FUTURE CYBORGS: HUMAN-MACHINE INTERFACE FOR VIRTUAL REALITY APPLICATIONS

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Abstract

From its inception as a technology, virtual reality has promised to revolutionize the way we interact with our computers and each other. So far, the reality of virtual reality has not lived up to the hype. This paper explores what the state of virtual reality interface technology will be in the future by analyzing the current state of the art, forecasting trends in areas relevant to virtual reality interface research and development, and highlighting the barriers to providing virtual reality environments that are immersive and interactively indistinguishable from reality (strong VR). This research shows that the evolutionary pathway of virtual reality technology development will not be able to overcome all of the barriers and limitations inherent in the current generation of interfaces. I use a reverse tree methodology to explore alternate pathways to achieve strong VR. Brain-machine interfaces (invasive and non-invasive) represent the most likely pathway that will lead to a strong VR interface. The US Air Force should continue to develop common VR interface technology using widely available interfaces, but should increase its funding and support for technologies that will enable enhanced brain-machine interfaces to ensure its dominance in training and simulation for the future.

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Introduction

Since the late 1980s, virtual reality has been heralded as the next technology that will revolutionize the way we use our computers in the future. Many experts in the virtual reality field were convinced that the technology would rapidly overcome the physical barriers it faced. Their enthusiasm for future possibilities created expectations from fields as diverse as the entertainment industry and the United States government. Many of the potential users were persuaded by the hype to invest significant resources into this next great technology.

But the return on their investments has been slow to be realized. Although virtual reality has been able to gain a foothold in specific applications and industries, it has not been widely accepted as a means for interacting with your computer. The problems that have plagued virtual reality technology vary widely from extremely limiting and cumbersome interfaces to a lack of applications that are able to take advantage of the medium. The early hype and resulting failure to deliver has created an environment where the mention of virtual reality future elicits responses that are extremely skeptical about its usefulness for anything but esoteric applications.

This skepticism is not without merit, but in order to explore the future of virtual reality technology, we must push aside skepticism based on past failures and extend our understanding of the fundamental problems with the current technology and its ability to deliver in the future. We must be able to cut through the baseless hype surrounding this technology and discover where the real issues lie and analyze them to realize what promise virtual reality holds for the future. This will allow us to make better resource decisions that will enable us to take advantage of the gains promised by virtual reality, while remaining grounded by its limitations.

This area is important to the US Air Force specifically because of its application to so many different areas. Virtual reality and its related technologies would allow better training at lower costs, increased situational awareness and data visualization of the multi-sensor battlespace, and the ability for mission rehearsal to be carried out using more realistic environments. Many of these applications already use available virtual reality interfaces, but in order to maintain our competitive advantage, we must continually push our technological envelope. We must seek out the most cost effective solutions for revolutionary technological change to ensure our technological advantage.

In the area of virtual reality, the primary issue is that in order to create the ideal virtual reality system, one must focus on the interface between the man and the machine. In virtual reality, the interface is the application. It is the interface that allows the man to become immersed in an artificially created world. It is the interface that allows him to interact with his artificial environment. It is the interface that defines the limits of this virtual environment. In order to improve the performance and usefulness of virtual reality, we must improve the interface between the human and the machine.

One of the failures of virtual reality has been its inability to create a generalized interface that will be useful for many different applications. Most of the research into improving virtual reality performance has centered on individual pieces of the interface. The research has been dedicated to creating improvements to existing interfaces – an evolutionary upgrade in the best of circumstances. Although this incremental strategy has improved the overall usefulness of our current generation of virtual reality, its future success may be limited by oncoming technological barriers. Incremental improvement, even when coupled with exponential increases in computing power and increasing market pressures, will not be able to shift the emphasis from ***virtual*** reality to virtual ***reality***.

In order to overcome these barriers, we must look for alternate pathways that lead to enhanced human-machine interfaces able to create more natural and realistic interactions. These revolutionary interfaces should be able to overcome the limitations of the current generation of virtual reality interfaces and allow us to sustain our competitive advantages in training and mission rehearsal. In addition, these revolutionary advances will allow for new and emerging applications of our computing power that will lead to gains in other areas that will allow us to continue our dominance in the battlespace of the future.

Methodology

In the next section of the paper I will outline a useful definition for virtual reality. I will briefly examine the concepts that are contained in the definition. This discussion will include a spectrum of "virtualness" that will provide a framework to analyze current and future interface technologies. This framework can be used to classify current and future VR systems by how well they replicate immersive and/or interactive environments.

The technological analysis will begin with a review of current virtual reality (VR) interfaces for each of the channels that correspond to the human senses. This section will also outline the primary research and development efforts that seek to improve the current VR interface. This section will provide a basic understanding of the state of the art interface for today and near tomorrow.

The technological forecast will be achieved through a combination of two primary methodologies: trend analysis and a reverse tree. My primary method of forecasting will be a trend analysis of computing power, market and industry forces, and system hardware gains. This analysis should provide an adequate forecast for what should be available along an evolutionary pathway using today's current technology. In order to capture technologies that are not included in this pathway, I will use an offshoot of the paths and trees forecasting methodology to identify alternate pathways that may achieve revolutionary gains in VR interface technology.

The last section of this paper will provide conclusions about the future of virtual reality interfaces, while outlining some of the relevant implications for the fielding of this technology. I will analyze the implications of having these advances available to us in the US Air Force. These analyses will be supplemented by three appendices that provide further information about related applications, military uses of this technology, and non-technological issues that may influence the development of VR interface technology.

What is Virtual Reality?

> *As long as you see the screen, you're not in virtual reality. When the screen disappears, and you see an imaginary scene…then you are in virtual reality.* – **Gabriel D. Ofeisch, Emeritus Professor of Educational Technology at Howard University**[1]

The word virtual has been overused to describe just about anything that deals with a computer–virtual banking, virtual MPF, virtual teleconference. Adding to the confusion is the overuse of the term virtual reality to describe any number of different computer applications that provide an artificial visual environment. This has contributed to a lack of understanding of what virtual reality is. In order to explore the future of virtual reality technology, we must begin with an understanding of what virtual reality really is.

The DoD definition of virtual reality is "the effect created by generating an environment that does not exist in the real world. Usually, a stereoscopic display and computer-generated three-dimensional environment giving the immersion effect. The environment is interactive, allowing the participant to look and navigate about the environment, enhancing the immersion effect."[2] Although this definition has elements that enhance our understanding of VR, it also limits our understanding of what virtual reality is by specifying hardware that is used to create the "virtual" effect. Other attempts at defining virtual reality in the military have suffered from a similar focus on current hardware. A 1996 SAASS research paper defined it as "the combination of real-time 3-D computer graphics with shading and texture mapping, high resolution stereoscopic large screen or head mounted displays, along with novel user interfaces."[3]

Both of these definitions limit an exploration of virtual reality by focusing too narrowly on the hardware aspects of the current generation of virtual reality. In order to forecast the future of virtual reality, one must start with a more generalized definition. At its core, virtual reality should be understood to be "an immersive, interactive experience generated by a computer."[4] Virtual reality must be an experience that allows the user to engage with his environment through natural means without breaking the illusion of the immersive reality.

