Virtual reality in anaesthesia

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Virtual reality has captured the public imagination and is the subject of some interest in the media. Considerable claims have been made for the potential benefits that it offers and the changes that it may effect. In addition to the well publicized applications in the entertainment industry, virtual reality techniques are already in use in industry. Power workers in Japan are trained to use complex monitoring equipment in virtual control rooms, created entirely by computers, before being given responsibility in real-life situations. The decommissioning of nuclear weapons has been made considerably less hazardous by the use of virtual reality techniques. By donning a virtual reality headset and special gloves, workers can inspect devices and practise disassembling components. They may even experience the problems caused should an accident occur, such as a warhead falling from a transporter. The crash site can be “visited” and inspected and the operator can “walk” around the damage, rehearsing the best ways to cope with the difficulties produced.

Medicine has developed an interest in the applications of virtual reality and several conferences have been held exploring its possible applications (for example “Virtual reality in surgery and medicine”, Leeds, April 1994). Unfortunately, as with previous advances in computing, there is a real risk that unrealistic expectations of the technology at too early a stage of development may lead to disappointment and disillusionment. The situation is similar to that which existed in the early 1970s, when artificial intelligence was hailed a major breakthrough which would revolutionize the practice of medicine. In practice, given the state of development of artificial intelligence at that time, it was never possible that these expectations could be fulfilled. In addition to the difficulties in translating the clinical diagnostic process into knowledge of engineering terms, there were also deficiencies in the design of expert systems and a failure by software engineers to appreciate the needs and requirements of medical users. The failure of expert systems produced a significant negative impact on computing in medicine.

What is virtual reality?
The use of the term “virtual reality” is first credited to Jaron Lanier, the founder of VPL Research, a pioneering company in virtual reality development. Other terminology used to describe this technology includes artificial reality, virtual environments, cyberspace, visually coupled systems, telepresence and virtual presence. The multiplicity of different terms to describe this concept suggests that a single concise definition is difficult to obtain. Definitions which have been proposed include: virtual reality is an advanced human–computer interface that simulates a realistic environment and allows participants to interact with it [13]; virtual environments are three-dimensional, computer-generated worlds which accurately model and simulate an actual environment, whether it be a physical structure or an aggregation of different types of data [7]; and cyberspace—a graphic representation of data abstracted from the banks of every computer in the human system [10].

In essence, virtual reality is simply a more imaginative way of providing a human–computer interface than the standard keyboard, mouse and screen system with which we are familiar (fig. 1). Virtual reality systems have been developed using high definition monitor screens with specialized tools for manipulating screen images, and the more popularly familiar fully immersive helmet-based systems seen in some games arcades. In virtual reality the user becomes part of an interactive world of data objects created by a computer. These objects may be used to recreate images of the real world or to construct a new and totally imaginary world. Objects may represent physical structures or such abstract concepts and data as existed within the cyberspace described by William Gibson in his seminal 1984 novel Neuromancer. In this novel Gibson describes a world where the telephone system has been superseded by the Matrix, the interconnected sum total of all the world’s computer network. Cyberspace is the term used for this alternative computer universe which information workers enter using a virtual reality system, and whose data content they are then free to explore as if the data themselves had a physical existence: “Cyberspace. A consensual hallucination experienced daily by billions of legitimate operators, in every nation ... A graphical representation of data abstracted from the banks of every computer in the human system. Unthinkable complexity. Lines of light ranged in the nonspace of the mind, clusters and constellations of data” [10]. Although Gibson’s
vision of the future is a far cry from what is achievable today, his vision has fired the imagination of many workers in this field.

The evolution of virtual reality

The roots of virtual reality can be found in research conducted by the aerospace and defence industries. During the 1950s flight simulators were greatly improved by the introduction of scenery generated by cameras which were suspended over scale models of airports and ground terrain. A fixed forward view through the “cockpit window” was later enhanced by the use of multiple cameras and projection techniques that provided a view of the “outside world” to the pilot that extended through 180°. The sense of realism produced by moving scenery greatly enhanced the fidelity of the simulation.

