AUTOSTEREOSCOPY IN MEDICAL TELEPRESENCE: THE MEDICAL READINESS TRAINER EXPERIENCE

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ABSTRACT

Improved sophistication of computer and telecommunications technologies facilitated rapid development of new means of projecting distant environments to the viewer, and giving the latter the sensation of "being there." In its broadest definition, the phenomenon of "telepresence" found its applications in business, education, and industrial and military operations. In medicine, however, with the exception of video conferencing, telepresence has not yet seen any practical uses. The paper describes the first ever creation and operational use of immersive telepresence environments, fusion of immersive telepresence environments with medical simulation devices (Human Patient Simulators), and their first use in the context of distance-based medical training and education.

Key words: medical telepresence, human patient simulators, autostereoscopy, virtual reality, distance education, 3D visualization, stereoprojection, medical training, medical education

1. THE CONCEPT OF TELEPRESENCE

Although the interest in three-D and stereoscopic imaging technology has a long history [1], its recent growth became almost explosive resulting from a combined effect of the technology development and a steady reduction of equipment prices. It is now estimated that by the end of year 2000, over 80% of all personal computers will have 3D accelerators allowing three-dimensional vision and 3D viewing will become the norm rather than exception [2]. The new possibilities opened by the rapidly advancing technology created confusing definitions of underlying concepts, with 3D graphics becoming an equivalent of stereoprojection and viewing [2], and a standard teleconference attaining the status of either 'virtual presence" [3], or assuming, with only a minimal degree of correctness, the mantle of "telepresence"[4,5]. Virtual reality (VR) environments which recreate physical envelopes that, typically, represent a physical location remote from the observer with which the observer may (at least in some instances) interact, have been also considered (with an equal lack of precision) as "telepresence" [6,7,8,9,10,11]. Standard TV transmission may also create sensation of telepresence[12], since the viewers are transported to a remote location at which they experience its live, real time reality as shown by Kim and Biocca [12]. However, in its most restrictive definition, "telepresence" is defined as "the experience of being fully present at a live real world location remote from one's own physical location" [13], where, under the most ideal circumstances, the observer would be able to behave, be stimulated by a variety of sensory inputs, and execute social interactions as if physically present at the remote site [13,14].

VR-based telepresence, while offering many of the attributes demanded by the formal definition of telepresence[14,15] both in the form of essential (but still quite rudimentary) haptic feedback and the environment in which appropriate social/professional interactions can be executed [15,16,17], has also a number of negative aspects. As defined [13], the environment in which the viewer is telepresent already <u>exists</u>. VR environments, on the other hand, need to <u>be created</u>, and the time and costs required to generate them at a convincing level of reality are substantial [16]. Moreover, despite the rapid emergence of low-cost VR systems, e.g.,"gloves&goggles" and PC stations[19,20,21], the complexity and cost of the physical facilities required for advanced immersive VR operations are still prohibitive [10,21,22,23,24] resulting in a comparative scarcity of such installations. Finally, the disturbing physiological side effects of VR exposure [16,25], some of which may persist long enough to affect activities in the non-virtual world [16], introduce yet another use-limiting factor. There is no doubt, however, that immersive VR offers a unique capacity for training complex skills [15,16,26,27,28,29] and preparation for executing complex procedures in unusual environments, e.g., training naval personnel in performing medical interventions in the sick bay of a warship at sea [our own pilot studies], preparation for command of large ships, warfare, etc. Altogether, while VR, particularly the immersive VR, may approach the reality of telepresence, the distant environments created in VR remain an artificial and, strictly speaking, a static creation since the current technology does not allow incorporation of real-time changes of the environment at the remote site as a simultaneous rendition at the VR facility. In summary, VR, while representing an almost ideal vehicle for advanced training [29], does not, despite occasional claims to the contrary [e.g..10], provide a suitable platform for operational activities.