Although better, this definition is too general to be able to evaluate the technology that will or could be available to create an immersive environment. The most helpful definition focuses on virtual reality as the interface between the computer-generated environment and the person who is experiencing this environment. In this respect, virtual reality may be seen as the sixth-generation of human-computer interface.[5] The interface creates an alternate reality for the user that allows them to navigate through the environment and interact with objects as they would in the real world.[6] The immersion of the user into the virtual reality is carried out by interfacing computer generated information through multiple sensorial channels – visual, auditory, haptic, etc.[7] The only reason we know anything about our real environment is due to the unique human senses that have developed as our interface to the world. Virtual reality interfaces work through these human interfaces to replace reality with an alternate reality generated by a computer.

When we refer to virtual reality throughout the remainder of this paper, it will refer to a computer interface that involves real-time simulation of an interactive, immersive environment through multiple sensorial channels. This definition encompasses all of the relevant facets of the other definitions, without limiting it to the currently available hardware or interfaces.

3 I's of Virtual Reality and the Holy Grail

> *Have you ever had a dream, Neo, that you were so sure was real? What if you were unable to wake from that dream? How would you know the difference between the dream world and the real world?* **– Morpheus (The Matrix)[8]**

Using the definition derived in the previous section there are three characteristics that allow us to evaluate the performance of any virtual reality system. One author refers to these characteristics as the 3 I's of virtual reality. These characteristics are immersion, interaction, and information intensity.[9]

Immersion is the ability for the user's senses to be isolated from the real world and for the computer generated environment to appear naturally enough for the user to be "transported" to another place.[10] Immersion allows the user to forget that they are experiencing an artificial reality. The degree of immersion of any VR system will be dependent not only on the type of interface that is used, but will also be a result of the number and type of user senses that are being stimulated.[11] Immersion then is a measure of how well the computer can replicate sensory information for a single channel as well as the number of sensory channels involved.

Interactivity is the ability for the user to change the computer generated environment in real time. Interactivity is what allows the user to affect the scene that they are being provided from the computer. The degree of interactivity is a measure of not only the speed that the computer reacts to the user's input, but also the ability for the computer to respond to a user's natural form of input or output. More interactive VR environments will not only allow the user to change the visual scene by moving their head or body, but will also provide tactile feedback and control of objects in the environment through their hands. The most interactive VR environments would allow the user to handle any object in a natural manner.

Although the words information intensive are not used in our definition of virtual reality, the concept they represent is present. Virtual reality is information intensive to support its ability to be immersive and interactive. The computer must be able to react to the inputs of the user and update the environment appropriately with a level of information that does not break the illusion of reality. The information generated by the computer must conform to all of the sensorial channels of the user – which creates an extremely intensive data processing requirement for any input/output channels.

In order to compare and analyze the current VR interfaces as well as any future advances, we must provide a framework for comparison. The degree that the virtual reality interface conforms to the characteristics of immersion and interactivity can be plotted in Figure 1 below. Strong VR is a VR interface that is highly immersive and highly interactive – making it difficult to distinguish from reality. Weak VR corresponds to a computing environment that is neither immersive nor interactive in a natural sense.

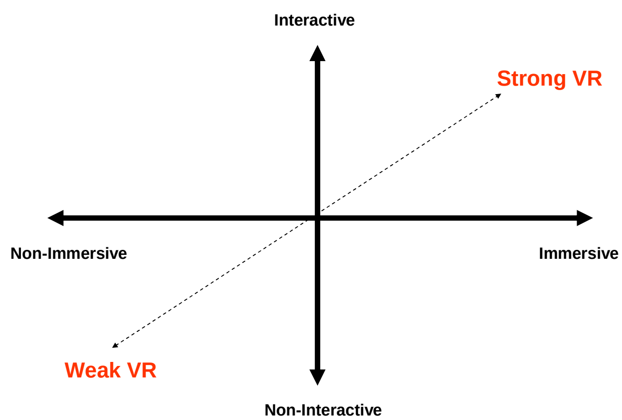

Figure 1

The so called "holy grail" of virtual reality interfaces is to have the user so immersed in an interactive environment that they are unable to tell the difference between reality and simulation.[12] This type of virtual reality has only yet been achievable in the imaginations of movie writers as seen in The Matrix and The Thirteenth Floor. Many of the early adopters of VR technology were eager to say that this type of VR was "not too far off."[13] Yet most of the current technologies for VR interface can be found either in the immersive/non-interactive or non-immersive/interactive quadrants. The challenge for our future is to discover what interface technology will be technologically feasible and that we should pursue in order to allow us to achieve the "holy grail."

Channels of Virtual Reality Interface

> *In virtual reality, the smallest details of sensory experience, the building blocks of human reality, are used to create environments.* ***—Ken Pimentel and Kevin Teixeira***[14]

According to our definition of virtual reality, interfaces must provide immersion and interactivity on multiple sensory channels. Most of the research and development has historically focused on the two channels of sight and sound. Recently VR developers have begun to concentrate on the sense of touch through haptic interface technology. Almost no VR systems include interfaces for the senses of smell or taste. In order to decide the best pathways to approach the "holy grail" of strong VR, we must evaluate the current state of the art for each of these sensory channels individually, and then evaluate their use in VR systems that attempt to combine multiple sensory channels.

Visual

The visual channel in virtual reality interfaces should provide imagery to the human eye that is "indistinguishable from that encountered in everyday experience in terms of quality, update rate, and extent."[15] In order to provide an experience that is both immersive and interactive, VR developers have used a number of different interfaces to fulfill the visual requirements. Their early efforts evolved from the use of CRTs that provided little immersive reality and interaction was limited to keyboard or mouse inputs. Although the current technologies provide a much greater immersive and interactive experience, there is still a large gap between visual displays and visual reality.

The main effort for providing visual immersion into virtual reality has been through head-mounted devices (HMDs).[16] The first attempt to create an HMD used two large CRTs in a device that was too heavy for the human head to bear without external support.[17] Most current HMDs still use two visual displays placed directly in front of the user's eyes that are held in place by the device which simultaneously tracks the movement of the user's head to provide cues to change the visual display. Development of HMD technology has been aided by the decreasing size of visual display technology and the increasing resolutions available on these same displays. Current generations of HMDs are being designed to operate within the form factor of a pair of eyeglasses.[18]

These systems are limited in their ability to provide an immersive environment by their field of view (FOV) and their resolution in relation to visual acuity. Generally speaking, the larger the FOV the HMD provides, the greater the immersive experience. But increased FOV usually requires a tradeoff in resolution which can degrade the immersive quality of the display. In addition, most HMDs on the market provide the same image to the visual display in each eye.[19] This decreases the complexity of the device, at the expense of stereoscopic vision. These tradeoffs lead most developers to design HMDs that are application specific in order to focus on the visual needs of their particular virtual interface.

An offshoot of the current HMD technology replaces the visual displays in front of the user's eyes with a device that is able to write the visual image directly on the user's retina. These are known as virtual retinal displays or retinal scanning displays.[20] They are best used in augmented reality interfaces, since they do not immerse the user into a space separate from reality. The user is able to see the real scene around them, but with the ability for the computer to generate information to be overlaid on the scene.

Although HMDs are the primary interface of choice for individual immersive applications, others have been developed that provide immersion for groups of users at one time. The CAVE technology, developed by the University of Illinois in the early 1990s, uses a large room with graphics being projected onto two or three walls and the floor. [21] The users must still wear head mounted devices to allow them to see the displays in stereoscopic vision, but this technology frees them to move throughout the virtual reality scene unencumbered by tethers to a computer generated display. It also allows multiple users to survey the same scene simultaneously without generating multiple visual channels of information.

