Future Therapy

Virtual Frontiers, Part 1: Fundamental Concepts and Recent Advances in Virtual Reality Technology

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ABSTRACT Systems that facilitate interactive visualization and manipulation of multimodality three-dimensional (3-D) biomedical images on standard computer workstations have been used for computer-assisted surgery and interventional procedures for more than a decade. These capabilities have provided surgeons with powerful computational support for both preoperative planning and postoperative evaluation. More recently, there has been growing interest in the development and implementation of virtual reality (VR) applications for medical and surgical training, rehearsal, and intraoperative support. Incorporation of data from multimodality 3-D biomedical imaging into the virtual environment offers the promise of highly interactive, natural control of the visualization process and hence realistic simulations ranging from basic anatomy to complex surgical procedures. However, to enhance the performance of tasks, including the practice of surgery, constraints such as computational and real-time update rates, as well as other technical and physiological requirements of human-computer interfaces, need to be addressed as the technology develops. To physicians, surgeons, and biomedical researchers alike, a knowledge of the fundamental concepts of VR is useful to understanding both its technical basis and potential clinical applications. In this light, the present work aims to examine this highly important and evolving technology.

Keywords Virtual reality, 3-D reconstruction, biomedical imaging

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A Virtual Reality Assisted Surgery Program (VRASP) is under development at the Mayo Clinic for eventual implementation into the hospital operating room (OR).[1–3] The goals of this program are to give the surgeon flexible and intuitive computational support intraoperatively without interfering with normal surgical activities. It will permit modification of very large image data sets in real time, and will register and display patient-specific virtual imagery in response to the surgeon's commands. It is intended that VRASP will allow surgeons to interactively visualize 3-D renderings of multimodality imaging data with hands-free manipulation of the virtual display, such as scaling and orienting the image from any desired perspective without perceptible computational or display lag. The clinical goal is dynamic fusion of 3-D body scans with the actual patient in the OR, to augment surgical performance through facilitating planning, rehearsal, and execution of the safest and most efficacious procedure. The customized interface will also permit ready online access to the preoperative plan, reference databases, and updated measurements and analyses based on the real-time OR data.[1–3] Understanding concepts fundamental to VR is therefore useful to gaining an appreciation of the clinical potential of this technology.

VIRTUAL REALITY

Although the popular concept of VR is a realistic simulation involving individuals wearing head-mounted displays and sensing gloves, describing VR in terms of the tools it uses is not adequate.[4] The term, coined almost a decade ago by Jaron Lanier, encompasses a wide range of concepts.[5] VR, which can be defined as a simulation in which computer graphics are used to create a realistic synthetic environment,[4] is a very powerful human-computer interface that fundamentally involves one or more users and computer technology. The synthesized "virtual world" is dynamic, responding to user inputs such as hand gestures, head position, and verbal commands in real-time (i.e., "instantaneously").[1,4,6] Successful virtual worlds are also characterized by the degree of immersion they offer the user and how well they generate a sense of presence and engage the user's imagination and perception (see below).

It should be noted that the terms "synthetic (or artificial) reality," "enhanced (or augmented) reality," and "optimized reality" may also be used in the context of VR. Synthetic reality refers to the modeling of the real world (or an entirely fictitious world) in a perceptibly artificial simulation; enhanced reality refers to the "fusing" (overlaying) of computer graphics or text with real-world images,[4,6] such as the merging of the real view seen by a surgeon through an operating microscope with graphics generated and overlaid in the field of view by a computer. This type of "reality," aimed at augmenting performance, is a perceptual state not normally available in the real world.[4,7] Optimized reality takes this concept one step further and refers to the creation of a totally synthetic environment that is indistinguishable from the real world.

Goals of VR

Two important constraints in VR are system response time and virtual world fidelity.[4] VR systems typically aim to register user input and modify the virtual world in an "instantaneous" manner to work effectively. To appear realistic, they also aim to use as many human sensorial channels as possible, from visual and auditory to tactile (or haptic) and olfactory.[4] Further, models or "objects" that exist within the virtual world must also be familiar in their appearance and behavior and must allow plausible interaction with the user. Devices used to register user input and convey computer output must also be practical and comfortable and must feel or seem to be as natural as possible. In surgery utilizing VR technology, the technology must adapt to the surgeon, not the reverse.[8] In both biological research and the clinical disciplines, a seemingly natural and immediate union of the generated image and model with real-world, real-time data is a prerequisite for VR expansion into these fields.[7]