A compromise solution between virtual reality-based telepresence and true telepresence has been also proposed. In these environments a “porthole” or a “portal” concept are used as the means of bridging the gap between passive and active awareness of ones surroundings [30]. In the former case, the system gathers static images of different environments then distributes them within the subscriber network [30]. The system uses a frame comparing software that allows detection of changes indicating human activity. In many ways, the operation of the “porthole”-based monitoring device resembles that of the currently employed perimeter security systems with the solitary difference of automated rather than human operator detected environment changes. The “portal” concept provides high fidelity static VR reconstruction of physical space as a background to the dynamic activity of the remote “collaborator.” [31,32]. The “portal” concept has been developed to its (probably) ultimate level of complexity by the Medical Readiness Trainer (MRT) group at the University of Michigan where combination of immersive VR, human patient simulation, and Internet-based resources allows human operators (emergency room physicians, nurses, paramedics) execute training activities within an almost entirely synthetic environment of an emergency room patient bay [33]. The validity of MRT’s approach as a platform for further development in the realm of advanced distributed learning (ADL) has been recently subjected to successful operational testing [34,35].

In a recently published essay, Eduardo Kac argued that true telepresence may be considered a new form of art [36]. Although the “Ornitorrinco on the Moon” project consists of nothing more elaborate than a telerobotic exploration of space based on the subjective (“whimsical”) commands of the remote operator of the robot, one of the most compelling arguments for the importance of telepresence provided by the author is that of primacy of real time over real space. Due to their very nature, many of the activities that require observation or robotic execution under the command of remote operator must be executed in real time, within the environment that may be subject to almost instantaneous, often unpredictable, changes. However, the “real space” of VR-based telepresence provides only an approximation of real time (by being “preconceived”, VR space determines the temporal nature of all events that may take place within its boundaries, but the temporal relations of these events are, essentially, “pre-planned”). On the other hand, operations such as inspection of hazardous material sites, high explosive disposal, telesurgery, etc. demand a real time, spatially coordinated response to the very real yet frequently random and potentially dangerous demands created within real space – a sudden tear in the repaired blood vessel, a shift of the explosive material resulting in the possibility of an imminent explosion, etc. Therefore, real telepresence, rather than VR-based telepresence, particularly when the former is based on stereoscopic visualization, allows immediate and spatially correct response whose effectiveness depend only on the training of the operator of the remote robotic device, and the performance limits of the device itself. Unsurprisingly, true telepresence found majority of its practical applications in the environments where temporal changes in space provide critical clues that dictate the nature of subsequent actions: in robot-based surveillance of battlefield or nuclear facilities and other hazardous sites [37,38,39], agricultural robot operations [37], remote inspection of commercial and defense facilities subject to international treaty agreements [40], and even as an aid in televisiting remote museums! [41]. Less visualization-dependent telepresence projects concentrate on integrating computers and high speed networks to allow remote control of research instrumentation by the distant users [42,43,44]. However, with the exception of military applications, probably the most dynamic development of advanced telepresence concepts takes place within medicine, particularly surgery.

2. CURRENT TELEPRESENCE VISUALIZATION SYSTEMS

Probably the most critical element of a telepresence system is the manner and quality of the displayed image of the remote site [63]. While the most common display in use is still screen of the desk-top CRT monitor, over the years, several different forms of stereoscopic technologies emerged, ranging from relatively simple to highly complex and costly devices [1,63,64,65,66]. Two types of stereo-viewing (3D) technologies appear to dominate the telepresence scene (63,64). Planar displays using anaglyph (color multiplexing), polarization multiplexing, and field sequential (time multiplexing) approaches are used in order to assure separation of 2D left- and right eye images [1,66]. The other approach is based on location-multiplexed displays represented by Head-Mounted Displays (HMDs), BOOM (Binocular Omni-Orientation Monitor) and, the latest advent on the scene, the 3DDAC (3D Display with Accommodative Compensation) displays. Planar systems require special viewing devices either in form of polarizing or color filters or liquid crystal shutters, the latter either attached directly to the front of the monitor or worn as “shutter glasses” [66]. Typically, sophisticated planar devices (e.g., ImmersaDesk systems) are more expensive than HMDs. Moreover, initial studies have shown that HMDs may be more effective in training interaction with large-scale virtual environments [67, but see 68]. The greatest concern posed by either type of 3D viewing devices is their adverse effect on visual physiology [69,70,71]. The use of HMDs in particular, one of the preferable source of visualization in telepresence robotics [37,38,72,73], has been associated with visual stress and deficits [74,75], general discomfort [75,76], and postural instability [77].