Another recent technology that has gathered some interest for use in the visual channel of VR interfaces is holography. This is another way to create an immersive environment that is shared by multiple users simultaneously.[22] This technology is opposite of the early VR thinking of providing resolution in a limited FOV. Holography attempts to produce a 3-D image with resolution that is not limited to one sight line. Although it took the first inventor 20 years to create a white light hologram,[23] the amount of research being applied to this particular area has rapidly increased its capabilities for use in VR interfaces in recent years.

Even though the technology for VR interface via this channel has received the primary weight of effort from VR research, it still has significant limitations that hamper its ability to provide an immersive, interactive environment. Most of these systems are not designed to take account of the dual nature of the human eye for tracking and focusing on objects individually, and few allow for true stereoscopic vision cues. The tradeoffs required between FOV and resolution limits the immersive nature of the interface due to the physical nature of the display devices. Immersion can also be disrupted through any perceived lag in visual feedback greater than 250 ms.[24] Most of the visual interfaces are unable to provide a seamless immersive experience indistinguishable from reality without lag due to lack of processing power in the computer video generation. Finally, all of these visual technologies may do an adequate job of providing a visually immersive experience, but none of them is conducive to providing a simultaneously interactive environment without an encumbering haptic interface device.

Auditory

The auditory channel has not received as much emphasis as the visual channel, but does not present the same level of challenges that the visual channel contained. The auditory channel attempts to create an aurally immersive environment that is also interactive in that the perception of the sound changes as the user changes their position relative to the source of the sound. There are two primary mechanisms for introducing the aural channel to the VR user: headphones or speakers.

Headphones are the preferred method for providing the aural information to the user.[25] This interface allows the computer to generate two different acoustic waveforms that can be made to correspond to the ear position of the user in the virtual environment. The differences in the waveforms are used to provide azimuth perception,[26] and the attenuation of the waveform is used to provide distance perception. Currently, the technology is able to provide aural cues that allow the user to resolve information received via headphones with an accuracy that closely approximates reality. The drawback to headphones is the need to wear a device on your head or in your ears that detracts from the immersive experience.

Speakers allow the user to be free from the tether of an interface device connected to their person, but are unable to provide the same levels of aural resolution as headphones. Particularly, speakers are unable to simulate a point source of sound that is remotely located from the speakers' locations. This degrades the ability for the user to explore their aural environment through the positioning of their head.

Auditory information is able to enhance the experience of the user by interacting with other channels, specifically the visual interface. Sounds help the user to understand the visual scene that is presented to them. It can also enhance their perception of the quality of the visual image by improving the quality of the sound. An MIT study used two side-by-side TV sets showing identical images with differing qualities of sound. People consistently rated the TV set with the better sound as having a much better picture.[27]

Haptic

The haptic channel is the least developed of the primary interface mechanisms. This may be due to the inherent complexity of "combining sensory functions with manipulative functions and with the use of electromechnical systems."[28] Compared to the previous two channels, haptic technologies must be able to provide a wide variety of feedback and input mechanisms. Visual and auditory sensations are each filtered through human organs that are specifically designed for their function. Sensations of force and movement are inseparable from actual physical contact because the sensations can occur at any part of the human body – both internal and external.[29]

Unlike the visual and auditory channels, the haptic channel is also able to both sense what is happening around the user and act on that environment at the same time.[30] This ability is related to the way the human body processes haptic information provided by its environment.

> Haptic sense is generally divided into two distinct sensory modalities: the kinaesthetic sense which includes perception of muscular effort as well as proprioception, and the tactile sense which provides cutaneous information related to contact between the skin and the external environment.[31]

In addition to the sensation of touch with an external object, this sense also includes the complexities of temperature, stickiness, texture, and frequency. These sensory inputs do not even take into account the body's ability to receive haptic information through its vestibular system.[32]At the same time, any haptic interface must not only provide a realistic output of what the body should be feeling, but it must accept the inputs from the human interface to provide updates to the environmental situation in virtual space.

The number and type of solutions for virtual reality interface devices continues to increase as each developer creates a unique solution for their particular application. The majority of haptic interfaces in use today are force-feedback joysticks and pads used in computer games and motion simulators.[33] The primary interface device for VR systems currently in use is the data glove that is used as an input device by measuring not only the location of the user's hand, but also the degree of bend or flex in each finger joint.[34] This data glove may be married with an exoskeleton to provide an output capability as well. The limited uses for these widely fielded haptic interfaces highlights the difficulties in replicating haptic interactions using existing technology.

Other technologies that have been developed to allow an expansion of the haptic interface beyond these limited uses are all very specialized in nature. Some of these technologies are dedicated to creating the illusion of force generated by a virtual object like exoskeletons, tool-handling force displays utilizing specific objects for specific application interface, and object-oriented force displays that are able to move or deform to simulate different shapes.[35] Other technologies are used to simulate the full-body haptics involved with movement or locomotion within the virtual environment. These devices are usually treadmills, foot pads, or pedaling devices that allow the user to more naturally move throughout the virtual landscape. Finally, some of these specialized technologies focus on the sensation an object creates on the user's skin. A micropin array has been created that is able to convey complex textures in a two-dimensional geometry.[36]

All of these solutions are quite capable of providing reasonable haptic interfaces for specialized applications, but none of them are able to provide a full-body immersive experience that accurately replicates the human experience in reality. These haptic interfaces are limited not only by the size and weight of the actuators needed to provide the illusion of force, but are also limited by the VR systems "ability to coordinate and calculate haptic feedback in real-time that match the human perceptual capabilities in accuracy and resolution."[37] The difficulty in overcoming these barriers, the complexity of the entire haptic system of the human body, and the lack of basic research in haptic sensations makes this channel the least likely to see significant progress toward the idea of "holy grail" virtual reality.

Taste / Smell

The channels of taste and smell have not historically been included in any of the commercially developed VR systems. This exclusion has generally been due to their inability to deliver content that is necessary for the most basic virtual reality simulations. These senses provide information to the human body during specific applications, but are not generally used to orient the person in their environment. They can, however, be used to enhance the immersive quality of an environment. Walt Disney World uses the sense of smell during their virtual reality ride "Soaring" to further immerse the rider into their illusion.

Both of these channels suffer from a general lack of knowledge about the human system underlying the sense as well as how to replicate these sensations among different people. Additionally, the human olfactory system is often strictly tangled with other sensory channels.

One author cites that humans are able to identify barely one third of odors if lacking inputs from the other senses.[38]

Both of these channels are difficult to deliver to the user with any accuracy of resolution. With the olfactory sense it is difficult to regulate the dispersion of the scent and the evacuation of the scent when no longer required.[39] Similarly, the sense of taste is difficult to introduce to the user without having a direct interface with their tongue. This would require an intrusive interface device that would degrade the overall immersive experience required for strong VR.

VR Interface Systems

Figure 2 summarizes where each of the current technologies lies within our framework for VR interface comparisons.