In the setting of surgical procedures, an ideal VR system must provide all the following: high fidelity (e.g., objects in the operative field image must have enough resolution and familiarity to appear real), multiple sensory inputs (e.g., vision, sound, touch, and force feedback), and appropriate interactivity and reactivity (e.g., the surgeon's hand and surgical instruments must interact realistically with tissues which, in turn, must respond in a natural manner).[9,10]

Major Concepts and Definitions

Five central and interrelated concepts in VR are immersion, presence, interaction, autonomy, and imagination (Fig. 1).[4]

1. *Immersion* The degree to which a user feels to be part of the virtual world.[4] This is dependent on such factors as the technology and practicality of the input and output (I/O) devices used (see below), the reality and familiarity of the models or objects in the simulation, and the user's own imagination.[4,11] Immersion can be an objective and quantifiable description of the overall functionality or efficacy of a particular system.[11]
2. *Presence* A measure of the number and fidelity of sensory inputs and outputs involved in the simulation.[12] Though related to the extent of immersion, presence is a more subjective concept, and represents the psychological sense of being in a virtual environment.[11]

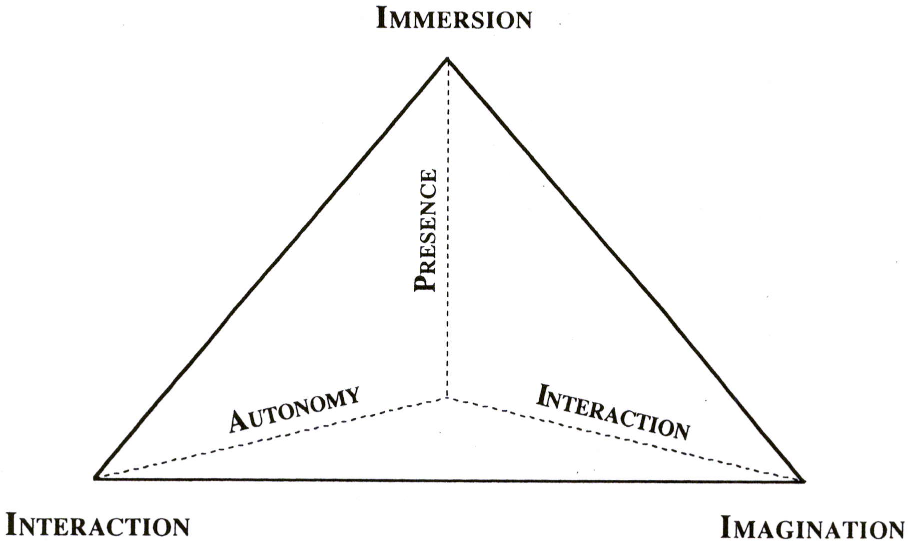

Fig. 1 Fundamental concepts in VR. Three key concepts in VR are the depth of a user's immersion, quality of interaction, and use of imagination. The overall efficacy of the VR simulation can be measured by the user's feeling of presence in the virtual environment, the autonomy of the simulated "objects," and the user-object interaction (adapted from Burdea and Coiffet[4] and Zelter[12]; see text for details).

3. *Interaction* The ability of a user's input to be detected and responded to ideally in a realistic and real-time manner by the VR system.[4] Also, the degree to which the user can work on models in the virtual world.[12]
4. *Autonomy* The degree to which objects in the virtual world have independent (or autonomous) physical and/or physiological properties—i.e., a degree of "intelligence."[12]
5. *Imagination* The ability of the user to form a mental image, and the creativity and resourcefulness of his or her mind (including acuity of perception and willingness to suspend disbelief).[13] This is critical to the overall effectiveness of the simulation.