3. AUTOSTEREOSCOPIC DISPLAYS SUITABLE FOR OPERATIONAL USE

Autostereoscopic devices [1,64,65,66] present three-dimensional images without the need for any additional viewing aids. Importantly, autostereoscopic systems offer not only the best optical approximation of the real object [64] but also support the physiological foundations of spatial vision, since there are, essentially, no differences in viewing objects rendered in autostereoscopic display from viewing them under natural conditions [66].

Probably the simplest among all autostereoscopic systems are those based on the re-imaging concept where mirrors (or lenses) are used as the image-transforming device [65]. While the concept is not new [79], the development of a mirror using stretchable membrane [79] made mirror technology a practical tool for 3D visualization. The MIRROR system developed at the University of Strathclyde, UK in association with Ethereal Technologies, Inc. (Ann Arbor, MI}consists of aluminized Mylar film stretched over a carbon fiber frame and tensioned under vacuum to form a concave surface approximately 120 cm across (Fig.1).

The construction of the MIRROR allows user-determined variation of the mirror's f/Number from optically flat surface to approximately f/1. Two lenses project the left and right view at the MIRROR and the projected image plane can be behind, on, or in front of the plane of the MIRROR which is used as a directional screen creating the real image of the lens assembly in a manner preventing "cross-talk" between the left and right eye views. Essentially, the system creates a pair of "virtual windows" through which the viewer looks in order to see the stereo

FIG. 1 Stretchable mirror (early version) used in the pilot technology demonstrations described in the text. *Courtesy EtherealTechnologies, Inc., Ann Arbor, MI*

image (Fig.2). Presently, the system is a single viewer display, although work is conducted on the development of multi-user units. However, even as a single-user device, contrary to HMDs, the use of the MIRROR does not cause either physical or optical discomfort (own, unpublished observations). Moreover, the controllable aperture of the MIRROR allows creation of large, very bright images that can be viewed in broad daylight. The advantages presented by the stretchable membrane display become particularly evident in austere environments, where available technology resources are limited due to financial constraints, environmental conditions, or lack of trained personnel capable of operating more complex telepresence systems.

One of the best examples of the other end of the spectrum, i.e., highly sophisticated autostereoscopic technology that entered the US market and approaches the concept of a "true hologram" is provided by the LifeVision^{TM} system. In similarity to the MIRROR device, the LifeVision^{TM} Monitor reached the level of technological maturity to be contemplated for routine practical use in medicine and medical telepresence. The LifeVision^{TM} 3D Monitor is offered by IntrepidWorld, Inc. (Los Angeles, CA) and is based on a Laser Optical Element (LOE) serving as a holographic diffuser. Images transmitted through LOE are perceived in three dimensions and are by utilizing a combination of lasers, optical lenses and mirrors, which record a diffusion pattern upon special film, and, with the potential of producing close to 100.000 line/cm, the image resolution of the LifeVision system significantly exceeds that of the human eye, resulting in the image of particularly high quality. Important from the user's standpoint is fact that LifeVision Monitors will be offered in a variety of viewing screen sizes (up to 100x180 cm). The range significantly enhances the flexibility of practical application by allowing desk-top mounting as easily as fitting of large, wall mounted display surfaces where the