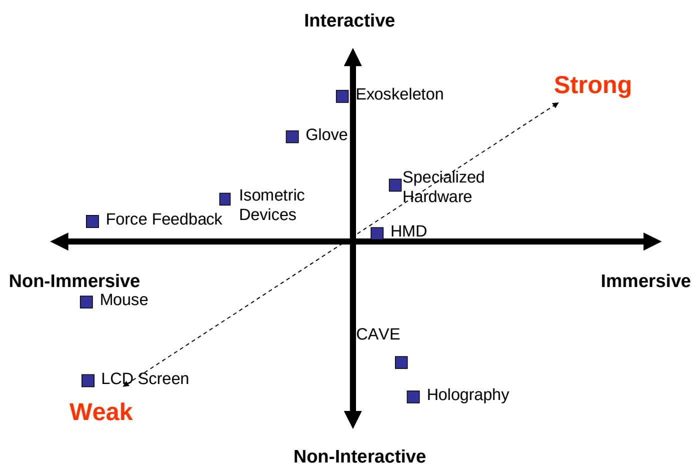

Figure 2 Current Technologies on VR Framework

As one can see from the discussion of the individual channels, each is able to contribute its own strengths to the entire VR experience. . But it is only through the synergy of multi-channel sensory experience that strong VR may be approached.

> "Virtual reality is more than the sum of its components; it is fundamentally a system technology. The components have no significance except as they contribute to a functioning whole."[40]

The search for convergence and synergy will continue to drive the VR interfaces described along an evolutionary pathway that will lead VR closer to the "holy grail". But these gains will also require that certain tradeoffs continue to be made as they have been made throughout virtual reality's short history. In order to understand how much these convergent interfaces will be able overcome the current limitations, we must understand what technological trends we expect to find that may influence the development of more robust VR interface solutions.

Technological Trends

Computing Power

One of the primary drivers for advances in the computing industry for most of its history has come to be known as Moore's law. This "law" states that computing power (measured by number of transistors on a chip) doubles every 24 months. This has held true from its first statement in the mid-1960s through today as shown in Figure 2. This constant doubling of computer processing power and speed is also accompanied by a reduction in the cost and size of comparable units. Both of these principles expose the exponential growth of computing power and will have significant impacts on the future of any computer-based technology in 2025 if these continue to hold true.

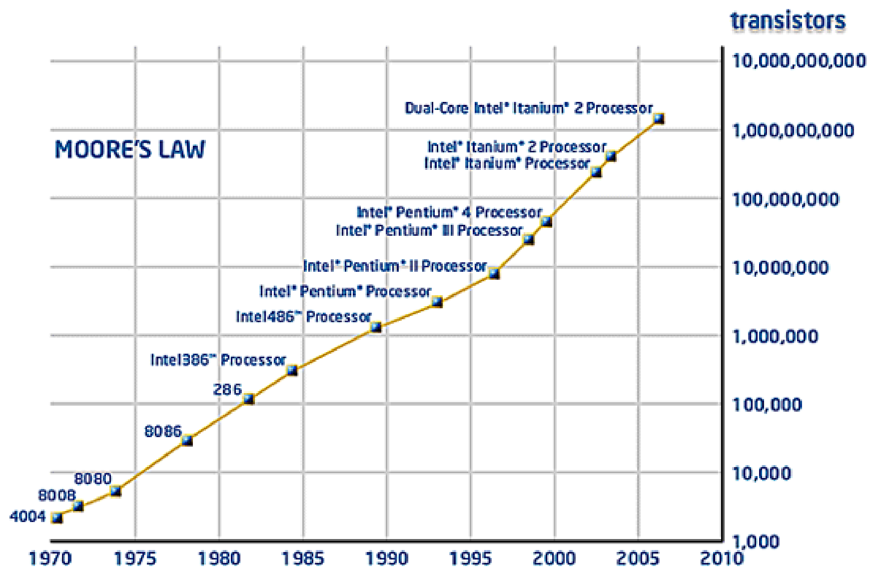

Figure 3 Moore's Law[41]

Many of the indicators for the growth of computing power continue to support Moore's law through at least 2025. A RAND study in 2006 estimated that Moore's law should remain in effect through 2015 and most likely would continue through 2020.[42] Although some experts have estimated that it will reach a physical limit based on chip construction technology, current research efforts in nanotechnology and quantum computing should allow Moore's law to continue beyond the current generation of chips.

As this continues to hold true, computers in the next 15 years should continue to become smaller, faster and cheaper to employ. Their storage space should also experience exponential growth within the same RAM form factors. Both of these factors will continue to drive computers to become more portable as the processing power can be pushed from a central processing unit to individual components. Portable devices will be able to contain the computing power of current chip technologies and storage mediums.

How will this continued growth of computing power affect the virtual reality interfaces? One author provides a critical link between computing power and human-machine interfaces.

"The evolution of computing has been so fast that we've only recently had enough low-cost computing power to spend it freely on improving the ease of interaction between you and your computer."[43] As computers become faster, there is more overhead in the system to build a better interface that is more natural and intuitive. This has been true in the past with the change of computer interfaces growing along with increased computing power from punch cards to command line to GUI.

Although better processing speed has enabled more intuitive interfaces, it has not had the same effect on the general virtual reality systems over the past 15 years. As shown in Figure 2, Moore's law was in effect over this period of time, but the advances in virtual reality technologies have not grown at a corresponding rate. In fact, most of the virtual reality interfaces in use today are merely evolutions of interfaces that have been in production since the start of the industry. Moore's law does not appear to have a one-to-one effect on the growth or development of virtual reality interfaces, but it has allowed for an increased level of immersive experience by dramatically changing the graphics capabilities available in general production computers. From these examples one must conclude that Moore's law will have some ability to drive virtual reality technology development, but may not be the primary driver for enhanced interface technology.

Market / Industry

Another factor that may drive innovations in virtual reality interfaces over the next 15 years is the market demand for these devices. Figure 3 shows the past growth and a forecast of industry growth through 2008. The overall trend is for 15-20% growth per year. Industry analysts expect the growth in particular areas of the virtual reality industry to experience significantly higher growth in research and production. Using these numbers we can begin to get an idea of the various stages of development that areas of the VR interface industry may be currently in. These will help us to forecast the trend toward future spending and development in each area.

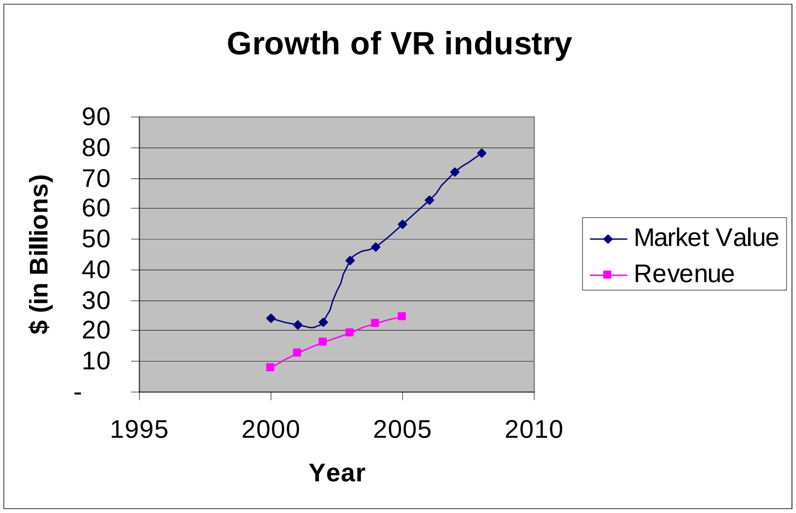

Figure 4 Growth and Forecast of VR market $

In his work on technological forecasting, Joseph Martino presents a model to explain the progression of technology from research to production. His model suggests that for any technology one can identify its different stages by the number of documents produced concerning that particular stage.[44] I suggest that these same stages may be discovered by examining the dollar amounts spent on each area. His model defines the stages as: basic research, applied research, development, application, and social impact. Using the market data for the VR interface industry, it appears that the majority of the industry is still somewhere between the applied research and development phases, although there are no certain indicators and the technologies themselves may go back and forth between phases.

