities, is a recent example of research in teleoperation.[20] The teleoperated master–slave system "Robonaut" allows an intuitive, one-to-one mapping between master and slave motions. The operator uses the FITT wearable interface to remotely control the Robonuat to follow the operator's motion fully in simultaneous operation to perform complex tasks in the International Space Station.

Supersensory. Supersensory refers to an advanced capability to modify the remote environment provided by a dexterous robot or a precise telepresence system. From the user's view, the user's manipulative efficiency for special tasks is enhanced when projecting onto a telepresence robot with supersensory. Green et al.[21] developed a telepresence surgery system integrating vision, hearing, and manipulation. It consists of two main modules, a surgeon's console, and a remote surgical unit located at the surgical table. The romote unit provides scaled motion, force reflection, and minimized friction for the surgeon to carry out complex tasks with quick, precise motions. Satava,[22] Schurr et al.,[23] and Ballantyne[24] have also applied supersensory in telepresence surgery.

Supersensory elements can also provide the user with a novel immersion feeling in a remote environment. For example, the user can control the zoom function of the camera on a telepresence robot to observe the small details of the remote environment, which the user does not normally see with the naked eye.

Anthropomorphic elements. In telepresence applications, nonanthropomorphic telepresence robots are usually designed to perform specific tasks. Many researches added anthropomorphic elements to their telepresence robots in order to improve the interaction between users and participants.[25–28] From the participant's view, anthropomorphic elements enhance the impression of the telepresence robot as a true representation of the remote user. The friendly interface and characteristics of the anthropomorphic telepresence robot also increase the interactive capability of the participant as a dialogist.

From the participant's view, the basic requirement for interpersonal communication using telepresence is that the participants must realize whom the telepresence robot represents. Therefore, the primary anthropomorphic element incorporated is the user's face displayed on an LCD screen mounted on the telepresence robot. Both Dr. Robot and the telepresence system PEBBLES described in the first section of the paper use an LCD screen to display the user's face.

In addition to using the LCD screen, creating mechanical facial expressions is another interesting field in robotic research.[29] Mechanical facial expressions can also be used to increase the humanoid characteristics of the telepresence robot to further encourage people to interact and communicate with the user.

Stereoscopic and stereophonic elements. In telepresence research, stereoscopic and stereophonic design elements are often emphasized to create a telepresence illusion of the remote environment or people aiming to increase the feeling of immersion for the user. For example, the user can identify the distance between an object and the telepresence robot by binocular vision;[30] the head-related transfer function (HRTF) for stereophonic effect enables the user to identify the location and direction of a sound.[31]

Telepresence videoconferencing is an important application using stereoscopic and stereophonic elements.[32–34] Telepresence videoconferencing enables the users and the participants to communicate more efficiently. In other words, the interactive capability of the participant as a dialogist is enhanced. Lei et al.[35] proposed a representation and reconstruction module for an image-based telepresence system, using a viewpoint-adaptation scheme and an image-based rendering technique. This system provides life-size views and 3D perception of participants and viewers in videoconferencing. The purpose of this research is to provide the feeling of a virtual-reality presence, in which realistic 3D views of the user should be perceived by the participant in real time and with the correct perspective.

Eye contact. In telepresence applications, eye contact can increase the immersion feeling of the user and the interactive capability of the participant as a dialogist. The only means to provide eye contact during interpersonal communication between the user and the participant through a telepresence robot is when the face of the user is displayed on an LCD screen. However, the placement of the camera on a telepresence robot is usually on top of the LCD screen, which hinders direct eye contact between the user and the participant through the telepresence robot.

Hopf[36] proposed an implementation of an autostereoscopic desktop display suitable for computer and communication applications. The goal of this research is to develop a system combining a collimation optic with an autostereoscopic display unit to provide natural face-to-face and eye contact communication without causing eye strain.

Autonomous behaviors. In principle, a telepresence robot is operated by a remote user, and does not possess autonomous behaviors. However, the telepresence robot should be able to deal with possible hazardous situations autonomously when the remote user is not aware of the hazardous situation, cannot control the telepresence robot properly, or the data transmission is lost. From the user's view, autonomous behavior increases the user's capability of projection to operate the telepresence robot safely and reliably in a dynamic environment. From the participant's view, autonomous behavior also increases the interactive capability of the participant as a dialogist. For example, a telepresence robot with the autonomous behavior of identifying the direction of the participant who is speaking can assist the remote user to respond more quickly and properly.

An interactive museum tour-guide robot was developed by two research projects TOURBOT and WebFAIR, funded by the European Union.[25–28] Thousands of users around the world controlled this robot through the Web to visit a museum. They developed a modular and distributed software architecture which integrates localization, mapping, collision avoidance, planning, and various modules concerned with user interaction and Web-based telepresence. With these autonomous features, the user can operate the robot to move quickly and safely in a museum crowded with visitors.

Basic data transmission structure and design elements of TRIC

As mentioned earlier, the telepresence robot *TRIC* developed in this research aims to be a low-cost, lightweight robot, which can be easily implemented in the home environment. Therefore the primary decision was whether to use the Asymmetric Digital Subscriber Line (ADSL) and the Wireless Local Area Network (WLAN), which are commonly found in the home environment, as the channel of data transmission.

Two-way audio and one-way video communication can be transmitted through a network Internet Protocol (IP) camera, which is also a common tool for home monitoring.