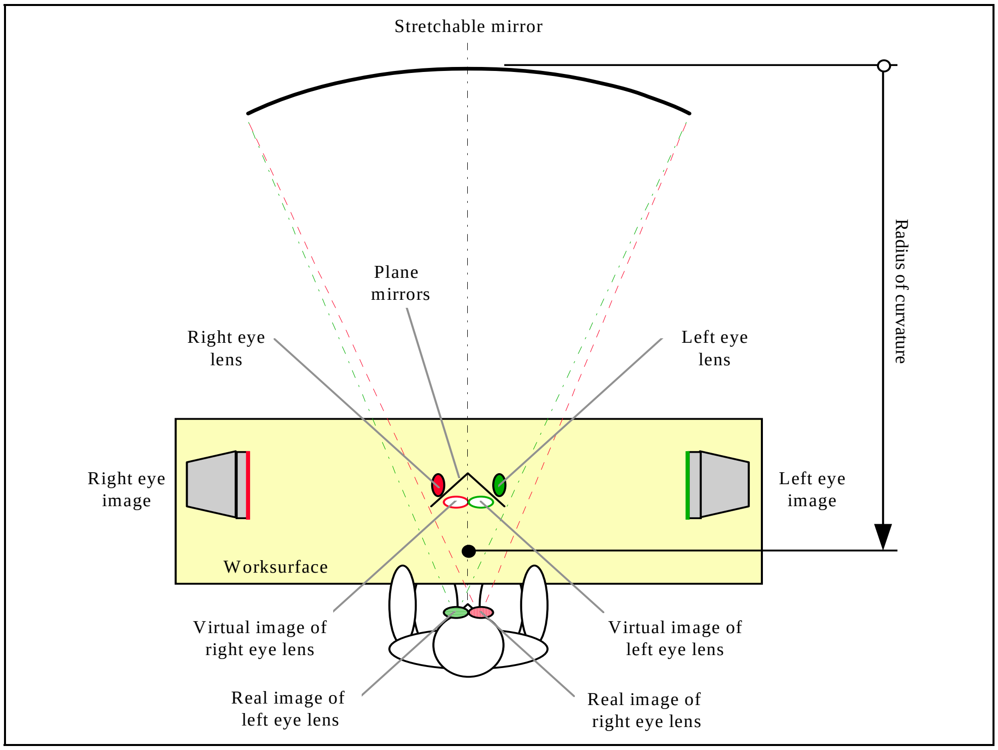

FIG. 2 Schematic diagram of the MIRROR system. *Courtesy Ethereal Technologies, Inc., Ann Arbor, MI*

picture can be viewed by more than one person. However, the significant complexity of the LifeVision Monitors which, apart from LOE, consist of several other major subcomponents, makes them better suited for stationary or “sheltered” environments of major visualization centers, where access to technical support is comparatively easy, and the degree of sophistication of the support personnel is typically rather high. This is in contrast to the MIRROR unit whose relative simplicity makes it highly suitable for the operations in the field where support requirements of the deployed system must be kept at their absolute minimum.

Both in the case of the MIRROR and LifeVision Monitor, the source of the images can be computer files, stereo film or videotape, or live transmission from stereo cameras. Either system combines advanced technology in electronics and optics with readily available computers and provide a pseudo-hologram image, where the light source appears to come from the model or subject itself and thus can be viewed as a floating object suspended in “free space” without special glasses. The latter aspect is particularly important in medical applications, where prolonged viewing of objects in prepapration for, e.g., surgery may result in significant fatigue of the user exposed to other devices such as HMDs or even immersive VR. From the practical point of view, the emerging autostereoscopic systems are independent of format, brand, or software issues. Whatever sources provide a stereoscopic output and can provide a video standard output (NTSC, video, S-video, RGB, VGA, etc) can be viewed. Since these sources include computers, stereoscopic VCRs and cameras, DVDs, etc., the flexibility is substantial, and the range of uses covers the entire spectrum of Web based material to real time medical training, consultation, and, in probably not too distant future – telepresence-based surgery and telesurgery [80].