The market value in Figure 3 includes the overall spending on VR interfaces as a whole, including research and development of future technologies. The values for revenue are specifically those dollars brought in by the industry from applications and fully functional interface devices. From the growth shown (and forecast) on the chart, the spending on research and development should continue to outpace the creation of applied interfaces and the revenues they bring in. The area of greatest interest for the industry for research and development is the area of usable haptic interfaces.[45]

These trends tend to suggest that we have yet to see the greatest improvements in VR interface technology. The efforts of the basic and applied research will not see development and application for 5-10 years. The levels of spending suggest that the industry as a whole will continue to value incremental improvements in current VR interface technologies, while continuing to search for new and better pathways for future applications.

The one area of the market that has seen the most rapid growth in application and societal impact is that of simple haptic interface devices like force feedback joysticks and other gaming devices. Although there have been attempts at introducing VR interfaces into mainstream media since the early 1990s, none have seen the rapid adoption by the public like the new Nintendo Wii. This gaming system is the most mature, user-friendly gaming interface system and has received widespread attention for its intuitive interface and engrossing game play. This adoption of a mature VR interface technology bodes well for the future research and development of improved systems of this type.

All of these industry and market trends suggest that entertainment dollars will continue to drive the types of VR interfaces as well as their adoption rates. The industry will continue to grow and adapt to new market spaces while finding new applications for existing technologies already in production. The economic potential of VR interface devices will continue to attract investment by new companies with new ideas for creating user-friendly immersive, interactive environments.

The market and industry drivers for VR interfaces should follow a familiar path of development. Earlier technologies have begun as specialized systems that were prohibitively expensive for the general user. The computer technologies for graphics and sound both began this way. Early in their development the chipsets for professional quality results were expensive and used only in professional applications. As these systems matured and processing power available continued to increase, these systems began to a see a rise in non-specialized applications that have led to their rapid adoption and ubiquitous use in every computer now sold.

VR should follow a similar pathway in the evolutionary gains toward a more user-friendly system. The hardware will become less specialized and usable in a variety of applications that will open the door to greater flexibility and usefulness by diverse sections of the population. This move to general user interfaces will make the technology cheaper to field and update. One indicator that this may already be happening is the military's investment into the GOSE simulators for maintenance personnel training with multiple aircraft using the same interface.[46]

Trend Analysis

The overall trend for VR interfaces is that they will continue to develop better resolutions for each channel and lighter and faster processing mechanisms which will provide enhanced immersion and interactivity. The technology will continue to advance along the evolutionary pathway toward improvement along individual channels of interface. There will be some convergence of technologies at the device level, but overall the gains will take place within the individual channels discussed previously.

One of the most significant developments for this technology will be its decreased reliance upon specialized systems with a move toward more generalized systems. The trend suggests that future VR systems will shift away from proprietary interfaces for specific applications and toward modular software based systems to interface with a generic system. Computer systems of the future may ship with a basic VR interface as a standard alongside the speakers, mouse, and keyboard. This interface will likely be made up of an enhanced tracking system, head mounted display and haptic feedback using a vibrotactile data glove for interactivity.[47] Systems like this will serve as a bridge between current legacy computer systems and future immersive VR configurations. But these evolutionary gains will only allow us to progress to a certain point on the continuum between weak and strong VR. All of the gains made available in each channel area will be unable to overcome all of the limits that are inherent in any interface that must be strapped onto a user's body.

What does this mean for the future of virtual reality interfaces? Is the "holy grail" of strong VR unattainable? Beyond this evolutionary pathway toward stronger VR, are there alternate pathways that may be explored to provide revolutionary disruptive changes to VR interfaces by 2025?

Alternate Pathways

These limitations by the evolutionary pathways toward better interfaces for each channel can only be overcome by trying to explore alternate pathways to the "holy grail" of VR interfaces. Most of the limitations of the current solutions are based on our limited knowledge of how our sense organs translate their information to the brain. A large portion of the advances in VR interface technology have come by exploiting the limits of the human senses – like creating motion video using 30 frames per second – to approximate reality. As we increase our understanding of the inherent functions of the senses, we will continue to increase our ability to take advantage of their limitations. But this still does not solve the greatest limitations regarding strong VR.

Using a reverse tree methodology, I have been able to break the possible solutions for VR interface into two distinct pathways. The first solution is to create external interfaces that provide the proper stimulation to the user's sense organs in order to replicate all sensations that are necessary to create the immersive and interactive environment. This solution set is represented by the evolutionary pathways presented above. The second set of solutions bypasses the external sense organs of the body, and replicates the necessary messages on the body's neural pathways to fool the body into believing that it is experiencing the virtual environment. These solutions would be able to overcome the majority of the limitations of the first solution set, while providing a significantly greater immersive and interactive experience.

These brain-machine interfaces have been envisioned in two primary ways: the first is a direct connection to the human brain and/or neural system to allow for direct input and output of the virtual reality information; the second is an indirect connection to the human brain through a variety of different mechanisms such as the electromagnetic spectrum and nanotechnology. The basic research required for these operations is still in its infancy, and its use in devices for development and applications are primarily in the experimental phases, but there are a number of indicators that suggest that interfaces based on these ideas may experience a rapid growth in research and implementation over the next 15 years.

Brain-Machine Interfaces

> *If real is what you can feel, smell, taste and see, then 'real' is simply electrical signals interpreted by your brain* **– Morpheus (The Matrix)[48]**

Brain-machine interfaces represent a revolutionary leap in the way that users may potentially interface with a computer. This technology is relatively new with the first demonstration of neural activity directly controlling a robotic manipulator coming in 1999.[49] But it has experienced an explosive amount of growth in the areas of basic and applied research primarily due to its potential to allow handicapped users to restore motor function to prosthetic limbs.[50] This impetus for research and interface design should provide some spin-off technology that will be directly usable by the virtual reality community.

Although this type of interface seems to be an unattainable leap, there are many current instances of the uses of technology that will continue to push our understanding of the human brain and its operations. Cochlear implants have become fairly common for people with significant hearing loss. This technology is a simple form of the interface that has been suggested with brain-machine interfaces. Hearing devices translate external sound information and directly stimulate the auditory nerve to augment the natural ear.[51] The next step toward a VR interface would be to replace the amplified real sounds with computer generated sounds.

There are other examples of how research is being conducted to help us understand the brain and neural systems with the intent to control via computer or other device that have direct applications in VR interfaces. Some individuals have been able to implant a chip in the neurons on their arm to record the neural messages generated by the brain to command hand movements. They were then able to play back these recorded impulses and have the computer command the same movements exactly as recorded.[52] Other researchers have implanted controller chips in the brains of cockroaches to allow them to "control" the movement of the cockroach in a maze.[53] Another set of research has focused on streaming video directly into the visual cortex of blind persons with limited success in repairing blindness.[54] One company is already testing the BrainGate™ system to enable users to control a computer and its attached devices through a chip implanted on the motor cortex of the brain.[55]

In addition to these experiments with invasive connections to the brain, other research has concentrated on non-invasive techniques to transfer brain functions. This research has centered on the use of EEG and fMRI technology to sample the activity of the human brain through sensors outside the body for control of computer cursors and mechanical manipulators.[56] Ray Kurzweil, a noted technology futurologist, forecasts that non-invasive "holy grail" VR interface will be available utilizing nanobot based implants that will serve as the direct connection to the brain. The input and output will be conducted via communicating with the nanobots wirelessly through the skull.[57]

Although some authors doubt that our knowledge of brain operations and the ability for us to connect to and decipher neural pathways will ever be good enough to support these interfaces, there are a number of experts in the field that have forecast that interfaces with the brain could be available as early as 2020. A RAND study of future technology labeled chip implants in the human brain as one of its "wild-card" technologies for 2020.[58] Most of the basic research needed to implement applied research and development could be available as early as 2010.[59] These timelines should only be helped by the increased emphasis on current research into these areas, as well as the exponential growth of computer processing power to help solve the current issues. This technology should be available in the future[60] and would provide an extremely valuable advantage to anyone who is able to utilize it.