In the early 1960s Ivan Sutherland pioneered the development of computer graphics. This technology allowed the representation of a three-dimensional real world by a flat screen projection of two-dimensional images. The first computer image generation systems for simulation were produced by the US General Electric Company for the space programme [17]. In 1965 Sutherland took the technique a stage further with the development of the first computer-based, head-mounted display. Instead of a picture being displayed on a conventional computer screen, miniature cathode ray tubes (CRT) displayed an image just in front of the eyes on a screen inside a helmet worn by the user. This development was taken up by the aerospace industry, which had been quick to seize on the benefits of computer-generated scenery in simulators for pilot training. Head-mounted displays offered the possibility of changing the image displayed as the user moved his head from one position to another—visual coupling. Visual coupling was also important in the development of head-up displays, where critical flight instrument information is projected directly into the pilot’s field of view.

The use of computer graphics in flight simulation progressed rapidly, with many valuable principles being established. Among these was the minimum rate at which images had to be updated in order to appear realistic, amount of detail required to recognize objects and creation of perspective and techniques for orientation of the user in relation to the display. The computer power required to create, display and update complex images was a limiting factor in development, and many original ideas could only be exploited as computer technology advanced. In 1985 the availability of low cost liquid crystal device (LCD) displays from hand-held television sets (Sony “Watchman”) allowed the construction of head-mounted displays which did not rely on the expensive high resolution CRT displays which had previously been used. This, coupled with the development of the VPL DataGlove, a device which allowed interaction with the computer-generated images, heralded an explosion of interest in virtual reality from a variety of sources, including the entertainment industry.

How is virtual reality created?

KEY CONCEPTS

Several key concepts in virtual reality may usefully be discussed at this point.

Immersion

Immersion is the degree to which subjects feel that they are actually present in a virtual environment. Presence itself is a subjective sensation, and research is still required to define how the different elements of visual, auditory and other sensory perception combine to provide a subject with sufficient cues that he feels that he has moved from the external real world into the virtual world. The success of a virtual reality system is often judged by the amount of immersion which is produced. Experience suggests that it is unnecessary to recreate in total fidelity every aspect of a virtual environment, but that there is a threshold beyond which a subject is prepared to suspend disbelief and enter the virtual world.

Interactivity

Interactivity changes the role of the user from that of observer to participant. When a virtual environment has been created, means must be provided by which the participant may move around the world and react with the various objects in that world.

Haptic/kinesthetic feedback

When, in the course of our daily practice, we turn on flowmeters, press monitor buttons or insert a cannula into a patient, the manner in which these actions are undertaken is governed both by previous experience and feedback from the actions themselves. Reduction in sensory feedback (even by something as simple as donning a pair of rubber gloves) requires some readjustment in performing routine tasks. Without that feedback many actions become difficult or impossible. One of the strongest criticisms of the latex models used to simulate tracheal intubation is that the forces required to intubate the model are
greater than those used in real life, and while providing reasonable fidelity in terms of anatomical construction the model does not "feel like the real thing". If practical skills are to be learnt in the virtual environment then force feedback from the tools used must at least approximate to the real world experience. Force feedback technology has been evolving concurrently with the complexity and capability of computers and applications [14].

The physical principles governing the design of these tools include: kinaesthesia, awareness of the movements and relative positions of the various parts of the body; and haptic cues, including tactile feedback, a sense of touch or pressure applied to the skin and force feedback, the weight and firmness of an object are relayed by joint and muscle proprioceptors when that object is grasped.

COMPONENTS OF VIRTUAL REALITY SYSTEMS

The components of a virtual reality system consist of software and hardware. Software programs create the objects and environment of the virtual world and control the interactions which take place between them. The hardware used includes computers to perform the enormous number of calculations per second required and graphics cards to produce the rapidly changing images of the virtual world. A display system presents the image to the user and further information about the world in terms of sound or feel is provided by specialized headphones and haptic feedback devices. Some means of interacting with objects within the virtual world must also be provided. Figure 2 shows the components of a typical virtual reality system in diagrammatic form and figure 3 a typical laboratory installation of a virtual reality system.