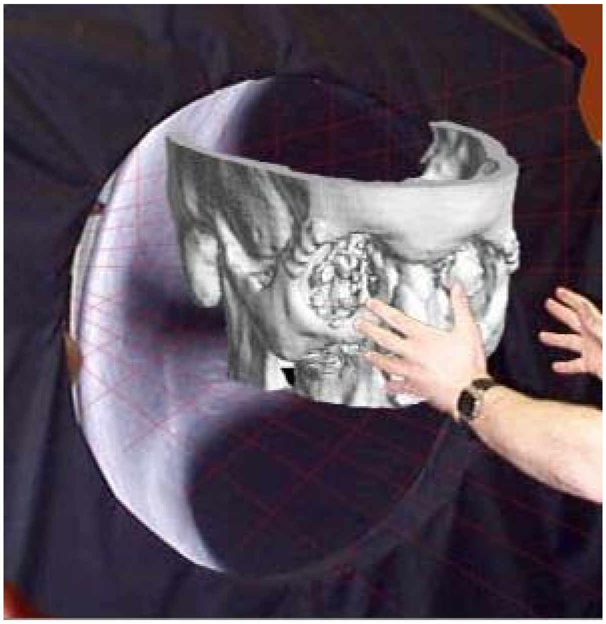

FIG. 3 MIRROR 3-D visualization of a human cranium as an example of facilitation in planning reconstructive surgery following major trauma. *Courtesy Ethereal Technologies, Inc., Ann Arbor, MI*

There is no doubt that autostereoscopic devices are particularly suitable for medical applications where high picture resolution, high quality of 3-D rendition, and the flexibility in the generation of images independent of the source medium (e.g., DVDs, CD-ROMS, Web, or realt time stereoscopic transmission) are as essential as the freedom of viewing without the assistance of external devices (e.g., HMDs.) As a result of these capabilities, autostereoscopic displays may soon become a very popular visualization platform in such fields as trauma and emergency medicine, neurosurgery, microvascular surgery, laparoscopy, reconstructive surgery, etc. Education and training of medical personnel working in the rural areas or at the remote sites is another preeminent arena for vigorous implementation of auto-stereoscopy that, for the first time, will offer the trainees the 3-D telepresence access to the training resources of the sophisticated medical training centers (see below). Finally, providing the established telepresence link is bi-directional, the otherwise unavailable medical experts can provide instruction in the execution of complex medical tasks being essentially in personal contact with the students. Thus, 3-D telepresence-based training can provide the solution to the hands-on medical education and skills maintenance that continue to present a major problem both in the rural areas of the developed countries as well as in the less affluent regions of the world [3,18,35]. Other uses, such as distant supervision of scientific experiments, demonstration of experimental protocols, distributed simulation of medical events, etc., can be equally easily envisaged.

4. TELEPRESENCE IN MEDICINE

As pointed in our previous publications [33,34,35], medical training expert continues to remain the scarcest resource, and ready access to such expert remains the major problem, particularly in rural and remote regions. Telepresence simplifies access to such expertise and, as we have shown in our recent study [45], telepresence of an expert medical teacher improves execution of critical emergency medicine procedures during training based on the extensive use of human patient simulators. Equally, surgical telepresence results in virtually immediate performance of surgeries and elimination of costly (and often life threatening) delays caused by the need to bring the required expertise to the distant patient or transport of the patient to the expert facility [45,46,47,48].

While many aspects of telemedicine, particularly teleconsultation, are rooted in the loosely defined sensation of telepresence [12,49,50,51,52], the most advanced medical approaches utilize the strict definition of *the operator experiencing real presence at the remote location* [53,54,55]. The narrowing of telepresence definition in medical applications is necessitated by the nature of the ultracomplex surgical tasks that are performed in 3 dimensions, demanding undistorted 3D visualization of the surgical field together with the exact reproduction of other sensory inputs (e.g., haptic feedback) that provide the operating surgeon with the required information [56]. Despite significant technical difficulties, experimental telepresence surgery has been performed in the areas as diverse as stereotaxic biopsies [57], vascular and open abdominal surgery [58,59], and neurosurgery [60,61,62]. However, introduction of telepresence surgery into clinical practice requires solution to many technical and non-technical issues involving ethical, legal, and technological dilemmas.

