What are virtual environments?

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Abstract

Virtual environment displays are interactive, computer generated displays that may become a new communications medium. Though they have arisen from vehicle simulation and teleoperations technology dating from the 1960's, the development of inexpensive, more widely accessible versions of the technology has sparked recent, widespread interest. Who uses these display, what they may be good for, and why their development may be pursued are discussed from the viewpoint of a NASA laboratory where the first low cost versions of the technology were assembled.

What is a virtual environment?

Virtual environment (VE) displays are interactive, computer-graphics based, head-referenced displays that create the illusion that their users are in a place other than where they actually are. This illusion is created through the operation of three basic types of equipment: 1) Sensors, such as a head-mounted 6 degree of freedom position sensor, to detect human action , 2) Effectors, such as a stereoscopic display, to influence the operators' senses and 3) Special purpose hardware to link the output of the sensors to inputs for the effectors so that they may produce sensory effects resembling those experienced by inhabitants of a physical environment. In a virtual environment this linkage is accomplished by a simulation computer. In a head-mounted teleoperator display, a display closely related to a virtual environment display, the linkage is accomplished by the robot manipulators, vehicles, control systems, sensors and cameras at a remote work site.

A number of different names have been used to describe virtual environment research. Some like the oxymoronic "artificial reality" or "virtual reality" suggest much higher performance than the current technology can generally provide. Others like "cyberspace" are puzzling neologisms not closely related to the meaning of their linguistic roots. Expressions like "virtual worlds", "virtual environment" seem preferable since they are linguistically conservative and may be related to existing well established terms such as a virtual image[1].

Why are virtual environments useful?

These displays potentially provide a new communication medium for human-machine interaction which will be cheaper, more convenient, and more efficient than former interface technologies. In teleoperation or planetary surface visualization, for example, applications of virtual environment can provide techniques for solving problems caused by long transport delays or inability to place remote cameras in optimal viewing positions. Additionally, the totally synthetic character of computer graphics based virtual environments allows the introduction of symbolic, geometric, and dynamic enhancements that can enable visualization and interaction modes that are totally unrealizable in physical environments.

Since virtual environment display systems amount to communications media, they are intrinsically applicable to practically anything; education, procedure training, teleoperation, high-level programming, remote planetary surface exploration, exploratory data analysis, and scientific visualization. One unique feature of the medium, however, is that it enables coordinated, real-time control of multiple objects and environmental characteristics. Tasks that involve manipulation of objects in complex visual environments and also require frequent, concurrent changes in viewing position, for example, laparoscopic surgery[2] are tasks that are naturally suited for virtual environment displays. Other tasks that may be mapped into this format also may uniquely benefit.