Software

Creating the world. Specialized software has been produced to create virtual environments. Using computer-aided design techniques, objects and backgrounds are created. Objects in the virtual world are created from flat two-dimensional shapes known as polygons. The greater the number of polygons an object consists of, the greater the detail that may be displayed. Polygons may be coloured and shaded and texture added to achieve heightened realism. This process is known as rendering. A simple representation of a view of hills may contain a 1000 polygons. A accurate representation of a real life living room could require as many as 80 million polygons.

Interacting with the world. A software simulation manager is responsible for interpreting the relationships between objects, and recognizing and responding to the various inputs to and outputs from the virtual world. This includes manipulation of objects by the user and detecting collisions. In a virtual world it is possible to walk through walls or put a hand completely through an anaesthetic machine, and the program must decide how to respond to these unrealistic events.
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Hardware

Computers. Computers capable of running virtual reality simulations range from desk-top PCs (486, Macintosh) to expensive graphics work stations (Silicon Graphics, Sun). In general the more detailed the representation the more expensive the hardware required. An endoscopic training simulator [11] has been produced using a conventional desktop 486 processor PC, while a product such as the elaborate infantry urban warfare training simulator (Division Ltd, Bristol) (fig. 4) requires very expensive state-of-the-art display systems.

A critical factor is the cost of rendering the polygons used in creating the virtual environments to provide real-time displays. There is a trade-off, in that greater detail requires increasing computation as the position of each polygon has to be recalculated every time the object moves or the observer changes position. The advances in video card technology are calculated by the increased number of polygons, the positions of which may be calculated each second. The increasing power and reduced cost of video graphics cards have most influence in bringing high quality realizations within the scope of those with more modest budgets. The fastest available image generation systems at present employ massive parallel computing techniques to display up to 5 million polygons per second, but may cost up to $1 million.

Displays. Vision is our most powerful sense and much of the interpretation we make of our own world depends on cortical processing of the image presented to our retinas. Similarly, in a virtual environment we rely heavily on our interpretation of image to make sense of that world. The image may be displayed using a number of different devices.

Much of the developmental work in virtual reality has centred on head-mounted displays (HMD) using helmets (fig. 5). The advantages of such a system are that the user is effectively isolated visually from the real world and the degree of immersion in the virtual environment is therefore enhanced. The main components of HMD consist of the display screen and the optics designed to present a focused image on a screen situated at a distance of only 5–8 cm from the eye.

The display screens themselves are usually liquid crystal devices (LCD), often culled from very small portable colour television sets. There are considerable problems with LCD displays. The resolution of an LCD containing 360 × 240 elements may be about 10 times less than that of a video graphics array (VGA) monitor screen used with a desktop PC when colour images are displayed. The image seen is of much lower quality than viewers have been used to, and gives a “cartoon” feel to the world. Also, LCD displays have a slow response time (40–200 ms) and produce blurring of a moving image. The characteristics of LCD displays are being improved and images equivalent to SVGA on conventional computer screens are beginning to be available.

Miniature cathode ray tube (CRT) displays with monochrome images of 1000 lines resolution are available and are used in the viewfinders of camcorders. These devices are usually mounted on the helmet near the ear and the image reflected into the user’s eyes. The advantage of these displays is that they produce bright high resolution images and they have been used for head-up displays in aircraft. The disadvantage is that a high voltage source is applied closely to a subject’s head. Colour images may also be produced, but require high scanning rates in excess of 180 MHz.

Images are projected from a remote high resolution CRT into one end of a fibrescope bundle and reflected into the viewer’s eyes in the other. This is a lightweight solution, but the design of the optics of the fibre display is complex and large numbers of fibres are required to produce adequate resolution of the displayed image.

HMD present their own problems. They tend to be heavy and tiring in use. Individual variation in physical factors such as inter-pupillary distance, astigmatism and the wearing of glasses calls for sophisticated correcting optics and adjusting devices for different users. Clearly, using a keyboard or answering the telephone is impossible, and the use of the helmet by several users raises problems of hygiene.