5. MEDICALREADINESS TRAINER and TELEPRESENCE: FROM CRT, THROUGH VR, TO AUTOSTEREOSCOPY

The establishment of Medical Simulation, Modeling and Advanced Research and Training Laboratory (MSMART) at the University of Michigan allowed the development and testing of a number of pioneering approaches to telepresence based education, training, and research in emergency and trauma medicine. The earliest studies conducted between MSMART and the Roosevelt Roads Naval Hospital and University of Puerto Rico School of Medicine involved CRT-based remote control of a complicated medical training device (Human Patient Simulator – HPS, see fig.4) and telepresence-based training of medical personnel over a very long distance (4500 km) confirmed the usefulness of telepresence as an operational medium in widely distributed medical operations. Importantly, telepresence-based training resulted in a measurable improvement in medical preparedness and confidence of the trained personnel [45,81,and in preparation]. Between 1999 and the present, the staff of MSMATR developed a hyper rich, VR-based telepresence portal (Medical Readiness Trainer [18]), where virtual reality environment surrounds Human Patient Simulator. While the Human Patient Simulator provides the haptic feedback element, the VR shell constitutes the telepresence environment which can be readily changed from one setting to another. Integration of VR and HPS technologies allows training under maximally realistic conditions emphasized by the environment-correct sounds and, if needed, motions (Fig.5) such as

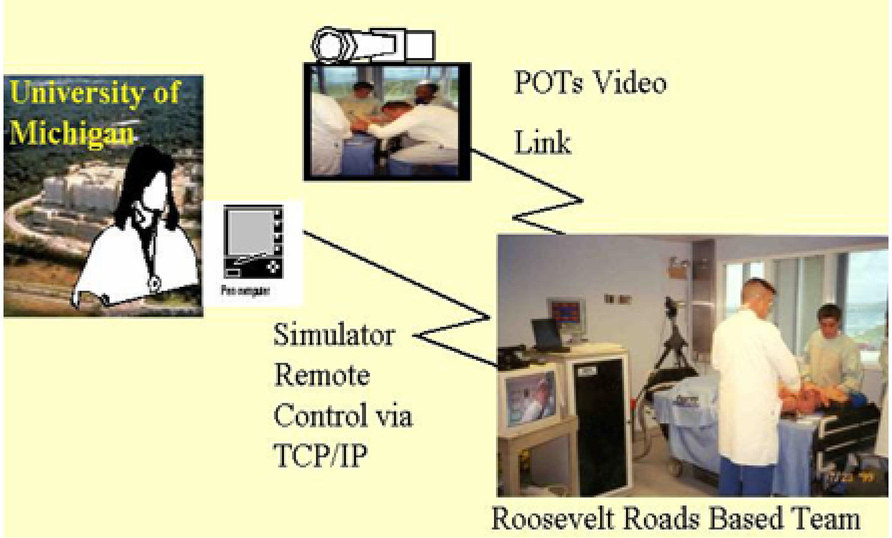

FIG. 4 CRT–based telepresence using standard 56 kbps modem, telephone line and TV display. Participants in Michigan and Roosevelt Roads are in voice/video contact. During this pioneering exercise, the training doctor in Michigan has full remote control of the Human Patient Simulator located in Puerto Rico, instructing the trainees (junior physicians at Roosevelt Roads) in real time. The course resulted in statistically significant improvement of medical readiness among the personnel in Puerto Rico [81].

variable degree roll of a sick bay in a ship at sea. Creation of "VR-mobile" environments allows preparation of medical personnel for work under the specific conditions they may encounter during real life operations [82], e.g., survivor rescue during winter storm in North Atlantic, airway maintenance in a helicopter subject to turbulence, bouncing ambulance, etc. In February 1999, MSMART performed a series of experiments that, for the first time, demonstrated autostereoscopic display (MIRROR) as a functional telepresence platform capable of "bridging" very large distances that may separate the viewer/operator and the site of the actual activity. The experiments also served as the initial validation of the 3-D portal concept as a foundation to the remote access and operation of the complex training equipment located at a distant site.