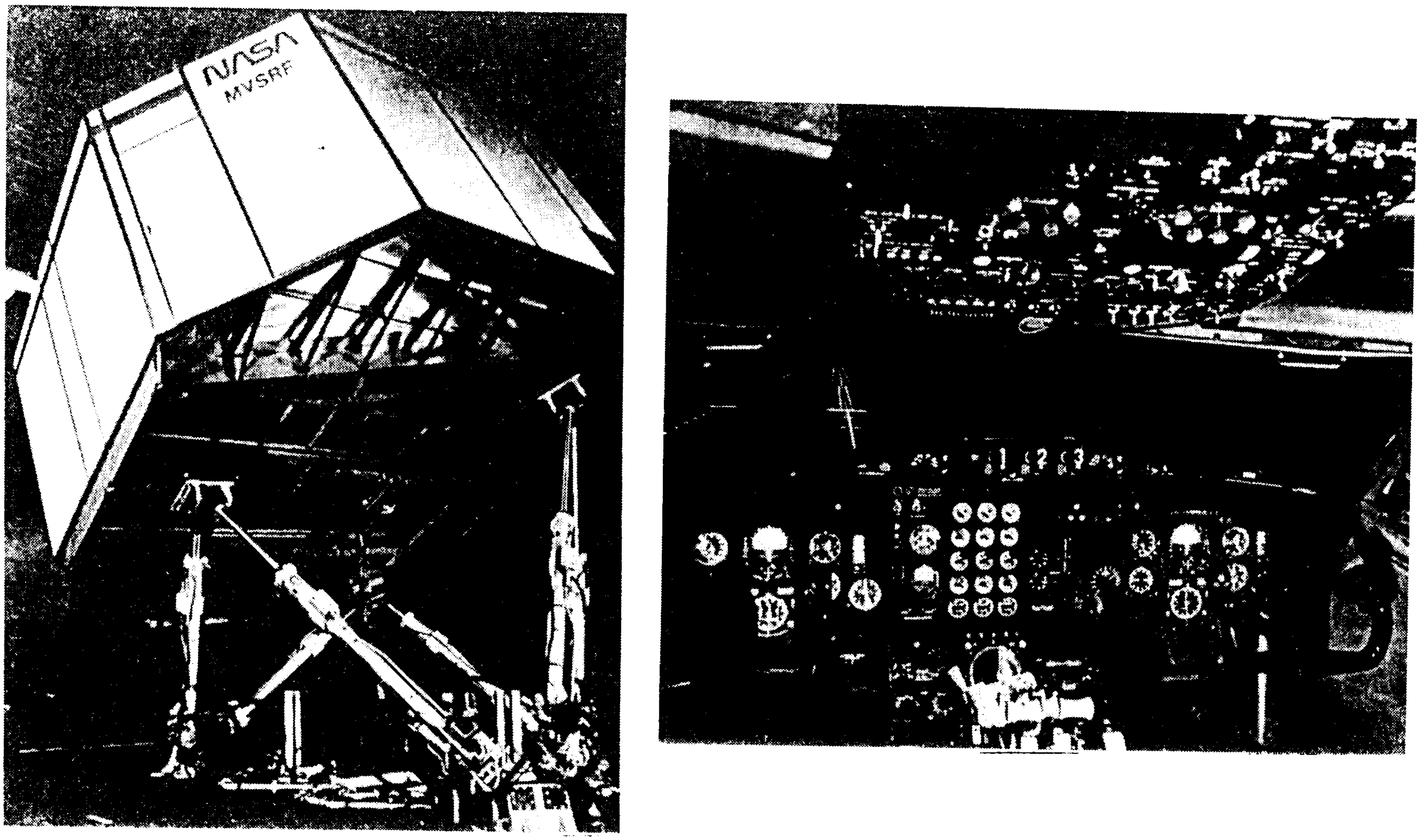

Figure 1. The left panel shows a moving base flight simulator at the NASA Ames Manned Vehicle Systems Research Facility. The right panel shows a cockpit view from the same simulator.

How are virtual environments made?

The display technology works by developing a real-time, interactive, personal simulation[3] of the content, geometry, and dynamics of a work environment directly analogous to that used for traditional vehicle simulation[4,5] (Figure 1).

But unlike vehicle simulation, typical virtual environment simulation is unmediated. The users themselves are in an environment, not in a vehicle which is in an environment, and the hardware producing the simulation is more often than not, worn rather than entered. The definition of a virtual environment requires three distinct operations. First, the shape and kinematics of the actors and object needs to be specified via a modeling program. Second, the modes and rules of interactions of all actors and objects need to be established for all possible interactions among them and with the environment itself. Third, the extent and character of the enveloping environment needs to be specified.

Where is virtual environment research and development conducted?

Components of virtual environment display technology have been under development since the eariy 1960 Philco[6](Figure 2) and Argonne National Laboratory[7, 8] work on displays for teleoperation using head-mounted, closed circuit TV systems.

