9. CONCLUSIONS

At the present time, visual, tracking, and primary user input interfaces are the ones best suited for practical VE applications. In each of these cases, there is a solid basis of commercial products for potential users to choose from. Auditory and haptic interface technologies currently are largely restricted to research applications, but are on the verge of becoming ready for use in practical applications where such interaction is deemed essential. Although widescale usage of auditory interfaces is expected to precede that of haptic interfaces, it is still some time away for both technologies. With respect to full-body motion interfaces, there are several entertainment systems that support limited types of highly specialized movement. Support for more general types of movement still is exclusively a research topic with a variety of different approaches being investigated and motion interfaces systems are unlikely to become suitable for practical use within the next three to five years. Current work on interfaces for passive motion is focusing on a new breed of motion chairs, largely intended for the entertainment market. Olfactory interface technology is the least mature of all the technologies discussed here and another unlikely to see practical usage within the three to five year timeframe.

All current VE interface technologies suffer from some limitations, even the more mature visual, tracking, and primary user input technologies. In no instance does the interface technology match human capabilities for the relevant sensory modality.

In the case of visual interfaces, HMDs and CAVES (typically using projection screens and passive glasses) are the only means of achieving an encompassing visual volume. HMDs, much more widely used than CAVES, suffer from several problems, with the most serious limitations being:

- Inadequate display update rates when responding to user head movements.
- Inability to provide both high resolution and a broad field of view.
- Weight that imposes an inertial burden and low levels of comfort that prevent prolonged use.

All these problems are well recognized and the first two are likely to be substantially reduced in the next few years through advances in LCD technologies. While smaller, lighter weight displays will help to reduce overall HMD weight, the necessity for bulky optics means that weight will continue to be a problem. A former problem, the expense of commercial HMDs, is becoming less serious as more low cost devices are becoming available, although these require the user to make some compromises in resolution and/or field of view.

So far passive glasses have not been widely used in VE applications, although new microelectronic fabrication techniques for creating polarizing filters at the pixel level may change this trend. Shutter glasses are quite widely used, usually with CRTs or projection displays. Here again, advances in LCD technology are likely to see an impact as LCD displays with faster switching time will help in reducing crosstalk problems. There is much research and development in the area of autostereoscopic displays and a small number of products is likely to come to market in the next two to three years. While these displays offer the advantage of not requiring any encumbering head gear, glasses, or head tracking devices, they also have some current limitations. The primary limitation, that users are restricted to a limited viewing area, is likely to be reduced with the development of flat panel displays with higher resolution and the simultaneous display of larger numbers of perspective views. Retinal displays are a new topic of research and development. While they have the potential for providing a fully encompassing visual display without the weight and limited resolution and field of view of current HMDs, it will likely be some years before black-and-white retinal displays come to market, and longer for color displays.

Systems for tracking head, hand, and body movements are available and many have seen widespread use. Even so, low latency, high accuracy systems for tracking in noisy, unprepared environments do not exist. The most serious shortcoming of current technology is the following:

- Inherent limitations in some combination of accuracy, intrinsic latencies, working volume, susceptibility to interference of obscuration, and cost.

Again, these are well-recognized problems that are expected to be the focus of near-term research and progress, especially for magnetic trackers, is expected. The most significant improvements in tracking performance, however, are expected to come from the use of hybrid trackers where many of the limitations inherent in a particular technology can be overcome. Research in the development of such hybrid trackers is underway. Although there are no products commercially available as yet, these are expected to start appearing within the next couple of years. Wide-area trackers are another area where commercial products are unavailable and, with only limited research being performed, this type of tracking interface is not expected to see widespread use any time soon.

Eye tracking also is a less mature type of tracking technology, largely because traditionally it has had a limited range of applications and, therefore, has attracted little research interest. In this case, the major problems appear to relate to:

- Limited accuracy and intolerance to user head movements.

The increased use of multimodal interfaces (in both VE and non-VE applications) that can benefit from the ability to monitor the direction of the user's gaze, however, is opening up new potential markets that should encourage further development of this type of interface technology.

A number of 3-D sound processors that can be used in VEs are commercially available. These range in capability from systems available for use with PCs, to high-end professional audio systems. However, a number of questions need to be answered and further research done before virtual audio can become a practical tool. Serious limitations are the following:

- Inability to represent sounds as being located in front of the user and to adjust sound spatialization to head movements.
- Inadequacies in acoustic signal generation.

Near term work is expected to focus on these areas, continuing to improve the realism and full-surround capabilities of the technology. Crucial support for this work will come from the development of improved algorithms, based on a more thorough understanding of how humans perceive sounds. As digital signal processing becomes less expensive, virtual audio is likely to become more widespread. This is already happening to some extent with many dedicated game systems, major computer companies, and audio chip manufacturers licensing low-end virtual audio technology. As a result of increasing availability and the lower cost of technology, these types of interface are expected to become a common component of VE systems within the next five years.

The development of glove-based devices for user input is an area of current growth. All the interface systems on the market are relatively new products and at least two additional products are expected to become available by mid 1996. The current set of products do allow the use of natural hand gestures for certain, limited interactions with a VE but the primary shortcoming remains:

- Limited joint resolution and poor discrimination between gestures.