Development of VR Technology

In 1929, Edwin Link designed a carnival ride that gave participants the sensation of flying a plane, an invention that eventually evolved into the Link Flight Simulator, which was used to train pilots decades later.[5] In 1962, the cinematographer Morton Heilig patented his one-person "Sensorama Simulator," the first VR video arcade. The potential of his initial patented design, "The Experience Theater," was unrecognized and unsupported by government, recording, and cinematography concerns.[4] It involved a cinema whose screen filled 100% of the visual field and incorporated stereophonic surround sound, controlled ambient temperature, seat vibration and tilt, and even wind and smell, in the overall "experience." Heilig also realized the possibilities of head-mounted television, patenting a simulation mask based on 3-D slide and sound projection in 1960.[4] Heilig's pioneering work was continued by Ivan Sutherland, who used two cathode ray tubes mounted along the ears to create the first functional head-mounted display in the mid-1960s. Sutherland also designed a computerized "scene generator," the precursor of the modern graphics accelerator and a key part of virtual environment hardware.[4] By the early 1970s, the military (followed by NASA in the early 1980s), became involved in research on "flight helmets" and "flight simulators," ultimately leading to the creation of the first VR system by NASA in the early 1980s. This "Virtual Visual Environment Display" (VIVED) included a host computer, a graphics computer, a head-mounted display, and a head motion tracking device.[4] In 1985, a "sensing glove" developed by Lanier and Zimmerman as a virtual programming interface for nonprogrammers was integrated into the system by Scott Fisher and, by the late 1980s, systems incorporating virtual vision and sound, along with head and hand motion sensing, became commercially available. Proficient integration of hardware was accomplished in the early 1990s by the British company Division Ltd., which introduced the first integrated VR workstation called "Vision" in 1991. One year later, a small U. S. company called Sense8 developed the first "WorldToolKit," a software package that facilitated the science of VR software development.[4]

General Uses of VR

Today, the market for VR is driven primarily by the entertainment industry, accounting for 40% of VR applications. Here, both arcade- and home-based systems predominate, although VR is gaining a larger foothold in the art world with the development of "virtual museums," "virtual music," and "virtual actors."[4] Military and aerospace applications account for 17% of the overall market, and are used for large-scale battle simulations, pilot and astronaut training simulations, and weapon and vehicle design. Commercial simulation and visualization applications account for 15%, as do, collectively, applications for industrial design (including robotics and manufacturing), business (including automobile design and "experiential advertising"), finance (stock market analysis), and architecture and interior design (enabling tours of virtual building, homes, or individual rooms). At present, only 12% of VR applications are for biomedical purposes. These include applications for basic research (cellular and tissue structure and function), diagnostic image visualization and manipulation, anatomy teaching, surgical training and planning of complex procedures (including surgical simulators and intraoperative informational aids), rehabilitation (both in diagnosis and therapy), and molecular biotechnology (molecular chemistry and drug design).[4–7,14–21]

THE VIRTUAL ENVIRONMENT

The VR environment is composed of one or more users and appropriate "enabling technology." The latter consists of various devices that collectively serve as an I/O link between the user, a collection of interconnected or networked processing units and databases, and the virtual world simulation (Fig. 2). VR hardware usually consists of a computer that generates the virtual world, although, to provide the computational power necessary to maintain real-time interactivity, a VR system may have several computers dealing with separate parts of the environment (e.g., one computer responsible for

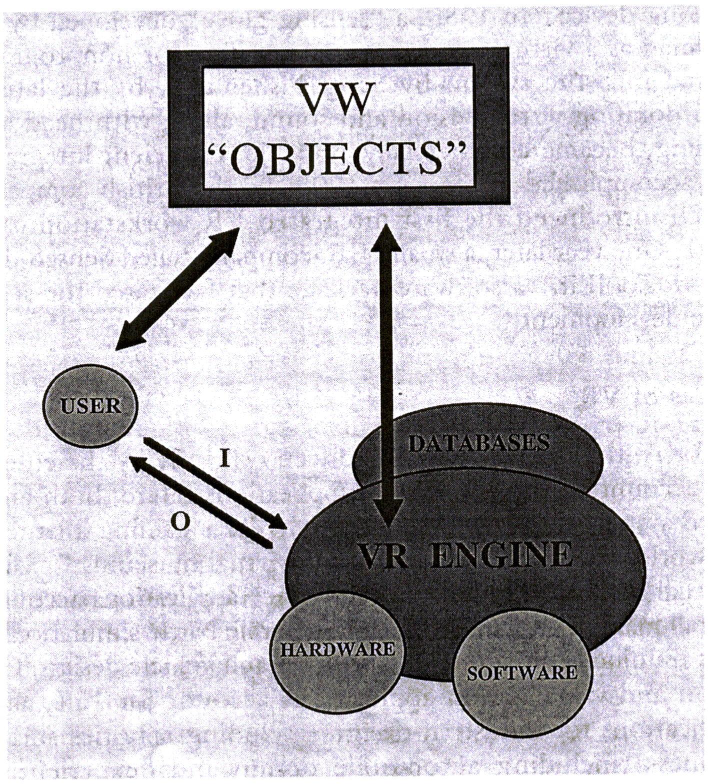

Fig. 2 Components of the VR environment. The VR environment is composed of a user (or users) coupled via input (I) and output (O) devices to the VR engine (a system-specific configuration of hardware, software, and databases). The VR engine is responsible for the generation and modification of objects in the user's virtual world (VW).