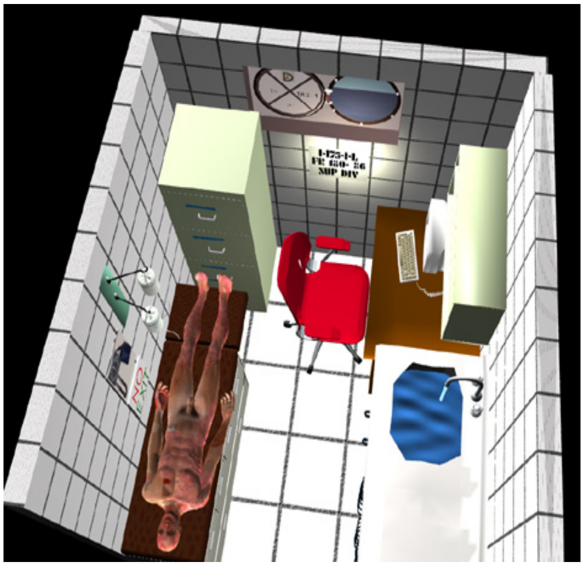

FIG. 5 VR-based medical telepresence system. The immersive VR (CAVE) environment represents the exact environment of the sick bay aboard US Coast 270ft cutter. The bay is capable of virtual movement (pitch and roll) controlled by the CAVE operator. Like in a real ship, sea sickness can be induced by varying the intensity of the "virtual storm." When the virtual sea state reaches 5 (moderate waves), the training personnel begins to roll their bodies to compensate for the "movement of the ship", despite completely stationary floor. The patient is the "first-ever" texture map (VR) of a badly burned survivor.

Altogether, the testing of medical telepresence involved 70 persons, most of whom were either physicians or represented allied healthcare professions (physician assistants, nurses, paramedics), medical educators, and information technology personnel. During the first experiment, visualization quality was determined by using the MIRROR side by side an HPS device, and comparing the subjective impression of the visitors observing the Human Patient Simulator directly then looking at its 3D image rendered by the MIRROR system. While the results were qualitative, the vast majority (82%) of participants in the demonstration (the faculty of the University of Michigan School of Medicine) expressed satisfaction with the quality of image, faithfulness of 3D demonstration, and the ease of PC-based remote control and use of the device. During subsequent experiments the MIRROR was located at the Old Dominion University in Norfolk, VA (approximately 1200 km away from Ann Arbor}. Using the MIRROR as a telepresence access, a senior emergency physician at Old Dominion trained 10 senior residents at the Department of Emergency Medicine at the University of Michigan in diagnosis and treatment of heart attack, near drowning, and anaphylactic shock. Human Patient Simulator (METI "B") located in Ann Arbor but remotely controlled from Old Dominion University was used as the training tool. Real time training using 3-D telepresence visualization and synchronized voice transmission used Internet2 as the bi-directional voice/videostream carrier. While there was an occasional loss of channel synchronization (drop of either left or right eye channel) and voice (static), the overall quality of real time 3-D video image at both sites was excellent, and the rare and brief disturbances had no impact on the quality of delivered training, procedure mistakes introduced by loss of vide transmission. During the final experiment, a group of military medical personnel (45 persons) at Telemedicine and Advanced Technology Research Center (TATRC) of the US Army at Ft. Detrick, MD was given remote control of the Human Patient Simulator through the MIRROR-based portal. Two independent, general use T1 lines at TATRC were made available. One line was used as the videostream/voice carrier, the second as a carrier of HPS control commands. Since line was dedicated to the exercise, unauthorized sharing of the available bandwidth with other users within the facility resulted in occasional severe degradation of transmission quality. Nonetheless, despite technical difficulties caused by interruptions of either video- or control command streams by third parties accessing either one, or, and at times, both lines, the trainees at Ft. Detrick were able to accomplish majority of the tasks within the specified time limit (1 hr). Moreover, majority of the participants (64%) expressed satisfaction with the quality of telepresence access during undisturbed segments of the exercise, and were convinced of the potential value of 3-D telepresence-based medical training. However, we believe that the positive outcome of the third experiment was, at least in part, the result of the participants awareness of the technology that has been never subjected to a prior test in the similar context, their prior realization of the existing technical issues that would affect optimal performance, and their overall professional seniority allowing for "mental compensation." Had the test been performed with medical novices (e.g., junior students) as the target audience, we believe the results would be largely unsatisfactory. The last experiment clearly underlined the critical issue of bandwidth available for 3-D real time telepresence operations and the requirement for its stability. It also provided an ample warning for future implementation of 3-D telepresence among less prepared users, where degraded quality due to easily preventable technical problems may lead to dissatisfaction and even rejection of the technology as a viable operational platform. To our knowledge, the demonstrations conducted by MSMART in 1999 were the first ever experiments that demonstrated the functional practicability of 3D telepresence concept (Fig.6).