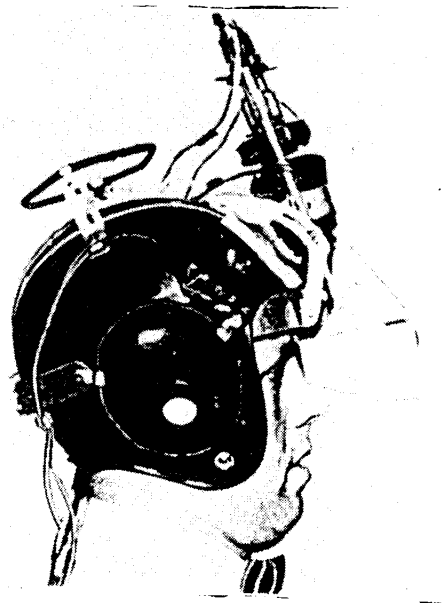

Figure 2. An early head-mounted display made by Philco engineers who used virtual image viewing optics resembling those in more modern head-mounted virtual environment displays.

It has been more recently associated with the development of computer graphics systems through the pioneering work of Ivan Sutherland at Harvard and Utah[9,10,11]. As an outgrowth of the association with computer graphics development, it has been most intensively pursued by aircraft simulation development groupsinterested in alternatives to expensive projection dome systems[12,13]. Most recently, interest in personal simulators provided by virtual environment displays has spread into telerobotics, scientific data visualization, planetary surface exploration, video game development, and interactive art (See Reference #14 for a recent review).

Because of the broad potential applicability, a number of NASA centers have followed NASA Ames' lead in 1985 and begun research and development programs using the technology[15]. Many of these programs have developed from others pursued under the aegis of a number of different programmatic titles, for example teleoperations, telerobotics (Figure 3), applied computer graphics, and scientific visualization.

Since the display technology is potentially the quintessential technique for scientific investigation of many psychophysical, physiological, human factors and perceptual questions, many biological, physiological and cognitive scientists are interested in the technology as a new tool for their research which itself provides information needed for the design of virtual environments[1].

Who conducts virtual environment research and development?

Early work in virtual environments was conducted in the flight simulation community and by those interested in robot simulation and teleoperation[16]. More recent interest has developed from computer scientists interested in interactive, computer graphics as a human-computer interface.

Scientists, developers and those with non-professional interest in virtual environment technology may be divided in two general groups. Those who wish to use the technology to advance their particular profession or interest and those who wish to develop and perfect the technology itself. One might contrast a marine biologist interesting in catching jellyfish at great depths with a human factors specialist who wish to improve the design of an interface for remote operation of undersea robot vehicles.

Figure 3. Virtual environment displays are being used at NASA to develop programming techniques for robots through simulation of the remote task environment. A DataGlove is used to control pop-up menus and to interact with the robot as well as the computer graphics parameters of the simulation. The head-mounted display illustrated here was the second in a series of displays made for a project begun by Michael W. McGreevy at NASA Ames Research Center in 1985[41].

The distinction between these two groups is not always clear as the hyperbole and sensational press coverage associated with some of this technology has led many potential users to overestimate the actual capabilities of existing systems. Though they may consider themselves to be users, interested users are actually developers who need to significantly improve the technology for their specific tasks. Unfortunately, because their expertise is frequently in a task domain, they can be unaware of the human-machine design needed to select and integrate appropriate equipment to enable them to efficiently achieve practical goals. Consequently, the product from development by such user groups may be a "conceptual demo" which suggests possible applications but which lack practical usefulness.