generating the audio, another for stereoscopic display, and others for registering user input devices or for tracking and information storage).[5] Software packages, on the other hand, are required to create and display the environment; such packages are usually referred to as "world-building" programs.[5]

Components of the VR Environment

User. An individual, or a collection of individuals, that provides input and receives output from the computer system. Many VR systems have been designed to accommodate multiple simultaneous users, and one system, used by the military, has been built to involve several thousands of users in the setting of a realistic "virtual battle" simulation.[4]

"Objects" and Models. An "object" is an item that forms part of the virtual world, and may be a chair, a hillside, a tank, or a patient's beating heart. The object must be modeled geometrically (pertaining to its shape—constructed from numerous interconnected polygons) and appearance (features such as pattern texture, surface reflection coefficients, and color), kinematically (pertaining to the object's positional changes, surface deformation, and collisions with other objects in the virtual world), physically (referring to object mass, weight, inertia, physical texture, compliance, and deformation), and behaviorally (i.e., its autonomous physical or physiological actions).[4,22] Unquestionably, geometric and physical modeling of a highly populated virtual world will result in a very complex overall model, made up of a very large number of polygons that are "costly" to the ability of computations to take place swiftly. As a result, the model may become sluggish in terms of update rate and interaction, a consequence that is undesirable in all settings, from military to surgical and entertainment simulations. Although beyond the scope of this review, several methods have been developed to maintain or improve the real-time nature of the virtual simulation. These methods, collectively referred to as "segmentation," include dividing the virtual world into smaller "universes" or "cells" (cell segmentation) or appropriately varying the level of model detail (detail segmentation), and are reviewed by Burdea and Coiffet[4] and Kalawsky.[21]

Basic Computer Software and Hardware. Computer-aided design (CAD) programs are used to model 3-D objects that form part of the simulation. Through the process of modeling, the size, shape, texture, color, and other physical properties are imparted to polygonal models (or "objects") in the virtual world. A VR "toolkit," which is a computer program used to insert 3-D objects into virtual worlds and assign certain characteristics to those objects, can be used to add specific behavior.[5] It should be noted that the cost of rendering virtual world polygons (whose positions need to be recalculated for each new movement as dictated by the user) to provide "instantaneous" display is an important issue in most, if not all, VR applications.[5] Therefore, when selecting hardware, the most important factor that must be taken into consideration is the speed at which data such as graphics, sound, and user-tracking are processed. The compromise is between providing real-time detail and accuracy and the "polygonal budget."[5,23] In this context, it should be noted that although personal computers (PC or Macintosh) do not currently have the processing power to generate complex, fully immersive simulations, they can cope with simpler ones. On the other hand, workstations, which are high-performance computers driven by powerful microprocessors, have the potential for greater fidelity[5] and, where possible, should be used in preference to personal computers for VR simulations.

I/O Devices. Input devices are tools that allow information to be conveyed to the computer from a user, while output devices provide feedback from the computer to the user (Fig. 2).[4,5] Such devices mediate the interaction between the user and the computer, and form the hardware component of the human-computer interface. A variety of input devices have been designed, and include mice (both desktop and desk-free "flying mouse" varieties), joysticks, trackballs (sensing, spherical, desktop devices that measure the directional torque and force applied by the user's hand), 3-D probes (small sensorized mechanical arms that sit on a support base and detect the motion of the user's hand at the probe's tip), and sensing gloves (a variety of gloves, some like mechanical exoskeletons and others like ski gloves) that detect the natural motion of the user's hand in a more intuitive manner and are no longer confined to a desktop.[4,21,24] Output devices include stereo "active" visual display monitors (configured individually as in computer workstations or as multiple, adjoining large-screen units typified in virtual arcade "caves"), head-mounted displays (liquid crystal- or cathode ray tube-based screens that are placed very close to the eyes, and utilize optics that allow filling of the user's field of view) or their less-expensive alternative "stereoglasses," as well as binocular omni-orientation monitors or "Booms" (high-resolution monitors coupled to a mechanical support and head-tracking arm), retinal display units (reflective devices that project the image directly onto the user's retina and can operate in a "see-through" mode), 3-D "surround" sound generators, and a variety of touch and force feedback devices (which impart the sense of surface force, vibration and/or texture to special "tactile" or "haptic" hand-held or hand-enclosing devices).[4,5,19,21,25–27]