Analysis and Recommendation

Using the technological trends forecast for the current VR interface technology and the potential promise of brain-machine interfaces, I have created future vectors for each of the technologies using the VR framework diagram (Figure 5). There is no doubt that given the increasing performance of computing technologies in general and the increasing attention being paid to VR interfaces, both in research dollars and systems fielded, should lead this evolutionary pathway closer to the concept of strong VR. But the limitations inherent in the current iteration of VR interface technology will limit the ability of these interfaces to achieve the "holy grail" of immersive and interactive environments indistinguishable from everyday reality. This does not, however, imply that the VR interfaces in use today will not have a place in our operations in 2025.

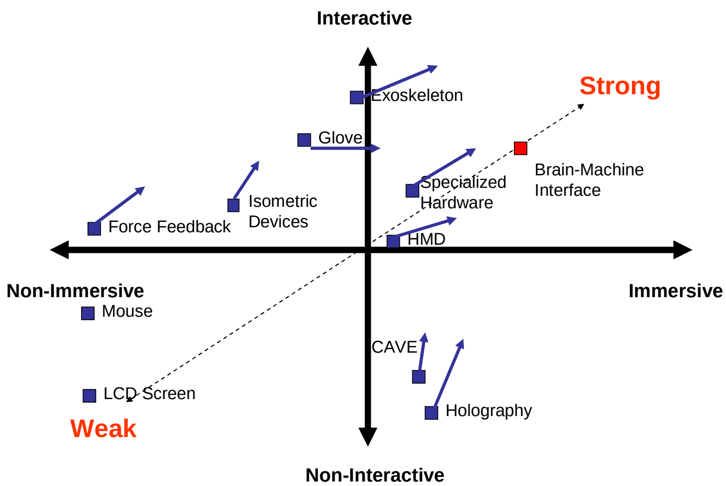

Figure 5 Location of VR interface devices and prospects for the future on Immersive/Interactive Continuum

On the contrary, they will most likely be the standard method of interface with most desktop computing systems for knowledge retrieval and manipulation. These current technologies will continue to become faster, cheaper, and more user-friendly with each new generation. They will make the leap from specialized hardware for specific applications to generalized, modular software-based systems that will create new opportunities for applications in all areas of computer training and data visualization.[61] These generalized interfaces will not gain market saturation until a "killer application" is created that drives the need for the technology to proliferate. The emergence of this "killer application" will signal the maturation of these VR interface devices for use in standardized systems.

The size of the VR interface industry and the market for many different types of VR modes and applications will continue to allow all of the current interfaces to occupy their own niche of the market. This will spur enhancements for each of the current technologies and even provide overlap for competing technologies within the market space. No one interface will be able to dominate the entire market based on the requirements for specialized interfaces in each application. In addition, the interfaces will continue to be dispersed at all levels of spending in the market, from cheap home-use VR interfaces, to expensive application specific hardware and software interfaces. But in order to achieve "holy grail" strong VR interfaces, a new revolutionary pathway will have to emerge.

This alternate pathway for future development will have to be able to overcome the physical limitations of the current VR systems, as well as the future systems they will become. The most likely candidates for this revolution in technology are found in the area of brain-machine interfaces. These systems allow the technology to overcome all of the physical barriers by bypassing the human sensory organs. This pathway contains both invasive and non-invasive methods for achieving direct connection/stimulation of the human neural system. Although the challenges in researching and fielding this technology are many and varied,[62] the basic and applied research continues to grow at an increasing rate.

A strong VR interface would provide a significant military advantage for its user in a number of disparate areas. Training of any skills would become cheaper and more effective, but the US Air Force would most likely benefit the most from gains in flying training. As fuel becomes more expensive and training ranges more restrictive, strong VR would allow us to shift the bulk of our currency training to the virtual realm with little drop in proficiency. Mission rehearsals could be carried out in the exact conditions expected for any possible mission. This increases the likelihood of success and could expose advantages previously unknown against enemy systems. Virtual reality data visualization will allow a more natural situational awareness tool that will allow our decision cycles to be shortened within an increasingly information-intensive battlefield. Finally, other spin-off technologies, like chip implants in the brain, may create asymmetric advantages at the individual soldier level that will enhance the entire force.

The US Air Force should continue to invest in research and development of the current VR interface technologies for specific applications. We should use off-the-shelf developments from the entertainment industry to the maximum extent to rapidly enhance our military systems. This will ensure that we maintain an advantage in training and simulation for as long as possible, while leveraging the entertainment industry advances to control short term costs. We should develop a standard desktop configuration VR interface that enables software to be developed to enhance our current training programs with modular, software-based applications. In addition, we must actively seek out the “killer application” for military uses of this technology. This application may be tied to our ever increasing information overload and this technology could provide us an interface that is more user-friendly under these data-intensive operations.

In addition to financing developments in the evolutionary pathways, the US Air Force should invest in basic research of the human brain and neural systems with a goal of mapping brain functions and neural pathways. We should fund applied research and development for brain-machine interfaces that enhance our ability to provide stronger VR interfaces. We must encourage the VR interface community to continually push to increase its ability to deliver highly immersive and infinitely interactive virtual environments that can accurately portray common Air Force mission and tasks.

Virtual reality is already in widespread use in basic applications throughout the US Air Force. These VR systems depend upon the interfaces to provide users with an immersive, interactive environment that closely approximates reality. The future trend is that VR will become more useful and more accessible. These advances will be enabled by the growth of computer processing power, the money spent on research and development of these systems, and better understanding of the human sensory systems. But these evolutionary advances will not be able to achieve "holy grail" strong VR. Brain-machine interfaces represent a feasible technological pathway to achieve an immersive, interactive computer-generated environment that is indistinguishable from reality. This level of VR would create a significant military advantage for the US Air Force that would enable them to maintain superiority in training and simulations for the foreseeable future.