Instead of using a PC, a Mobile Data Server (MDS) was developed as the core of *TRIC*. Figure 2 shows a picture of the laboratory prototype of the MDS, which consists of a PIC server mounted on a peripheral application board. The PIC server integrates a PIC microcontroller (PIC18F6722, Microchip, Chandler, AZ), EEPROM (24LC1025, Microchip) and a networking IC (RTL8019AS, Realtek, Taiwan, ROC). It provides networking capability and can be used as a Web server. The peripheral application board as well as the program in the PIC microcontroller can be easily customized to adapt to different sensors and applications. The dimensions of the MDS prototype are $40 \times 85 \times 15$ mm. Internet and serial interface (RS-232) are the primary communication interfaces of the MDS with client PCs and other devices. The MDS also receives external signals (e.g., sensor signals) through specific analogue or digital I/O ports, and provides interintegrated circuit (I^2C) communications to allow connections with external modules. A Multi-Media Card (MMC) in the MDS can be used to store data in FAT16 file format. Compared to a PC, the MDS is low cost, has smaller dimensions, consumes less energy (thus, can be powered by batteries), is not affected by viruses, and is safer and more reliable.

Figure 3 shows the basic data transmission structure of *TRIC*. The user projects herself/himself to *TRIC* in the remote environment by sending control commands to *TRIC* through the Internet gateway. The user is able to immerse in the remote environment from the sensory feedback transmitted through the Internet gateway. *TRIC* uses a WLAN the the connector by connecting to the WLAN in the home environment. MDS takes charge of receiving commands from the user and sending commands to specific modules which coordinate with each other to perform specific tasks. Finally, the user can have physical interaction and verbal communication with the participant by controlling *TRIC* as his/her physical extension in the remote environment.

Under this basic structure, Table 2 lists the design elements currently planned for the design of *TRIC*. The implementation of teleoperation in *TRIC* is quite fundamental. Teleoperation allows the user to move *TRIC* through the environment while controlling the pan and tilt of the IP camera from a remote client PC. Supersensory ability is reflected in the zooming capability of the IP cam and the sensing capability of the various sensors installed for environment detection. With the limited processing ability of the MDS, the user's face cannot be displayed (so eye contact is also not possible on this telepresence robot). Instead, mechanical facial expressions are incorporated as the anthropomorphic element. Sophisticated

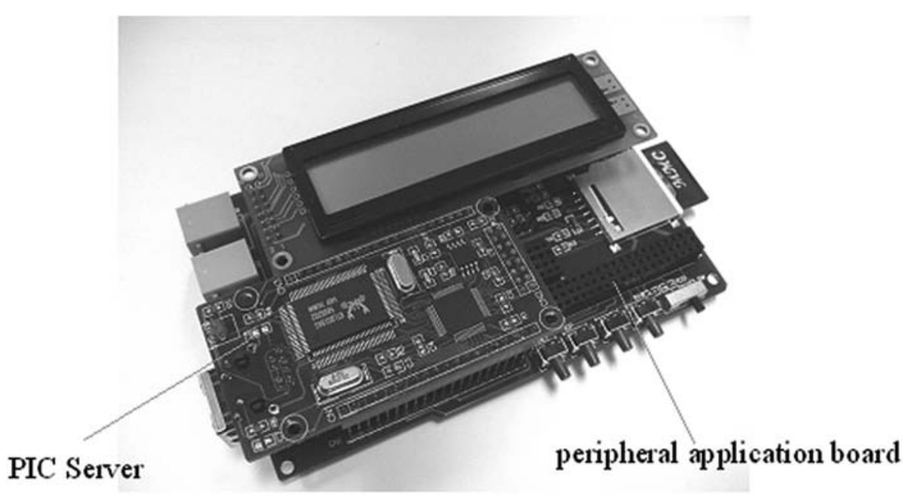

FIG. 2. A picture of the laboratory prototype of the MDS.

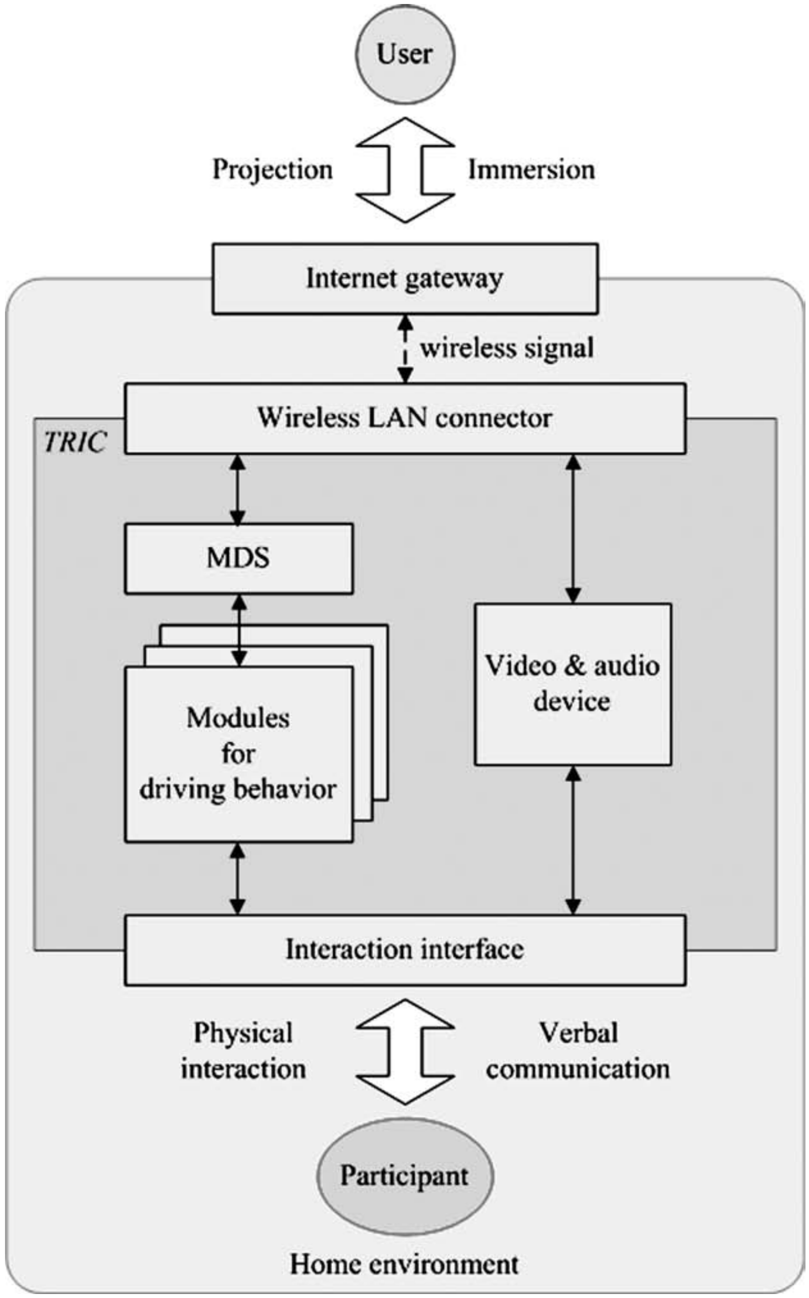

FIG. 3. The data transmission structure of *TRIC*.