The experiments performed in two instances over a distance of approximately 1200 km, both the practical applicability of 3-D telepresence based on autostereoscopy and its preeminent suitability for real-time stereoscopic rendition of distant and constantly changing complex environments. Most importantly in the context of dissemination of 3-D stereoscopy applications as an integral concept of Advanced Distributed Learning (ADL) and Distributed Interactive Simulation (DIS), our qualitative observations clearly indicated that, at the subjective (qualitative) level, 3-D real time telepresence exceeded the "true life" capacity offered by any of the standard 2D telemedical systems available. Still, despite very encouraging initial success, our preliminary results can be viewed only as the indicators of the very large potential capacity of autostereoscopy-based telepresence in medicine that can be confirmed only through rigorous quantitative testing and experimentation conducted over a period of time, with a number of different target audiences representing wide variety of technical sophistication, and using different forms of technology. The latter aspect is particularly important in the context of the wide variety of resource characteristics of the environments in which such technology is used. Thus, at large medical training centers richly endowed with sophisticated technical support, routine use of more sophisticated systems (such as, e.g., that of the IntrepidWorld, Inc.) is far more realistic than in the environments characterized by the paucity of such support, or in which simplicity of deployment and operation are the elements of paramount importance (e.g., front line military operations, humanitarian relief activities, etc.) While we believe that under the latter conditions, devices such as the MIRROR (Ethereal Technologies, Inc.) may be extremely useful, also this assumption is the target of one of our forthcoming experiments in which different forms of 3-D autostereoscopic technology will be evaluated under operational conditions in the field.

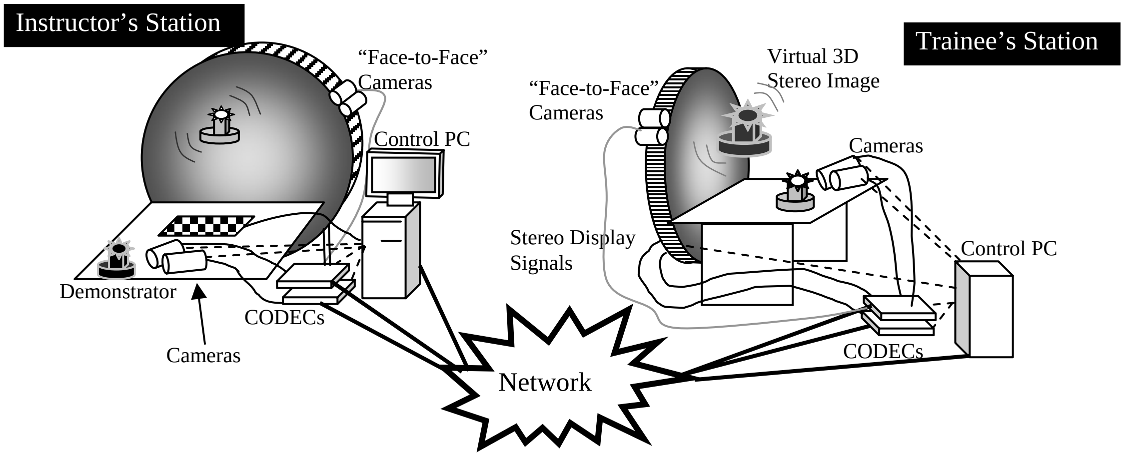

FIG. 6 Schematic illustration of the two training stations and their connections using two MIRROR autostereoscopic displays, two pairs of mini CCD cameras, two pairs of MPEG video codec units, and a high speed data network (Internet2, frame relay, ATM, IP with QoS). The system can be used for realtime transmission of complex 3-D information. It has been used for the first time in unprecedented 3D-based training of medical personnel in emergency and trauma procedures. The distance separating the physician trainer and the students was approximately 1,200 km. See text for details.

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