One alternative is to consider the use of binocular omni-orientated monitor (BOOM) displays. These are high resolution CRT displays mounted on a counter-balanced articulated arm incorporating 6 degrees of
freedom in its lightweight motion (fig. 6). This design produces stereoscopic displays which are “head-coupled”, but allow easy return to the real world. Interactive buttons may be incorporated on the boom. These devices are more suitable when the users are required to refer to other sources of data or when they more closely mimic the real world situation. For example, most endoscopic procedures are now conducted while watching an image produced on a remote monitor screen and the endoscopist needs to refer both to the screen and the position of his hands on the instrument [3].

In a head-up display an image is projected from a CRT onto a transparent glass screen positioned in front of an observer. Head-up displays are used widely in military aircraft to ensure that critical information is instantly available to the pilot without his having to redirect his gaze away from the outside world towards the instrument panel. This technique of overlaying an image on top of a real world view may well have applications in medical diagnostics. Researchers at the University of North Carolina, Chapel Hill, have investigated the use of an ultrasound scanner connected to transparent goggles in order to project real time ultrasound images of a fetus directly into the view of a obstetrician as he examines a pregnant patient (fig. 7).

INTERACTING WITH THE VIRTUAL WORLD

In order to interact fully with a virtual world a participant must undertake several tasks. These include: navigation, moving through the world from one area to another; selection, choosing objects in the virtual world before performing an action on or with that object, for example selecting the vaporizer on an anaesthetic machine before changing the concentration; command, moving, turning or relocating an object, for example turning a vaporizer on or off. In a totally immersive HMD system some means must be provided of issuing commands as the user is unable to use a keyboard.

Tracking devices

Tracking devices monitor the position of the user in order to create a sense of presence by moving the image displayed as the user himself moves. This creates the illusion of travelling through the virtual environment. Usually it is sufficient to detect head and hand movements, but whole body sensing suits have been created. Devices used with HMD rely on the changing nature of a particular signal detected by a remote sensor as the position of the head moves. An initial reference point is established, usually the corner of the room, and all changes in position are related to that. The methods used to detect changes in position include: electromagnetic—three coils in source and sensor (Polhemus); mechanical—linkage arm between headband and controller; optical—infra-red sensors, pupillary tracking; ultrasonic—uses three transducers and three microphones; and inertial—uses miniature gyroscopes.

Factors which are important in the design of sensors include lag (above 50 ms affects performance), the rate of update of information (usually 60 Hz) and possible interference from physical factors such as electrical supplies and walls. The accuracy of position and orientation, and the range of the source to sensor impose physical constraints on the system design.

Interactive devices

Interactive devices allow the user to move and manipulate objects within the virtual environment. The choice of device is often governed by the preference of the user.

Wired gloves. These have been associated with virtual reality for some time. The objective is to describe the
action and position of the hand by using sensors running across the joints. These sensors may be fibreoptic bundles where the change in light intensity caused by bending is detected by a distal sensor or electromechanical sensors. The best known of these devices is the VPL DataGlove (fig. 8). Despite their popularity gloves have proved difficult to calibrate and the electromechanical devices are heavy and cumbersome.

Wands. These are devices containing a 6 degrees of freedom sensor and several buttons or switches to allow interaction with the virtual world. Software interpretation may give the wand any desired appearance, for example a laryngoscope or a surgical scalpel.

Force balls. These are cricket ball-sized objects fixed to a platform and incorporating strain gauge sensors. As force is applied to the ball in an attempt to move it in a particular direction this is sensed and the virtual environment changed accordingly.

Mice. Similar to the standard desktop pointing devices, but incorporating a 6 degrees of freedom sensor.

Biosensors. Future developments may include skin electrodes which will sense movements in the muscles surrounding the eyes or tracking devices which will sense pupillary position. There is research under way to control computers by using amplified EEG signals of between 0.5 and 40 Hz [6].

Voice recognition. Effective voice recognition software eliminates several difficulties by allowing the user to issue commands directly without having to use an intermediary device.

Feedback devices
Tactile feedback. A major difficulty in creating virtual environments at present is the simulation of a sense of touch. Several tactile feedback devices have been produced including the use of small inflatable air bladders over the surface of the hand, vibrating transducers or shape memory alloys whose shape changes as an electric current is applied. None of these is entirely satisfactory. One recent development is a thimble suspended above a desk which exerts a variable force on the user's fingertip. This creates the illusion of touching solid objects, including a "squishy fingertip tour of a rectum and prostate gland" [1].