stereoscopic and stereophonic elements have been omitted to keep *TRIC* a low-cost, affordable homecare robot.

Autonomous behavior is the design element that received the most attention during the planning of *TRIC*. In principle, a telepresence robot is operated by a remote user who possesses complete control authority. However, a major emphasis of this research is to implement key autonomous behaviors in *TRIC* in order to increase the user's operating capability and reduce the user's workload during operation. By doing so, the aim was to also increase the interactive capability of elderly people as reciprocal communicators.

Adding autonomous behaviors implies that the control authorities of the telepresence robot are shared with the participant or the environment it is interacting with. Several possible features for sharing control authority with the remote participants are discussed below.

TABLE 2. DESIGN ELEMENTS INCLUDED IN *TRIC*

Design elements	*Corresponding technological strategies*
Data transmission	Use MDS for the core of system
Teleoperation	Design of mobility platform
Supersensory	Provide zoom of IP cam, implement various sensors for environment detection
Anthropomorphic elements	Design of mechanical facial expression
Stereoscopic elements	Not included
Stereophonic elements	Not included
Eye contact	Not available
Autonomous behaviors	Share control authority to participate and environment

"Look at that!" Participants engaged in a face-to-face conversation often share the same view by pointing to an object in discussion. However, it will be difficult for the user to either point to a certain object or to find the object the remote participant is pointing at through the telepresence robot. A 2 degree-of-freedom robot arm equipped with a laser pointer is used as a joint attention device to realize the "look at that!" function. The remote participant can direct the view of the telepresence robot by pointing the laser pointer to the object in question.

"Where is the speaker?" It is not easy for the user to locate the source of sound in 3D space through the telepresence robot. When interacting with the remote participant, "Where is the speaker?" enables the telepresence robot to automatically locate and track speakers without control from the user. With this feature, the participant controls the telepresence robot by using her/his own voice.

"Come here!" and "Follow me!" In "Where is the speaker?" the telepresence robot can locate the source of the sound. Therefore the "Come here!" feature allows the user to command the telepresence robot to go to the source of the sound. "Follow me!" is another interactive behavior which is common in interpersonal communication. The passive infrared motion sensors combined with ultrasonic range-finding sensors are used to perform the low-cost and reliable function of "Follow me!" where *TRIC* continuously follows the intended participant.

Several possible modes in sharing control authority with the remote environment are discussed below.

Obstacles avoidance. It is difficult for the user to identify environmental information from the robot's limited viewing angles. Therefore, automatic obstacle avoidance is necessary. When an obstacle is detected within a specific distance from the robot, the obstacle avoidance algorithm is activated, and the robot deviates from the movement direction controlled by the user in order to avoid this obstacle.

Self-maintenance. The most fundamental self-maintenance function is the ability of *TRIC* to automatically recharge its battery when needed. This includes the ability to detect energy capacity, self-positioning to locate and move to the charging station, and automatic parking control to dock the robot in the charging station.

Hardware design of TRIC

Figure 4 shows a picture of *TRIC*, and Figure 5 shows its spatial configuration. *TRIC* integrates an MDS, an IP camera with pan/tilt/zoom functions and two-way audio communications, a wireless LAN adaptor pair, a speaker and microphone, and a 12-V LiFePO4 battery (10 Ah) with power management system, all within a mobile platform. Table 3 summarizes the basic specifications of *TRIC*.

In Section 3, the basic data transmission structure has been defined (Fig. 3). Following this structure, Figure 6 shows the control structure for *TRIC. TRIC* has its own IP address and is connected to the world via a wireless Internet link. The WLAN adaptor pair provides a standard wireless network for the MDS and IP camera. The MDS is the core of *TRIC* for data transmission, which receives commands from

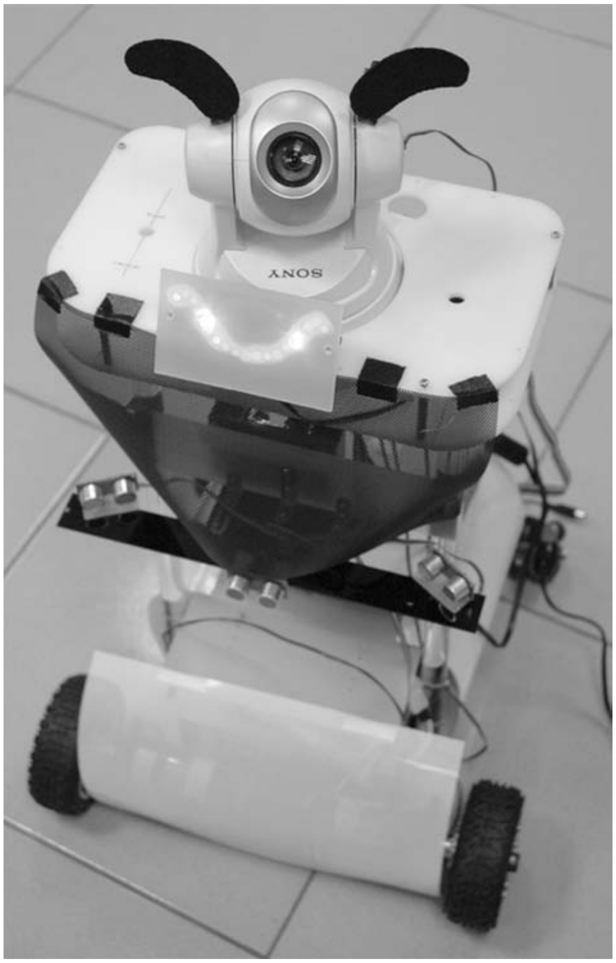

FIG. 4. A picture of *TRIC*.

the user via the Internet and sends commands to the various modules using the I2C bus.