END NOTES

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[4] Pimentel and Teixeira, *Virtual Reality through the New Looking Glass*, 7.
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[6] Simulation Based Design Center, "A Primer on Virtual Prototyping " Simulation Based Design Center, http://www.gcrmtc.org/sbdc/prototyping.html.
[7] Grigore C. Burdea and Philippe Coiffet, *Virtual Reality Technology* (Wiley-IEEE Press, 1994)., 4
[8] Internet Movie Database, "Memorable Quotes for the Matrix " http://www.imdb.com/title/tt0133093/quotes.
[9] Michael Heim, *Virtual Realism* (New York: Oxford University Press, 1998), 7. The author has his own definitions for the terms included in his 3I's concept. I have used my own definitions and expanded them to include degrees of immersion and interactivity. I have further extended these concepts by placing them on a graph which allows for measure and comparison of VR interfaces.
[10] Ibid.
[11] For a good discussion of the spectrum of the degree of immersion see Pimentel and Teixeira, *Virtual Reality through the New Looking Glass*, Fig 8-6. This chart lists more of the details that help to define degrees of immersion from a visual standpoint only.
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[13] Haywood, "Improving the Management of an Air Campaign with Virtual Reality", 2.
[14] Pimentel and Teixeira, *Virtual Reality through the New Looking Glass*, 10.
[15] Nathaniel I. Durlach and Anne S. Mavor, eds., *Virtual Reality Scientific and Technological Challenges* (Washington, D.C.: National Academy Press, 1995), 120.
[16] Ibid., 48.
[17] Pimentel and Teixeira, *Virtual Reality through the New Looking Glass*, 44.
[18] Jannick Rolland and Ozan Cakmakci, "The Past, Present, and Future of Head Mounted Display Designs," (University of Central Florida: 2005), 8.
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[21] Maxine Brown, "What Is a Cave," http://www.sv.vt.edu/future/vt-cave/whatis/.
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[29] Hiroo Iwata, "Haptic Interfaces," in *The Human-Computer Interaction Handbook*, ed. Julie A. Jacko and Andrew Sears (London: Lawrence Erlbaum Associates, 2003), 218.
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[34] Pimentel and Teixeira, *Virtual Reality through the New Looking Glass*, 65.
[35] Iwata, "Haptic Interfaces," 208.
[36] Ibid.

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[38] Gobbetti and Scateni, "Virtual Reality: Past, Present, and Future.", 10.
[39] Ibid.
[40] Burdea and Coiffet, *Virtual Reality Technology*, xi.
[41] Intel, "Moore's Law - the Future," http://www.intel.com/technology/mooreslaw/.
[42] Richard Silberglitt et al., "The Global Technology Revolution 2020, in-Depth Analyses," (RAND, 2006), 5.
[43] Negroponte, *Being Digital*, 89.
[44] Joseph P. Martino, "A Review of Selected Recent Advances in Technological Forecasting," in *Technological Forecasting and Social Change* (North Holland, 2002), 721.
[45] Antonio Valerio Netto and Maria Cristina F. de Oliveira, "Industrial Application Trends and Market Perspectives for Virtual Reality and Visual Simulation," (2004), http://www.producaoonline.ufsc.br/v04n03/artigos/PDF/042_2002%20.pdf.
[46] "Generalized Operations Simulation Environment (GOSE) Phase II," (Southwest Research Institute, 2006).
[47] Ibid.
[48] Internet Movie Database, "Memorable Quotes for the Matrix ".
[49] Mikhail A. Lebedev and Miguel A.L. Nicolelis, "Brain-Machine Interfaces: Past, Present, and Future," *TRENDS in Neurosciences* 29, no. 9 (2006): 1.
[50] Ibid.
[51] Clark, *Natural-Born Cyborgs*, 16.
[52] Ibid.
[53] Ibid.
[54] "Humanity 3000 Proceedings" (paper presented at the Humanity 3000, Bellevue, WA, 2004), 116.
[55] Cyberkinetics, "Braingate Neural Interface System," http://www.cyberkineticsinc.com/content/medicalproducts/braingate.jsp.
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[57] Ray Kurzweil, "The Human-Machine Merger: Are We Headed for the Matrix?," http://www.kurzweilai.net/meme/frame.html?m=6.
[58] Silberglitt et al., "The Global Technology Revolution 2020, in-Depth Analyses," 15.
[59] Michio Kaku, *Visions* (New York: Anchor Books, 1997), 115.
[60] Most of the research suggested that it could be technically feasible for this technology to be available within the time frame of this report. A few of the reports suggested that the technology barriers would not be the primary hurdles for this technology. For a discussion of the non-technical factors that may inhibit or enhance the development of this technology, see Appendix C of this report.
[61] Richard A. Blade and Mary Lou Padgett, "Virtual Environments: History and Profession," in *Handbook of Virtual Environments*, ed. Kay M. Stanney (Lawrence Erlbaum Associates, 2002), 1171.
[62] See Note 60 above for discussion of barriers and challenges to brain-machine interfaces.

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Appendix A: Related Technologies

Although the focus of this paper was almost solely focused on virtual reality and the human-machine interface required for it, there are many closely related technologies that would also benefit from an improved human-machine interface. These technologies each have their own areas that they are best suited for, and they provide increased impetus for us to pursue an interface that is closer to strong VR. Most of them have a limited use in the US Air Force currently, but their use would be greatly expanded with improvements to interface technology.

Augmented reality (or mixed reality) uses interface hardware similar to virtual reality to overlay computer generated images onto reality in real time. It adds digital information to the everyday scene.[1] A HUD is an example of an augmented reality that can be used to help pilots understand more about their environment around them through the use of computer information. With an enhanced user interface, this technology could be expanded to be used to overlay maintenance diagrams directly over the aircraft system to provide better maintenance performance.[2] It may also be used to enhance the situational awareness of airspace controllers (in a control tower) by overlaying aircraft information as they scan their airspace.

Teleoperation uses similar human-computer interfaces to allow the user to remotely operate a piece of equipment as if they were physically manipulating it.[3] It may be considered an offshoot of virtual reality that provides the same interface with the computer, but the environment is not *created* by the computer, it is merely *communicated through* the computer. The primary difference between this systems and a VR system is the teleoperation system must have the capacity to accurately communicate conditions as they actually are, which may require a significant amount of bandwidth. These types of systems are in use today by surgeons who are able to operate on patients remotely as if they were in the same location.

Teletravel and telepresence are also related technologies that allow a user to interact with other users in a different location as if they were together. It is the next generation in "virtual teleconference" applications. These technologies rely on the full sensory experience to allow individuals to hold meetings while physically separated that approximate the experience of being in the same room.[4]

In addition to these related technologies that are in development today, VR interface research could create new spin-off technologies. One possible area for spin-offs in the brain-machine interface is in the area of chip implants in the human brain.[5] Chip implants would allow human soldiers to enhance their ability to store and process information. They may also allow for increasing the physical abilities of the user by stimulating the proper areas of the brain to achieve the desired effect.

Appendix B: Military Applications

The military already uses virtual reality extensively in its training and simulation. These efforts began with flight simulators and have recently been expanded to include simulators for other disciplines like convoy driving and cultural training.[6] These applications allow the military to put their personnel into realistic situations that can sharpen their skills and help them perform at their peak during the real task. The bulk of the simulators in use for training use specialized systems that utilize a real object to act as the interface between the user and the virtual world. This object provides the physical feedback and link between the training and the objects use in the real world.[7]

An extension of using virtual reality for training is to use it as a mission rehearsal device. The application of virtual reality would increase the chances of success for any mission by allowing the users to rehearse their mission in the exact conditions that would be found during the actual mission. In addition, the virtual world would allow them to simulate a variety of changing factors to help the planners be prepared for any other situations that could wreak havoc with their plans. Virtual mission rehearsal would also increase security by not alerting the enemy to the United States' preparation for missions in a particular location. A "virtual Sontay" would have allowed the raiding force to practice their assault on the prison camp while simulating various changes to the environment. The "virtual Sontay" would have been secure from the prying eyes of the enemy and the element of surprise would have been maintained without having to take down the structures every time Soviet satellites were overhead. Using this same logic, the United States could protect its tactics, techniques, and procedures, as well as its strategy, while continually exercising them to learn their strengths and weaknesses.