One of the remarkable aspects of activity in this area has been the flourishing of interest among nontechnical groups and organizations without specific expertise in the underlying technology and scientific issues, e.g. the Meckler Foundation and the Education Foundation. Some of these groups have sponsored conferences or workshops which have attracted crowds of 100's of paying customers who are interested in learning what the field is, what wonders it may produce, and how they might participate in it. Though these meetings have attracted some of genuine developers of this field, the variable content of the programs at these meetings is underscored by a remark by of one of the more enthusiastic proponents of "virtual reality". He claimed virtual reality to be a very special field, "it's a field where there are no experts, and everyone can be one!" (Robert Jacobson, Meckler VR Conference, San Jose 1992)

Nothing could be more false. There are scores of experts who have been associated with vehicle simulation and teleoperations interface development who have appropriate training and expertise to design useable virtual environment displays and have been doing so for years and telling the world about their progress in courses on simulation like those periodically offered at MIT and SUNY Binghamton on flight simulation. Virtual environments are best viewed as extensions of the technology discussed in these courses; in fact, the first head-mounted displays were specifically developed in an attempt to replace costly dome-projection flight simulators[17, 18].

Another measure of the extent of national interest in the technology are the numbers of workshops and conferences sponsored by national professional associations whose members are indeed expert in the technologies necessary to make a virtual environment, for example the National Research Council , National Science Foundation[18], the Engineering Foundation[20], and NASA [21] and Office of Naval Research (Forthcoming, May 1993). These meeting have been and are continuing to be called to help establish national agendas for research.

When will virtual environments be available?

Virtual environments have been commercially available as flight simulators, for example the CAE fiberoptic helmet mounted display[17], for years, but achievement of the required performance specifications in practical systems still is very expensive, costing on the order of millions of dollars. Much cheaper systems have recently begun to be commercially available.[22, 23,24, 25, 26, 27]. The market for the cheaper virtual environment systems has generally tolerated much poorer performance than the flight simulator market. However, poor performance and reliability appears to have been partially responsible for the fall of the the former market leader, the now dissolved and reorganized VPL Research[28].

Most of the extent virtual environment systems using the cheaper, more accessible technology have rarely passed beyond the stage of conceptual demonstration to the stage of enabling useful work, especially when compared to cheaper existing alternatives. This stasis in a perpetual stage of conceptual demonstration and further development leading to further conceptual demonstration is characteristic of almost all of the cheaper systems that have been assembled so far.

The principle reason for this problem is that the technical solutions to the many difficulties in producing a personal simulation of sufficient fidelity are still expensive, and many of the research groups investigating the technology simply don't have sufficient resources or expertise for adequate development. A second major difficulty is that applications of the technology are sometimes fundamentally misconceived. For example, the use of a derivative of the DataGlove[29], the PowerGlove distributed by Matel ultimately sold only for novelty value and failed to endure as a commercial product because its software applications proved physically very tiring to use and were never shown to enable uniquely any desirable activity. Unfortunately, exploratory software development by outside programmers which might have solved some of the implementation problems was discouraged through a variety of technical means by the initial distributor of the DataGlove[30].

The difficulty encountered by the PowerGlove project is characteristic of many of the apparently evident application areas of virtual environment technology: those advocating and sometimes even developing virtual environment displays for a particular application fail to fully understand the performance required of both the technology and the operators for successful use. Field use of the viewing technology can be especially difficult as illustrated by attempts to use telepresence interfaces in harsh environments such as Antarctica where NASA workers have attempted to use head-mounted viewing devices for teleoperation. As shown by the experience of the flight simulation community, this understanding for a single application environment can require considerable human factors and engineering expertise and experience[4], a requirement frequently underestimated by those suggesting extensions into other domains.

Those advocating the use of virtual environment displays generally have the significant task of demonstrating that such displays can be produced with sufficient symbolic, geometric and dynamic fidelity to enable useful work at an accessible price. In fact, as discussed above, much of the technology embodying virtual environment displays is not new but may be directly traced to developments in vehicle simulation dating from the 1920's and teleoperation technology dating from the 1940's. Consequently, the reasons why virtual environments or the related teleoperation viewing technology have not become a major commercial product out side of flight simulation in the last 30 years is a significant question that must be answered.

Why have the related applications in telepresence not caught on?