As shown in Figure 6, currently three modules have been implementd: the IP camera with facial expression control module, the environmental perception module, and the DC motor driver (DMD) module. Each module has one slave microprocessor for control and data processing, but the master MDS has higher priority for taking corrective actions from the user's decisions. The design of each module is described in details below.

IP camera with facial expressions control module. The controls of pan/tilt/zoom functions for IP camera, controls of facial expressions, and a passive 2 degrees-of-freedom arm are integrated into a module. The IP camera provides RS232 interface for controlling its pan/tilt/zoom functions. The slave microcontroller receives pan/tilt/zoom control commands from master MDS then sends them to the IP camera via RS232 interface. Facial expressions are created via the various positioning of eyebrows and an LED mouth. Motions of eyebrows are driven by two servomotors. A matrix of light-emitting diodes (LEDs) is implemented to display happiness, sorrow, and normality. Motions generated by servomotors and LEDs symbolize emotions of the user.

The joint attention "Look at that!" function described in Section 3 is achieved by the passive 2 degrees-of-freedom arm. The participant manipulates the passive arm equipped with a laser pointer to point to a specific direction, which is then measured and transformed into viewing coordinates for the IP camera. Then the user activates the "Look at that!" function from a remote client PC, and the IP camera rotates to the viewing angle so that the user shares the same view as the participant.

DC Motor Driver (DMD) module. *TRIC* has two differential driving wheels on its middle axis. Its mobility is controlled by the DMD module that includes a slave microcontroller driving two motor controllers with H-bridge DC motor control circuits. Each motor is equipped with an incremental encoder counting 128 clocks per rotation. Velocity and position data are available from two optical encoders for precise closed loop control. The slave microcontroller in DMD module performs four basis tasks: (1) communication with the master MDS via I2C bus, (2) generation of Pulse Width Modulation (PWM) duty cycle, (3) reading counts from each encoder, (4) reading 4-bit binary code from an environmental perception module.

The DMD module receives commands from the user through the Internet, so that the user can navigate *TRIC* to move around freely in the remote environment. The DMD module also cooperates with other modules to achieve the autonomous behaviors described in the previous section.

Environmental perception module. The environmental perception module is designed for the user to acquire information about the environment around *TRIC*. This module uses six ul-

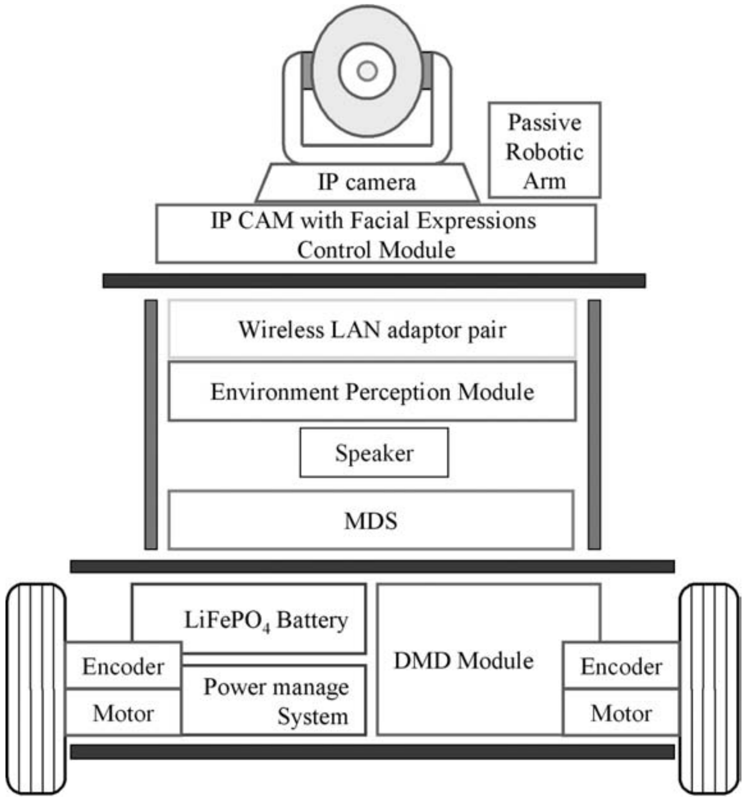

FIG. 5. Spatial configuration of *TRIC*.

trasonic sensors, a digital compass, and a temperature sensor for environment perception, collision detection, and the "follow me" function. Six ultrasonic sensors, with frequency of 40 kHz, an effective range of roughly 3 cm to 4 m, and approximately 20 to 35 degrees of measurement cone, are arranged around *TRIC* as shown in Figure 7. The slave microcontroller in this environmental perception module manages measurements from the ultrasonic sensors to generate information such as whether there are objects around *TRIC*. Urgent stop or backward commands are then sent to the master MDS when objects are detected in the "close" region in front of *TRIC*.

Human factor and interface design of TRIC

As mentioned earlier, the *TRIC* robot is intended to be used as often and as easily as a home appliance. Therefore, human factors considerations are very important. The current height of the robot is 75 cm, with the camera positioned at approximately 70 cm tall. At this height, optimal viewing distances were determined to fulfill two human factors considerations: limiting neck flexion to less than 20–30°[37] during prolonged interaction, and maintaining an acceptable viewing distance for the elderly.[38] Anthropometric data on Taiwanese elderly was used to determine appropriate horizontal positioning distances for taller and shorter participants between themselves and the robot.[39] When the participant is standing, the optimal viewing distance lies between 110 to 154 cm, depending on the height of the participant.