Force feedback. Robotic research has employed force feedback techniques for some time and the experience gained is being applied in virtual environments. An early example was used in 1985 by the University of North Carolina project Grope III. This molecular docking system allowed chemists to move virtual molecules into appropriate docking sites with each other while observing a stereoscopic display. As the molecules approached, forces were produced on the remote manipulator which approximated to the attraction and repulsion of the molecules. Care had to be excised as injuries to the user from over-zealous use of the manipulator were reported. The production of force feedback is an important part of many medical simulations, from laparoscopic surgery to intubation and cannulation.

Sound
Sound is an important sensation, particularly in a busy operating theatre. We listen to flow of gas to detect obstruction of the breathing system and the vocalization of a patient whose anaesthetic becomes "too light". The rhythmic sound of the ventilator provides security and subconscious perception rapidly alerts us to changes in pattern (obstruction, disconnection) or machine failure (cessation). The monotonic persistent bleep of the ECG machine has in many instances been replaced by an oximeter whose bleep pitch changes to reflect alteration in oxygen saturation. The comments of surgeons and the incursions of (often confusing!) auditory alarms from patient monitors combine to make anaesthesia an auditory rich experience. Sounds may be sampled digitally, altered, stored and played back by computer systems. Added realism may be achieved by localizing accurately the sound in the virtual environment by three-dimension sound display.

Anaesthetic applications of virtual reality
CURRENT INITIATIVES

Much of the current interest in virtual reality in medicine centres around minimally invasive (minimal access) surgery, laparoscopy and endoscopy. The reasons are both social and scientific. The concern generated both within and without the medical profession by the well-publicized complications resulting from laparoscopy surgery have prompted the establishment of training centres and programmes such as that developed by the Minimal Access Therapy Training Unit at the Royal College of Surgeons. At the same time many of the present technical problems of virtual reality associated with cumbersome HMD and low resolution images can be avoided by the presentation of high quality, possibly stereoscopic, images on monitor screens, simulating the environment in which the endoscopist or minimally invasive surgeon works. Several centres are currently developing laparoscopic training simulators which aim to provide haptic feedback during instrument manipulation of virtual tissues and organs. It is intended that in these simulations surgeons may feel contact forces from surgical instruments as they interact with simulated tissues. This type of training process should be more efficient and effective. Ultimately surgeons who only occasionally undertake certain procedures will be able to dial up the simulation for that procedure and practise before conducting the actual surgery. This will make the procedures safer and reduce time spent in the operating theatre, thus reducing the cost of surgery [15].
The pattern of specialist postgraduate training in medicine is set to change radically within the next few years. The introduction of shorter lengths of specialist training, coupled with a progressive reduction in the working hours of trainees will inevitably reduce the amount of exposure to clinical material during training. At the same time it is essential that standards are maintained and on completion of specialist registration the trainee will be expected to provide a competent service over the wide range of clinical problems within his or her discipline. It is necessary to supplement the time honoured apprenticeship system with a far more structured and task-oriented training programme. In response to these challenges, institutes of education have been established in several Royal Colleges, including that of anaesthesia, and working parties established to develop and evaluate training methods and requirements. These requirements are far from being precisely defined and considerable research will be required into the efficacy of different training methods. Inevitably a considerable amount of, at least basic, training will be undertaken using training devices rather than patients, and more advanced training and assessment will be conducted using simulators.

Anaesthesia as a specialty consists of an exciting mixture of the exercise of practical skills and intellectual challenge. Anaesthetists spend much of their working lives anticipating the unexpected and must be trained to respond rapidly and correctly to a wide variety of circumstances occurring during surgery, many of which are critical to the well being of the patient. Response to critical events can be trained and assessed objectively [9, 20], Critical events develop rapidly in anaesthesia, and the anaesthetist must recognize the situation and react appropriately in a short period of time. Experience would seem to indicate that the ability of an anaesthetist to react appropriately to a critical event is directly related to training experience, and inversely related to the time elapsed since training. The low incidence of critical events, coupled with a reduction in exposure time during training will have the result that trainees do not experience all of those life-threatening situations to which they will be expected to respond correctly in independent clinical practice.

