1. INTRODUCTION

This report reviews virtual environment (VE) interface technology from the perspective of the user, that is, the devices and requirements that are imposed on the user in order to interact with a VE. In this report the term VE is used synonymously with *virtual reality* and *synthetic environment*. There is no widely accepted definition of the term, and the approach chosen here is to describe a VE system as a computer-generated world with which the user can interact with the purpose of altering the state of the user or of the computer (Durlach and Mavor, 1995). The intent is to provide the user with a meaningful environment with which he can interact in a natural, multi-modal manner. For example, in a medical training application, a surgeon can practice particular surgical procedures on a virtual patient. In addition to visual images, the surgeon's major form of interaction with the system is by means of specially-modified versions of his customary instruments that provide realistic haptic feedback sensations as the surgeon manipulates virtual body tissues (Hunter et al, 1993). A virtual prototyping application might surround a designer with the visual representation of a new Space Station design which he could then move through to determine the ease of access to critical maintenance hatches. In this case, the major form of interaction would arise through the user's body movements, not only in walking to different parts of the space craft, but in seeing whether he could reach a given bolt with enough maneuvering space to exert the necessary torque to release it (Tanner, 1993).

Both of the above examples are representative of immersive VE systems, where the user is essentially surrounded by the virtual world to the exclusion of the real world. VE systems may also be non-immersive. In this case, the user views the virtual world indirectly through a computer monitor or some other display and, typically, interacts with the VE using more traditional keyboard, mouse, and trackball interfaces. A third alternative is augmented reality systems where the virtual world is superimposed over the real world. Here the intent is to supplement the real world with useful information, for example, guidance in performing a real world task. This report focuses on interface technology for immersive VE systems, although some of the material also is applicable to non-immersive and augmented reality systems.

Why has so much recent interest focused on VE systems? Quite simply, the potential of these systems is enormous. First of all, they offer a more intuitive metaphor for human-computer interaction. The user can exploit his existing cognitive and motor skills for interacting with the world in a range of sensory modalities and, in many instances, the experience he gains in the VE is directly transferable to the real world. Also, VE technology opens up new application areas that, hitherto, have been too expensive, too dangerous, or simply impractical. The examples already given illustrate cases where previously unavailable training and practice opportunities can be provided without risk to actual patients, and how critical design decisions can be checked early in the design process without the construction of expensive physical mock-ups. A VE system can also be used to simulate a world not based on reality, or a world distorted in some meaningful way. For example, the ability to manipulate the laws of gravity while observing the effect on objects offers a valuable tool for high school physics education (Dede, Loftin, and Regian, 1994). Research chemists can benefit from a VE system that allows them to directly manipulate representations of binding forces between molecules (Brooks et al, 1990). The full scope of possible applications for VE systems, and their potential benefits, is still to be determined.

In some respects, VE systems are not new. Aircraft simulators have been in use by the Department of Defense (DoD) and the airline industry for many years, and are an obvious example of what are now called VE systems. In general terms, any computer simulation is itself a VE, although the user interaction with such simulations historically has been very restrictive. The primary innovation in today's VE systems lies in the user interface, that is, the ability to support multi-modal interaction with a simulation.

Before continuing, it is important to note that VE technology is still in its infancy. Instances of all the mentioned examples already exist or are under development and there have been VE systems that have demonstrated practical effectiveness (see, for example, (Hancock, 1993), (Magee, 1995), and (Finch et al, 1995)). Nonetheless, current systems are quite primitive, particularly with respect to their user interfaces. Not only are advances in interface hardware and software required, but a better understanding of many user issues is needed. Without question, VE technology is promising, but one that has yet to fully mature.