Augmented reality is another offshoot application of virtual reality interfaces that promises tremendous gains for the military. Heads-up displays (HUD) are a rudimentary augmented reality display that provides information about the battlespace as an overlay. More recent cockpit upgrades have begun to create a HUD that is not mounted on the aircraft, but is embedded in the visor of the pilot. This technology may also be expanded for use by maintenance personnel on the ground. Augmented reality would allow the maintainer to overlay part and supply information while looking at an aircraft system. It would also allow them to have repair instructions overlaid on the actual job as they perform it. This application would allow more efficient use of our maintenance personnel while simultaneously ensuring the job was being performed accurately. An augmented reality system is already in development for training C-130 loadmasters at Little Rock.[8]

One of the most promising applications for virtual reality is in data visualization and data analysis. Large amounts of data are being collected by the increasing number and type of sensor platforms on the battlefield. This explosion of information that is being collected will continue to increase as sensors become smaller, cheaper, and more capable. The amount of information is rapidly outpacing the human ability to sort it and make sense of it. Virtual reality can provide a more natural interface for the user to interact with complex data – allowing them to delve deeper into the data to extract meaningful information.[9] Some of the more useful applications for this technology would be to allow a “Virtual Common Operating Picture” for the JFACC and the AOC to analyze the battlespace in 3D. Airspace controllers could also use this technology to fuse all of their information into “virtual airspace” to help them make the best decision with all of the information in a more intuitive display. These two applications would allow the users to “see” information like closure rates, proximity to restricted airspace, instrument approaches, and weapons flight paths and to analyze their effects to operations.

Another application of VR interface technology that could enhance military acquisitions is virtual prototyping.[10] This application allows a designer or engineer to model a new weapon system or control mechanism in virtual space. The users could then operate the new system in a realistic environment to provide feedback on the usability of the system. Virtual prototyping allows most design changes in a system to be made prior to fabrication of any pieces of the system. This decreases the time needed for engineering and development, while simultaneously ensuring the finished product is more suitable in the first iteration.

Appendix C: Non-Technical Factors

Although the technical hurdles for a working brain-machine interface are considerable, they may not be the biggest hurdles overcome. There are other non-technical factors that may affect the development of brain-machine interfaces in the future.

Social

Brain-machine interfaces may be difficult to implement unless people are willing to accept a technology that is intimately tied to the functions of their brain. Although we are generally accepting of computer technology within our lives, most people realize that computer glitches are not uncommon. Some users may be reluctant to use any technology that interferes with their neural control of their body. Fail-safe mechanisms and less error-ridden code must be developed to overcome societal resistance to brain-machine interfaces.

Brain surgery stands as another huge barrier for direct-connection brain-machine interface technology. The surgery required to implement an invasive brain-machine interface would be a risky surgery that would entail a tremendous period of recovery and training to enable error-free use. The cost in money and hospital procedures without significant gains from the surgery would deter the majority of users from having it done. But some experts believe that this societal reluctance may be overcome easier in future generations. They point out that there is already a tremendous industry of surgical self-modification, especially when the surgery can provide a professional advantage (memory or attention-span).[11]

Although one could argue either way about individual choice, the individuals may never have the ability to make that choice. A RAND study stated that public policy issues will be the biggest damper to their development. The barriers to acceptance by government regulators may be the biggest hurdle for these interfaces to overcome.[12] It is difficult enough for new drugs or plastic surgery procedures to be approved within our regulations, but an elective surgery to implant a chip or connection within a human brain may take decades to convince the government that its use and implementation does not represent a health risk to the public.

Non-invasive brain-machine interface solutions will be the easiest to assimilate into our culture. Our culture is already willing to hang technology from our bodies if it provides us an advantage and we can remove it when not needed (cell phones and watches). Solutions for brain-machine interfaces that do not require a permanent modification of the human physical condition may be used much like other technology that we accept on a daily basis. But this assumes either no need for nanobots or other foreign material in the human neural system – otherwise the barriers are the same for invasive connections.

Moral / Ethical

In addition to the medical and physical barriers that VR connections may encounter, the ability to create strong VR, indistinguishable from reality, may expose moral and ethical issues that our culture or legal system is not equipped to handle. These issues may blur our understanding of morality by creating virtual infidelity and virtual adultery. Our culture may have to come to an understanding of what is morally acceptable behavior in virtual environments that are perfect substitutes for reality. We may also be faced with ethical issues surrounding aberrant behaviors carried out in virtual environments. Does the murder of virtual characters increase the likelihood of the user carrying out violent acts in reality? These issues are not sharply defined, nor can they be forecast enough to provide legislation to answer these questions for our entire country. The ethical debate surrounding violent video games and their effect on young people is one indicator that these issues are not easily understood. The outcome of these problems may present a large hurdle for widespread acceptance of strong VR interfaces.

Psychological / Physiological

Current VR interfaces are limited in their use due to physiological limitations of the human body. Some users of current technology have experienced VR motion sickness, caused when the visual cues in the virtual environment do not match with the vestibular cues of the user. The brain is unable to decide which of the systems is not correct and the result is physical illness and may be accompanied with vomiting.[13] This sickness is a result of the current interfaces' inability to overcome its physical limitations as discussed in the channels section. Strong VR (the "holy grail") should not have this same problem because, in theory, all of the user's senses would experience the proper cues for the virtual environment and the body would not experience any disconnects between senses.

This sub-area also is closely related to the social discussion above. There would be a lengthy process for research and development of any invasive VR technology or non-invasive technology that utilized nanobot technology for communication. The US government would serve as a major barrier for this technology due to its regulatory oversight for any medical procedures of this nature. But this may only serve as a barrier in the US and nations with similar policies regarding medical testing. If a nation believes that the gains from research of human-machine interfaces would be significant, it may have an incentive to override its normal procedures. Furthermore, not all nations have the same restrictions on testing and research. This may create an opportunity for an emerging nation to gain critical technological insight ahead of the rest of the international community.

APPENDIX END NOTES

[1] Clark, *Natural-Born Cyborgs*, 51.
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[3] Durlach and Mavor, eds., *Virtual Reality Scientific and Technological Challenges*, 17.
[4] Ibid., 42.
[5] Silberglitt et al., "The Global Technology Revolution 2020, in-Depth Analyses."
[6] This reference refers to the large amount of development being pored into simulators like the cultural simulator designed by DARPA and fielded to help soldiers prepare for what they may experience in Iraq. They also have a convoy simulator to help prepare the soldiers before they encounter a particular situation.
[7] Burdea and Coiffet, *Virtual Reality Technology*, 308. This article discusses the use of the Virtual Stinger Trainer which helps users learn how to use a particular surface to air missile system. Other systems are in use to help military members receive personal weapons training also.
[8] Larry Clemens, "TSPG Advanced Planning Briefing to Industry," http://proceedings.ndia.org/61A0/Clemons.pdf.
[9] James J. Thomas and Kristin A. Cook, eds., *Illuminating the Path: The Research and Development Agenda for Visual Analytics* (National Visualization and Analytics Center, 2005), 73.
[10] Simulation Based Design Center, "A Primer on Virtual Prototyping ".
[11] "Humanity 3000 Proceedings", 194.
[12] Silberglitt et al., "The Global Technology Revolution 2020, in-Depth Analyses."
[13] Clark, *Natural-Born Cyborgs*, 93.