While improvements in sensor technology will help to reduce this problem, it is likely that advances in software-based gesture recognition will play a more important role. Gloves already are a fairly common VE input device but their use is expected to become more widespread as gesture recognition capabilities improve. There seems to be little ongoing research looking at the use of exoskeleton-based devices and these are not expected to be widely used, but limited to highly specialized applications.

A fairly diverse range of 3-D pointing devices is available. These products represent mature technology and, while new products may appear over time, no major changes in this area are expected.

Tactile and force feedback interfaces for VEs have been able to exploit previous work in the areas of, respectively, sensory substitution devices for the disabled and teleoperation. Both represent active areas of research and development. In the case of tactile interfaces, researchers are investigating how to provide contact force, slip, texture, vibration, and thermal sensations. Products intended to simulate contact forces that occur when a user touches a virtual object and that provide temperature feedback are already commercially available. The ability to support other types of tactile sensation is more problematic. Although prototype devices exist, each tends to be specialized to one particular type of sensation. Moreover, all existing devices, both commercial products and prototypes, limit the presentation of sensation to a small area, usually the fingertip, and are unlikely to be able to scale up. While these devices are relatively small and lightweight, at least compared to HMDs, they are encumbering to some extent and can constrain finger movement. In addition to shortcomings in tactile interface hardware, much work is still needed in developing the software models needed to drive the generation of tactile signals. Consequently, the major limitations in the area of tactile feedback can be summarized as follows:

- Limitations in the ability to represent surface characteristics such as texture, local shape, and slip.
- Inability of devices to present a range of tactile sensations.
- Limitation of tactile feedback to small areas.
- Lack of models and algorithms for efficient generation of tactile signals.

As stated, this is an active area of research and much progress is expected over the next few years. Nevertheless, although several prototype applications are expected, tactile interfaces are unlikely to see common use within the next two to three years.

The majority of current force feedback devices can be distinguished as exoskeleton devices that deliver forces to the shoulder, arm, or hand; tool-based devices that deliver forces to the hand via a knob, joystick, or pen-like object held by the user; thimble-based devices that deliver forces to the user's fingertips; or robotic graphics systems that move real objects into place to provide natural forces to the user. Here again, each type of device is limited in the type of interactions it can support, in this case largely because of the intrusive nature of each device. Consequently, although several devices are on the market, each provides very different capabilities and is suitable for different types of application and, as yet, these devices have only seen limited use. The serious limitations of force feedback interfaces are, in many respects, similar to those given for tactile interfaces:

- Inability to provide force feedback for a variety of different VE interactions.
- Limitation of force feedback to a restricted number of joints.
- Intrusive nature of force feedback devices and their constraints on user movement.
- Lack of common models and algorithms for efficient generation of kinesthetic signals.

Burdea and Zhuang (1991) cite deficiencies for teleoperator systems that also apply here. These include the inadequacy of current actuators, coupling between degrees of freedom, and high system complexity from mechanical design, hardware, and control software issues. Since this is an active area of research, considerable technology advances are expected to occur in the next three to five years. In the interim, force feedback interfaces are unlikely to see much practical use, with the possible exception of those used in medical applications.

A number of approaches and devices have been developed to facilitate a user "moving" through a VE. The simplest, and most common of these, is for the user to point in the desired direction and for the visual scenes to be adjusted accordingly. A number of entertainment systems provide highly specialized interface devices allowing, for example, the user to simulate hang gliding or sledding. Unfortunately, there has been little progress in providing interfaces that allow a user to simply walk or run through a VE. Of course, active self-motion within a small area (for example, 10 x 10 feet), over a uniform surface that provides the necessary haptic cues presents no problem. Technology that can support a user moving through a large area or across a surface with varying characteristics, however, has only recently begun to be investigated. A number of diverse designs for interface systems have been proposed and a few prototypes built, using both mechanical and non-mechanical approaches. While such systems may see use as advanced prototypes, none are expected to come into common practical use within the next three to five years. The potentially large entertainment market also has fostered the development of passive motion interfaces. In the last year, several motion chairs have been developed that employ techniques ranging from inflatable chair cushions to motion bases to provide the user with a sense of motion. These devices may become widely used for a diverse range of low-cost simulators.

Three commercial systems that support the use of olfactory cues in entertainment applications are available, two of these providing controlled release of odors. There are no olfactory delivery products that support a controlled air space. A small number of research efforts are underway and at least two prototype systems are being developed. While more prototype systems might be developed in the next few years, this technology is not expected to become practically available in the near future. Some problems that are being addressed by ongoing research include:

- The encumbering nature of delivery systems and the need for miniaturization of systems components.
- Difficulty in controlling the user's breathing space.

While the ability to provide olfactory cues may be important for specialized applications, such as surgical training, the utility of such cues remains to be demonstrated.

In addition to further research and development on actual interface hardware and software, all the areas of interface technology discussed in this report will benefit from a better understanding of the role of sensory cues and human perceptual issues. This improved understanding not only is required to know how sensory cues can be delivered or simulated, but when and how they should be used. This is not to say that full fidelity of sensory cues is the ultimate goal. Even if achievable, high levels of fidelity would be expensive and not always desirable. What is needed is to determine the fidelity required for specific applications and how best to satisfy those requirements.

One issue that seems to be have been ignored so far is that of usability. VE interface technology is primarily concerned with human-computer interaction and yet there have been no reported evaluations of the usability of particular VE interfaces. This type of study is keenly needed to guide both the use of existing interface systems and the ongoing development of new systems.