The weight of *TRIC* is approximately 8.7 kg when the battery pack is installed. This is the lowest achievable weight of *TRIC* while maintaining all of its current functions. Two common ergonomic tools were used to assess the weight of the robot for lifting purposes from a height of 12″ to a height of 32,″ with a horizontal distance of 12,″ and a frequency of 1/8 hours or once a day. Both the revised National Institute for Occupational Safety and Health (NIOSH) lifting equation[40] and Mital et al.'s[41] tables for lifting/lowering limits resulted in a lifting limit of 15 kg for 90% of the female pop-

Table 3. Specifications of *TRIC*

L × W × H	*400 × 410 × 750 mm*	*Battery type*	*$LiFePO_4$ Li-ion*
Weight	8.7 kg	Battery capacity	12.8 V 10Ah
Speed	20–25 cm/seconds	Battery operation time	120–150 minutes
Circumrotation radius	34.5 cm	Battery recharge time	90 minutes (6A)

ulation. However, since *TRIC* was designed to communicate with elderly participants, a correction factor for age was needed to account for decreases in strength. From the graph depicting a decrease in total body strength with age by Voorbig and Steenbekkers,[42] at 80 years and above, strength falls to 57% of peak body strength among women. Therefore, the 15 kg limit found via the revised NIOSH lifting equation and Mital's Lifting/Lowering tables was multiplied by 0.57 to result in a corrected lifting limit of 8.55 kg. This new limit accounts for a larger majority of the general population than set by typical ergonomic standards, and accounts for the majority of elderly populations as well. The weight of *TRIC* falls within 0.15 kg of the new corrected lifting limit. Thus, we can assume a low risk of injury among a large majority of the general and elderly population for lifting and lowering *TRIC* once a day from the locations mentioned above.

It is also suggested to maintain *TRIC* 's speed below typical walking speed—1.2 m/second for pedestrian crossings, but higher than the lowest walking speed found among elderly people undergoing rehabilitation—0–0.17m/second, to prevent collisions from occurring due to differing speeds between the robot and

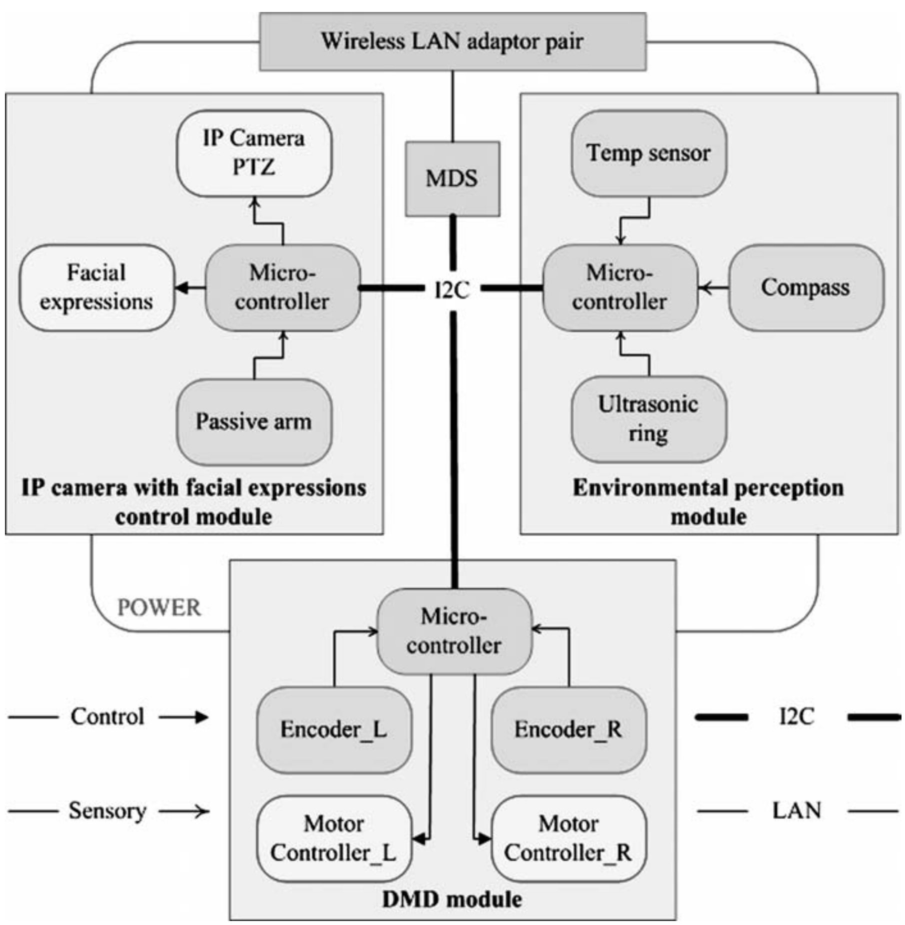

FIG. 6. Hardware architecture of the control system.