1.1 Purpose

One of the major recent publications in this field is the National Research Council's review of VE scientific and technological challenges (Durlach and Mavor, 1995). Prepared at the request of a consortium of federal government agencies, this review provides a overview of the current state of research and technology, a summary of major applications areas, and recommendations intended to guide a "rational and systematic development" of the field. Recent books, most notably those by Burdea and Coiffet (1994) and Barfield and Furness (1995), also provide excellent descriptions of the current state of VE technology and how these technologies work. The purpose of the current work is not to repeat any of these previous efforts, but to provide a supplement to that work. Focusing exclusively on VE interface technology, it describes some currently available commercial products and some current research and development efforts. This information provides a baseline against which the current state of art can be extrapolated to predict how VE interface technology might evolve over the next few years. In addition, the descriptions of available products are expected to provide a useful resource to potential consumers, while the descriptions of ongoing research and development efforts might serve to help researchers keep abreast of the overall directions of current work.

1.2 Scope

The interface technologies that are discussed are visual, auditory, tracking, primary user input (that is, glove-based, exoskeleton, joystick, trackball, 3-D mouse, and similar device-based input), haptic, full-body motion, and olfactory interfaces. The role of visual interfaces is obvious and needs no discussion except to point out that humans are strongly oriented to their visual sense, even to the extent of giving precedence to the visual system if there are conflicting inputs from different sensory modalities. While tracking is a type of interface that is largely transparent to the user, it is critical in keeping the VE system informed about user movements so that sensory inputs can be correlated to the user's position. Auditory interfaces can play a key role in providing informational inputs to the user, increasing the realism of a simulated environment and promoting a user's sense of presence in a VE. In addition, they are used in sensory substitution where, for example, a tone is sounded to indicate when a user comes "in contact" with a virtual object and so substitute for the sense of touch. The term primary user input interfaces is used here to refer to those means whereby the user provides direct input into the VE system, for example, commands that control the operation of the system. Haptic interfaces provide the tactile and kinesthetic feedback arising from user contact with objects in the environment. Full-body motion interfaces fall into two categories. Active self-motion interfaces allow a user to move freely through an environment, for example, walking over various types of surfaces or climbing stairs as necessary. Passive motion interfaces reflect the use of some type of vehicle to move a user through the environment. The final interface technology to be discussed is that of olfaction, where odors are used to provide the user with additional sensory cues about his environment.

The scope of the work reported here was limited by available resources. Invariably, the choice was made to focus on technologies that are specific to VEs at the expense of those that are well-defined areas in their own right. Accordingly, speech recognition and generation, natural language processing, gesture recognition, computer image generation, and cabin simulator technologies are not covered here. Similarly, application-specific interface devices, such as special-purpose knobs and switches, or steering wheels, are excluded.

With respect to research and development efforts, the focus is on *ongoing* work. No attempt is made to provide complete references to earlier efforts, although some mention of previous work is made where this directly impacts the current work discussed.

1.3 Limitations

The commercial products and research efforts discussed in this report were identified from a number of sources. In the case of products, the primary sources were published lists of vendors and advertisements found in several of the trade magazines. Research efforts were primary identified from researchers already known to be active in the VE field and the technical literature. The resulting information should not be regarded as comprehensive, but rather as providing a representative sampling of the available products and ongoing research. In particular, work that is regarded as proprietary, or unpublished for any reason, was unlikely to be identified.

The VE field is an active and fast-moving one and, therefore, the information contained in this report potentially has a short half-life. In each case, the product and research descriptions have been reviewed by the applicable vendor or researchers[1]. Accordingly, the details reported were accurate prior to the release of this report but subsequently may have changed. Ideally, the same details would be provided for each commercial product of the same type. While attempts were made to preserve consistency wherever possible, in some case the desired information was unavailable.

1.4 Organization

The following sections of this report discuss each of identified types of interface technology in turn. Where applicable, these discussions start with an overview of capabilities of the relevant human sensory systems. This material not only builds a picture of the psychophysical interactions that take place, but indicates some requirements for particular interface devices. Short descriptions of commercially available products are followed by descriptions of on-going research in the area. The discussion of each technology area is concluded with a summary discussion and some statements of expectations for technology advances in the next few years. The report closes with a concluding section that provides an overall picture of the major limitations in current VE interface technology and gives some projections on how this technology is expected to advance in the near future.

[1] All specification data was supplied by the vendors and researchers concerned, and was not subject to independent analysis.