As trainees’ exposure to potential critical events in the operating theatre is reduced, so the importance of providing realistic simulations is increased. Virtual reality offers the possibility of creating simulations which recreate an anaesthetist's working environment. The advantages of simulation are summarized in table 1.

### Table 2 Simulator attributes

<table>
<thead>
<tr>
<th>Simulator attributes</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reproduces near exact phenomena</td>
<td>Good for experienced practitioners</td>
</tr>
<tr>
<td>Good for new skills/knowledge</td>
<td>High fidelity</td>
</tr>
<tr>
<td>Expensive</td>
<td>Requires an instructor-trainee interface</td>
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<tr>
<td>Anticipates prior knowledge by trainee</td>
<td></td>
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### Anaesthetic simulators

Computer simulation of anaesthesia has been developed over several years [2]. The attributes of a simulator are summarized in table 2. The Anaesthesia Simulator Recorder developed by Schwid and O'Donnell [19] consists of interacting lumped models representing the circulatory system, respiratory physiology and an anaesthesia-related pharmacodynamic–pharmacokinetic model. The interface to this simulator, which runs on a desktop computer, used iconographic representations controlled by keyboard and mouse. Although the behaviour of the models was satisfactory the interface was not realistic.

The modelling components of this package have now been included in the CAE Virtual Anaesthetic Simulator. Here actual monitors and an anaesthetic machine are connected to a computer console which controls the response of a manikin. Simulations are conducted under the control of the computer operator, who has a choice of more than 40 simulated events [16]. The effectiveness of this simulator as a training and assessment device in anaesthesia has yet to be evaluated, although some success from a small group study using a less sophisticated simulator has been reported from Leiden [4, 5]. An alternative approach is to replace the anaesthetic hardware with a recreated virtual anaesthetic world, incorporating a patient who may be programmed to respond in a realistic way to any number of different situations. The creation of a virtual patient, correct both morphologically and physiologically, is clearly an important objective. JACK is a fully jointed and articulated computer-aided design model of a human being (GMS Ltd, Middlewich). The figure has been developed for use in virtual reality programs investigating human factors design, such as the development of helicopter interiors and NASA space station projects. Modelling of tissue, the response of tissue to surgery and the manner in which internal organs change morphologically during an operation, for instance draining bile from a gall bladder during cholecystectomy, are currently being investigated. Many of the problems encountered are not particularly relevant to anaesthesia, where an accurate physiological or pharmacological response to an event is more likely to be shown by variation in monitored variables, and perhaps by changes in skin colour.
VIRTUAL REALITY POSSIBILITIES

Critical event training

Systematic critical event training has been shown to be of value, as has the introduction of group training in events such as cardiac resuscitation [12]. The use of multiple players in virtual reality simulations is being developed, particularly in aviation and defence application. The development of broadband communications using telephone links between computers offers the opportunity to transmit large amounts of data rapidly over considerable distances. This implies that participants in simulated tank or aircraft exercises need not be at the same physical location. In medicine this offers the opportunity for tele-presence, where a remote expert can receive sufficient information about an operation or clinical situation that he may be able to offer advice and assistance as though he were physically present. In the future it may be possible to observe, assist and be tutored by an expert in a particular procedure who may be residing on the other side of the world. The types of critical events that may be suitable for virtual reality simulation include the management of anaphylaxis and malignant hyperthermia.

Procedure training

Image-guided neurosurgery uses a three-dimensional representation of a patient’s head reconstructed from two-dimensional scan data. The image is used to register the position of a mechanical pointer attached to the patient’s head in relation to the preoperative scans. Localization of the tip of the pointer in relation to internal or external structures is shown on a computer screen. This technique will replace frame-based stereotactic neurosurgery. Developing the application further, a Bristol-based group have modified the pointer by using a telescopic arm [18]. In this way “virtual penetration” of a solid structure such as the orbit may be represented on the computer screen without the tip of the pointer actually passing through the tissues. The incorporation of haptic feedback produces a powerful tool for the training of, for example, local anaesthetic blocks of the orbit for eye surgery.