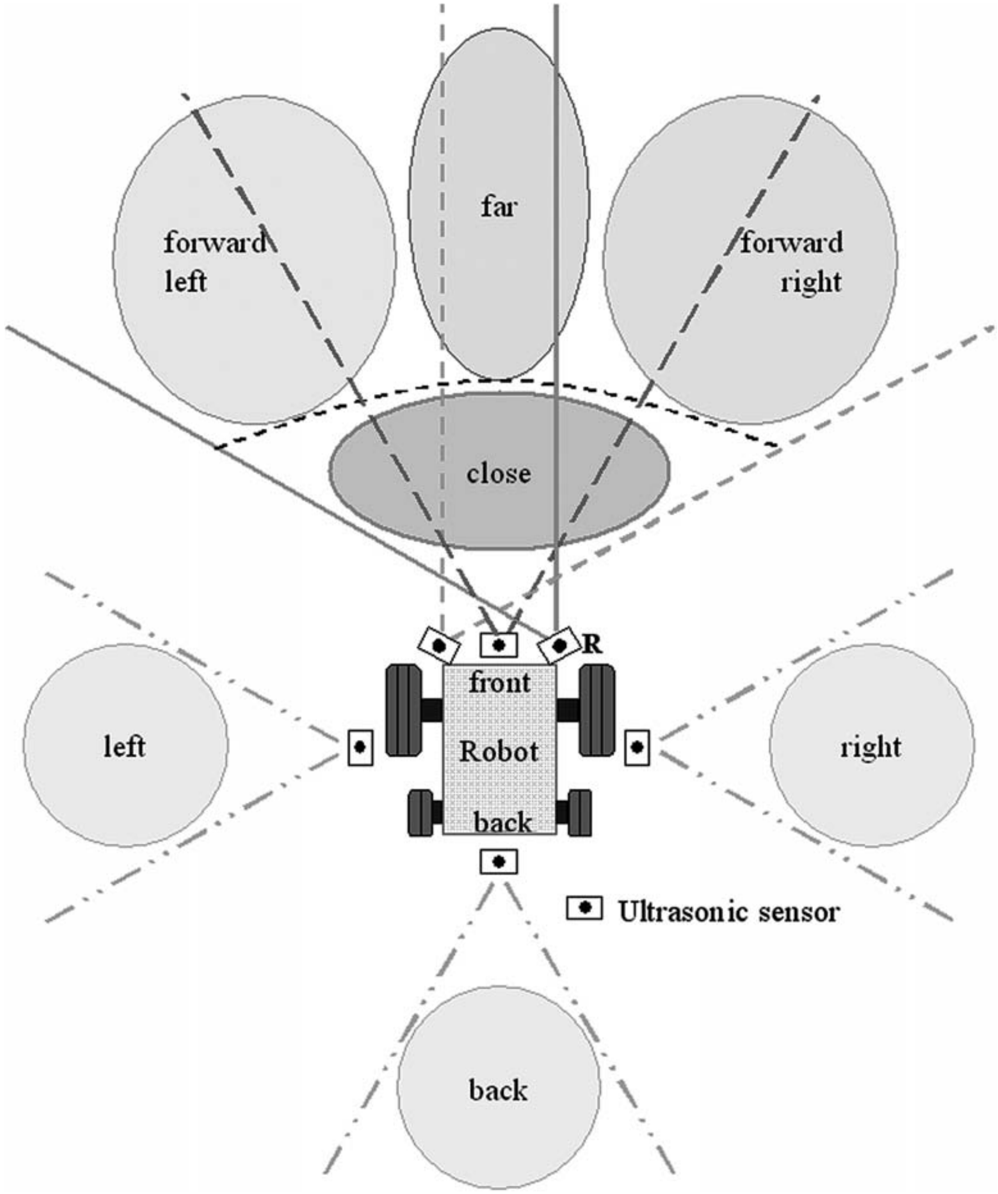

FIG. 7. A specific arrangement of six ultrasonic sensors.

the participant, while maintaining a reasonable speed of transportation for the user.[43] Therefore the current speed of the robot is set to 23 cm/second. In addition, the robot is equipped with obstacle detection sensors that cease the robot's motion when a certain minimum distance is breached. This will also prevent the robot from colliding with its participants and the participant's environment.

A primary consideration for communication between the user and the participant via *TRIC* is sound quality for projection and receiving. It has been identified that as we age we prefer louder sounds for hearing speech sounds adequately.[44] For this reason speakers capable of 85 dB of sound, with volume control, are mounted to *TRIC* so that elderly participants would be able to hear speech sounds produced by remote users clearly. In addition, the closest point for communication is on *TRIC* 's "head" (the highest point on the robot). Therefore, a microphone is placed as close as feasibly possible to the head of *TRIC* in an attempt to optimize voice capture from the participant to the user. It has also been suggested that a remote control with various functions for *TRIC* be created in the future that would include a microphone to further improve voice capture from the participant.

Figure 8 shows the user control interface for *TRIC* containing five sizeable frames. Each frame provides some panels to handle different tasks. The user first inputs the IP address for the MDS and the IP camera in the upper-right corner. The MDS and the IP camera can share the one physical IP using different ports. An authorization process using passwords can also be implemented.

The large frame on the left-hand side of the screen contains a video image from *TRIC*. The lower left-hand frame provides buttons for controlling the movement of *TRIC*, as well as the button for detecting environmental situations. The frame for environmental situations allows users to adequately assess the distance of objects around *TRIC* by processing the measurements from the environment perception module. Other environmental information such as temperature is also displayed in this frame. The lower right-hand frame provides the control buttons of the IP camera for pan, tilt, and zoom. Users can express emotions by pushing the corresponding buttons in above the IP camera control frame. Basic autonomous behaviors can be activated by pushing the control buttons in the middle right-hand frame.

A preliminary evaluation for usability for the remote user

Experimental data is necessary to assess *TRIC*'s success as a telepresence communication device. *TRIC*'s evaluations will be extensive, as there are two realms of concern. Objective measures of functionality are required from a technical perspective to ensure that *TRIC* is capable of performing each intended command. Objective measures of usability are also required to determine if *TRIC* proves to be a realistic, useful communication tool. Last, subjective measures from users and participants are needed to determine how accepted *TRIC* is in a domestic environment for its intended purpose.