Trackers. Devices that can determine and "track" the real-time position and orientation of some part of the user (e.g., the user's head, eyes, arms, or hands) relative to some stationary object. This function is fundamental to registering the input of the user in the virtual world. Tracking systems generally employ a number of transmitters and receivers (the latter may in fact be built into an I/O device such as a dataglove or head-mounted display), and utilize a 3-D Cartesian coordinate system to track translations and rotations along the three axes.[4,5,21] Electromagnetic, mechanical, optic, ultrasound, and inertial tracking systems are used variably in VR systems, each with relative advantages and disadvantages, beyond the scope of this review. Biocontrol sensors (which "track" neuromuscular electrical activity) and voice recognition sensors (which respond to the user's verbal input) are examples of tracking devices whose development and refinement are the subject of current research.[5,21]

Databases and "Engines." The former term refers to collections of data describing the properties of objects (shape, appearance, behavior, etc.),[4] while the latter term refers to the system-specific infrastructure of computer software and hardware (Fig. 2).

"Network." An integrated system of workstations.[14] High-performance computing can be accomplished by multiple central processing units (CPUs) computing simultaneously on parallel tasks or by distributed load sharing within a network.[14] For example, simulation infrastructure can be based on a series of independent but linked computers spread over a local area network that interact using a defined communication code such as Internet Protocol (IP) multicasting protocol.[7]

Concept of Validation

Zelter[12] proposed a three-dimensional measure of the "goodness" of an integrated VR simulation. The three parameters of the evaluation are degree of autonomy, presence, and immersion (Fig. 1). However, evaluating the overall performance of an interactive imaging system or a VR simulation is somewhat subjective. Undoubtedly, certain expectations appropriate for most users must be met. First, the rate at which images or frames are displayed and updated must be greater than 15 to 20 frames per second (i.e, high frame and refresh rates are required) and the latency between user input and system response must be less than 60 to 80 ms (i.e., low lag times are mandatory) to facilitate effective interaction (enhanced "task performance") and avoid "simulation sickness" (similar to "motion sickness" caused by oculovestibular mismatch).[4,22] Second, more than one (ideally all) sensory modalities should be addressed in the simulation (visual, auditory, tactile, and even olfactory).[4,22] Third, the technology employed in the imaging/simulation process should account for both the physiological and psychological components of each and every sensory modality affected.[4,22] For example, visual *physiological* conditions such as normal field of view, spatial resolution, depth perception, and color and lighting levels should be satisfied, in addition to visual *psychological* conditions, both passive (e.g., scene realism through overall view, shading, texture, and detail) and active (e.g., appropriate coupling between input devices and their virtual world representations, and model compliance with physical and physiological laws). Fourth, I/O devices should be comfortable, practical, and in keeping with natural expectations. Fifth, both biomedical images and objects in VR simulations must accurately and precisely reflect the structure and function of the real objects being imaged or modeled (i.e., they must be familiar and realistic). Sixth, there must be appropriate integration or coordination of the various I/O tools and the sensory modalities they affect.[4,22] Lastly, biomedical imaging and VR technology can be evaluated from the point of view of their impact on the professions and societies they touch—that is, from their overall effect on activities such as learning, design, analysis, action, and communication.[4] It should be noted that certain objective methods are in place for the overall evaluation of 3-D biomedical imaging and VR technology. For example, the Visible Human dataset from the National Library of Medicine (NLM) is being used by a large number of investigators to develop, test, and compare virtual 3-D anatomical models and visualization methods with reality for evaluation of their eventual application in clinical diagnosis and therapy.[28] Further, studies of this technology can be carried out using phantoms (synthetic physical models), in addition to multi-trial comparisons, both in the laboratory and the clinical arena.

CONCLUSION

VR technology offers the promise of natural control of multisensory interaction in a wide variety of environments ranging from entertainment and military to business and the gamut of biomedical fields. Considerable progress has been made toward the establishment of a working, productive infrastructure supporting this technology. Concomitant with the ongoing growth and development of this field is the necessity for continued evaluation of the many new and evolving devices and techniques. The clinical goal of VR, which is the dynamic and intuitive fusion of multimodality 3-D imaging with patient-specific data, has the potential to augment surgical planning and performance and facilitate the execution of the safest and most efficacious procedure. For clinicians, a working knowledge of this highly important and evolving technology is therefore mandatory if this goal is to be realized.

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