Teaching practical procedures such as central venous cannulation, peripheral nerve block, extradural and spinal blocks will be greatly facilitated by the use of computer graphics which may be made to display the anatomical relations to the end of the device as the procedure continues. The value of ADAM, an interactive anatomical training aid, in these procedures has yet to be established. Preliminary work on the construction of a tracheal intubation simulator is being undertaken by my own group, and although haptic feedback will probably delay the production of a simulator with acceptable fidelity, a trainer in fibreoptic intubation is well within current capabilities.

Rapid prototyping

One of the major uses of virtual reality outside medicine is in the area of rapid prototyping. During the design phase of most appliances, be they the interior of motor cars, the bridge of a naval destroyer (fig. 9) or the control room of a power station, a physical prototype or mock-up is constructed. This is an expensive procedure and often takes place at the stage of a project when major changes are difficult to incorporate and redesign, and alteration of the prototype time consuming and expensive. The creation of a virtual prototype is much cheaper, more flexible and allows alterations (which are software-based rather than physical) to be made much more rapidly. In addition, the influence of human factors in the operation of the product may be assessed using the virtual prototype and incorporated in the design. In the same way changes in anaesthetic equipment, patient monitors and such features as alarm cascades may be created and tested in a variety of critical situations without compromising patient safety in a virtual environment.

FUTURE DEVELOPMENTS

There is at present a considerable gap between the promise virtual reality holds and the technology that is available to fulfil expectations. However, technological advances in this field have been rapid. Currently, high resolution, fully rendered real-time displays of virtual environments require the type of processing power only available in computers such as a Silicon Graphics workstation costing around £100 000. There is an expectation that a new generation of high performance video cards will deliver this type of performance in desktop computers for a few thousand pounds. Improvements in liquid crystal displays will produce the type of high resolution head-mounted displays that fully immersive techniques require. Cumbersome data gloves will be replaced by biosensors and realistic tactile feedback. All these developments may reasonably be expected within the next 10 years. The possibilities offered by virtual reality simulation are summarized in table 3.

In software the development of object-oriented modelling and programming technique allows the construction of objects and classes of objects with defined characteristics. Libraries of objects, such as patients and apparatus, may be developed and used to provide the component parts for a variety of
virtual environments. When an object has been created it may be used again and again and, provided compatibility standards are defined, may be used in the applications designed by different groups. The initial high expenditure in programming time will decline and future software development costs should be more modest.

**HOW WILL THE PROMISE BE REALIZED?**

All of the foregoing begs two important questions. Who will undertake these developments and how will they be funded? Past experience suggests that the “hobbyist” approach to computer developments in medicine rarely produces a deliverable marketable product. The artificial intelligence field is littered with discard applications which, despite working satisfactorily in their home environment, never achieved portability to other institutes or widespread acceptance.

There is a wealth of experience in virtual reality in those industries, particularly defence, engineering and aviation, where training and simulation have had a high priority. Simulation has had military, commercial and manned spaceflight applications for many years. The collapse of the Warsaw Pact, and diminishing defence budgets has led to the need for diversification in this market. Not surprisingly, some of those companies are now viewing medicine as a potential (lucrative) market for their expertise [8]. While it would be foolish to ignore the skills and experience that they offer, the way in which expertise in medicine is achieved has proved itself particularly difficult to quantify. The risk in allowing commerce to dominate is the production of devices that either fail to satisfy training needs or which offer an unacceptable degree of fidelity to users. A more effective approach will be that of collaboration between industry and academic based medical groups whose interests encompass research into training methodology and training devices. The concern at present is whether or not any commercial partner is likely to recoup what will inevitably be a major outlay. The market for top end virtual reality medical simulators costing £250 000 or more must be fairly limited. It is likely that a more cautious approach will predominate, with the production initially of lower cost prototypes for demonstration purposes, while the cost of technology continues to fall and the requirements of the marketplace are defined.

**References**