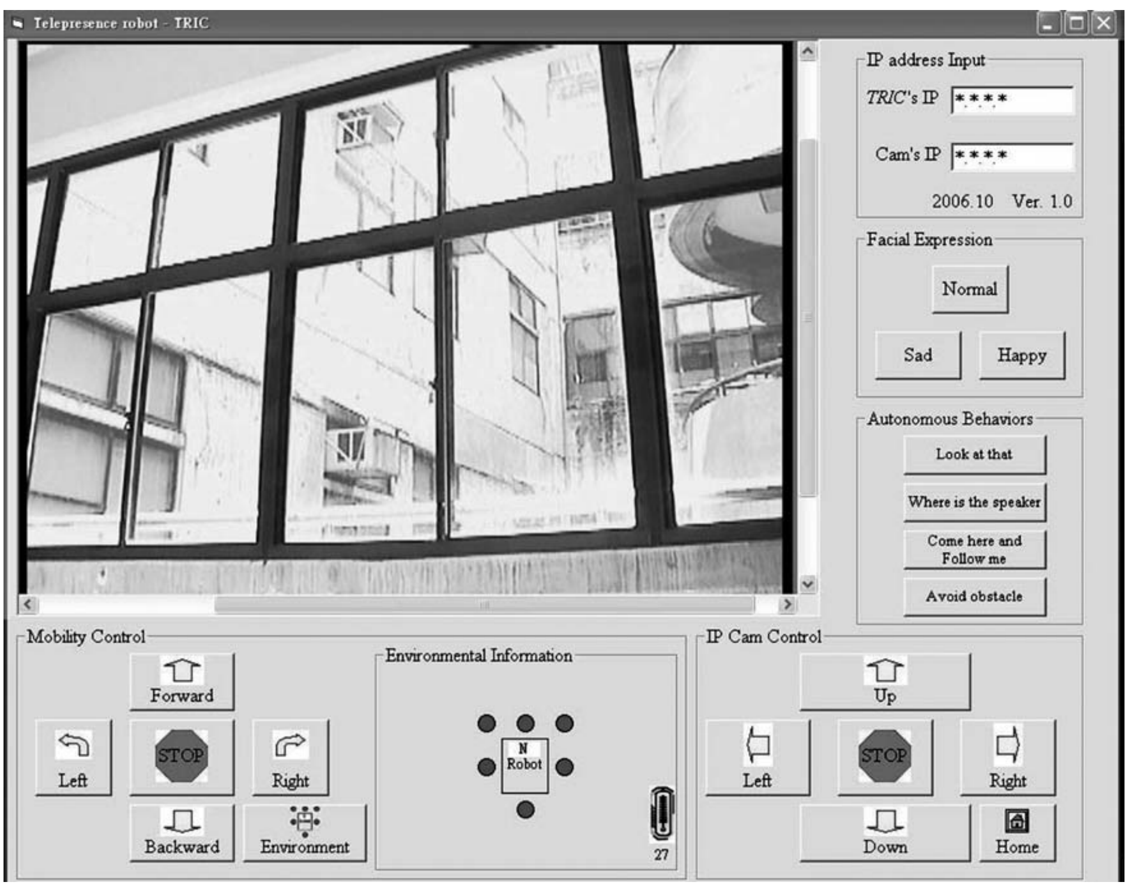

FIG. 8. Control interface for *TRIC*.

This section describes a preliminary evaluation for assessing usability and functionality of *TRIC*. The purpose of the evaluation was to assess how efficient new users were at navigating *TRIC* through a fixed obstacle course (similar to that of a furnished, domestic environment), to assess the efficiency of new users using the multidirectional viewing camera to locate predetermined targets, and to assess whether there was a significant improvement in time across users with practice for both navigation and visual objectives.

In this test, seven users, unfamiliar with *TRIC*'s navigation interface, were asked to navigate *TRIC* through a predetermined route to a specified target (Task A). Once the target was reached, users were then asked to locate two separate target objects with *TRIC*'s adjustable camera in sequential order (Tasks B and C). The test was then repeated two more times by each user (Trial 1 to Trial 3). Users were located in another room such that they had no visual contact with *TRIC* nor the remote environment other than the first-person visual display transmitted to the PC operating interface. In addition, users were familiar with the experimental space and the location of the target objects before testing commenced. This was done as it was assumed that potential users would be familiar with the environment of the participants.

Due to the small number of subjects and subsequent samples, statistical analysis was not conducted on the raw data scores from these preliminary evaluations. Table 4 shows the average time of the seven users to complete each task from Trial 1 to Trial 3. For each task, an "optimal time" achieved by a skilled user after many practices was used as a reference for calculating the "efficiency" of each user on this task. From the efficiency scores, the navigation task (Task A) seems to be the most difficult task for the new user. However, a trend of an increase in percent efficiency from Trial 1 to Trial 3 is clear, which implies that the users' performance improves quickly after practice. The efficiency scores of Task B and C for locating objects in the remote environment through *TRIC* maintained at 80 to 90%, which shows that the users had no difficulty with these tasks.

Overall, it can be assumed that users are able to effectively achieve navigational and visual target goals, while improving with as little as three attempts. Extensive tests are planned in an environment similar to that of the intended use (a domestic environment) with both users and the intended participants (older adults), to determine objectively and subjectively *TRIC*'s practicality as an effective tele-health communication device.

TABLE 4. DATA FOR THE PRELIMINARY EVALUATION FOR USABILITY FOR THE REMOTE USER

	Trial 1	*Trial 2*	*Trial 3*
Task A			
Average time (seconds)	96.43	80.00	69.57
Efficiency	51.85%	62.50%	71.87%
Task B			
Average time (seconds)	22.43	17.71	17.14
Efficiency	71.34%	90.32%	93.33%
Task C			
Average time (seconds)	10.57	10.29	9.57
Efficiency	85.14%	87.50%	94.03%

CONCLUSIONS AND DISCUSSIONS

This paper presents the development of a teleprepresence robot *TRIC*. The main aim behind *TRIC*'s development is to allow elderly populations to remain in their home environments, while loved ones and caregivers are able to maintain a higher level of communication by establishing a true sense of shared space among geographically remote persons.

TRIC allows users to project a sense of self via telepresence. By controlling *TRIC*'s IP camera, navigational actions, real-time voice communication, and limited nonverbal cues the user is able to communicate and monitor the elderly participant in a manner above video–audio communication. Human factors considerations have also been implemented to allow for optimal communication and use by both sets of users (local and remote), and to lessen any risk of potential injury.

With a simplified design in place, safety factors accounted for, and widely accessible via the Internet and a personal computer, it is believed that *TRIC* would be a cost-feasible opportunity to provide an enriched communication and monitoring experience for the elderly, their loved ones, and their caregivers. Preliminary functional tests have shown that new users were able to effectively navigate *TRIC* and easily locate visual targets. Their efficiency in doing so increased significantly in as little as three trials. Further tests in domestic environments with elderly participants are needed to further assess objective functions and to capture subjective ratings on *TRIC*'s potential as an effective communication device.

Besides interpersonal communication, there is also a potential of using *TRIC* for home telehealth monitoring and tele-homecare visits. Figure 9 shows the structure of the Portable Telehomecare Monitoring System (PTMS) developed by the authors.[45] The PTMS is a decentralized system. Instead of using the centralized database structure that gathers data from many households, a single household is the fundamental unit for sensing, data transmission, storage, and analysis in the PTMS. The monitoring data is stored in the Distributed Data Server (DDS), which is exactly the same as the MDS used in *TRIC* inside a household.

As shown in Figure 9, sensing data from sensors embedded in the home environment are transmitted to the DDS, which is the core component of the PTMS. Sensing signals are then processed and stored in the DDS. Authorized remote users can request data from the DDS using an Internet Web browser (through an application server) or a Visual Basic (VB) program (direct access to the DDS). Event-driven messages (mobile phone short messages or e-mails) can be sent to specified caregivers when an urgent situation is detected.

Using the PTMS structure described above, an "Activity of Daily Living (ADL)" monitoring system is under developed using the MDS of *TRIC* as the core to monitor the change in pattern of daily physical activities, to recognize the transition of a senior from a healthy, independent state into a state of incapacity and dependency, and to remind the caregivers to take early actions. Special-designed sensors embedded in the home environment detect activities such as eating, bathing, using the toilet, lying in bed, and watching TV. Sensor signals are transmitted to the MDS through a battery-powered RF transmitter. Caregivers can read real-time sensor data, download historical data,

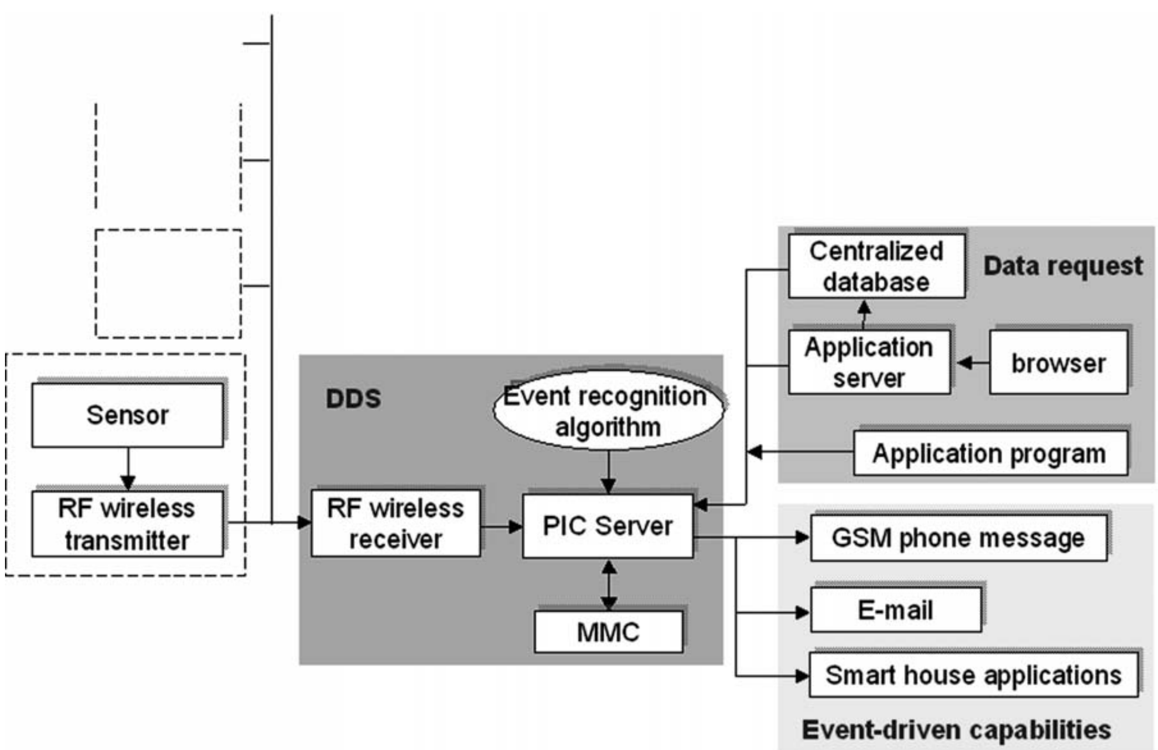

FIG. 9. The structure of the PTMS.

perform various analyses, or set up event-driven messages (mobile phone short messages or e-mail messages) once any sensor is activated.

TRIC can also become a station for vital sign parameter (VSP) measuring. Commercial VSP measuring devices can easily be integrated with the MDS. Integration of an electronic sphygmomanometer and a glucose monitor with the MDS has been successfully demonstrated. The data acquired from these two measuring devices can be transmitted to the MDS through RS-232 serial interface for data processing, storage, and further analyses.

One obvious advantage of using *TRIC* in home tele-health monitoring is its mobility and capability of interpersonal communication. Family members and caregivers can actively approach the elderly participants through *TRIC* to express care if abnormal signals are detected. Doctors and nurses can also use *TRIC* as a tool for tele-homecare visits. Therefore, future development of *TRIC* will emphasize on enhancing its functions in home tele-health monitoring.

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