This question is particularly salient for many telepresence applications which significantly overlap synthetic virtual environment displays based on computer generated scenes: Both use head-referenced or head-mounted displays. Such displays were first implemented at Philco in the early '60's and extensively advocated for space and other applications in widely circulated journals and magazines , for example, Aeronautics and Astronautics[31]. Since the key innovations of the display technology are human interface issues, the reasons for the failure of this viewing technology to diffuse into numerous possible applications are most likely associated with the cost and performance characteristics of the human interface. Some of the earlier discussions of the limitations on the viewer technology are strikingly contemporary yet date from the 1960's. Goertz's discussion about why a 1000 line TV system can have at least 165 time poorer resolution than the human eye, for example, is especially revealing (Figure 5)[8].

Advances in boom-mounted displays[32,33] (Figure 4), improved interfacing techniques, and 6 dof tracker characterizations[34] may provide a solution to the resolution problem as well as the transport delay problem that is one of the principle constraints on practical use of virtual environment systems. However, examples of practical use of virtual environment displays to date still remain isolated for displays in the moderate to low price range, for example less than about $150,000 for a complete system. These displays clearly potentially can provide a compact format for personal training simulators of hand-held systems such as Hand Held Maneuvering Units for use in space (Figure 6)[35] or Stinger antiaircraft missile launchers[36], but even these applications are still essentially conceptual demonstrations awaiting further improvements in their relatively inexpensive technology.

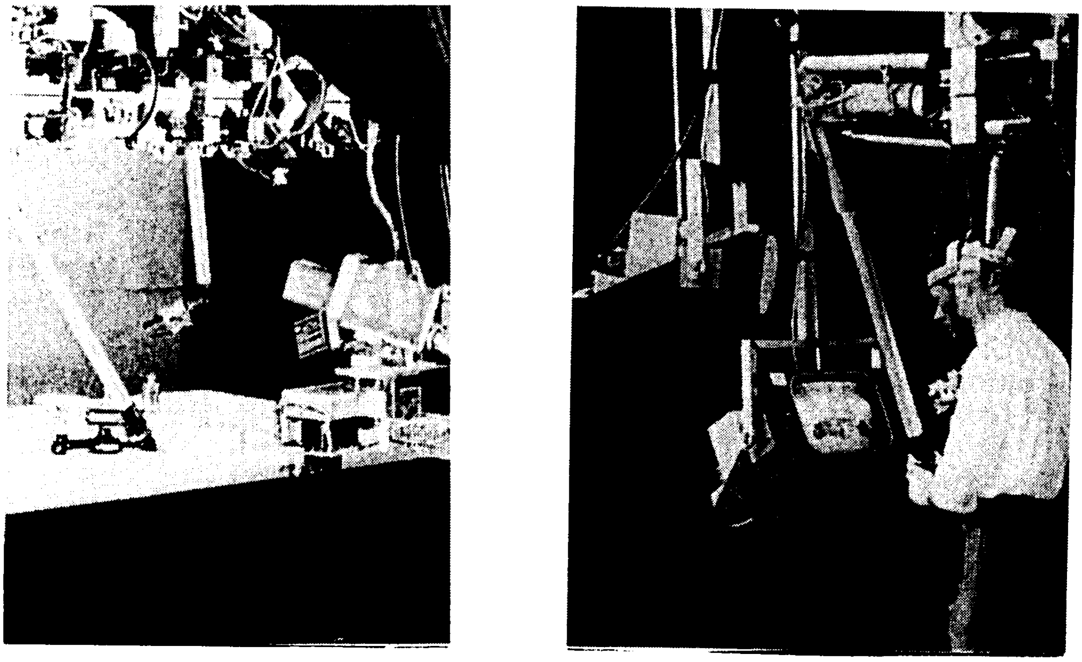

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Figure 4. A multiple-exposure photograph of the experimental head-controlled television system developed at Argonne National Laboratory in the early 1960's which used a mechanically driven "boom" mounted TV display which was intentionally not viewed through magnifying optics because of the poor visual resolution that would have resulted.

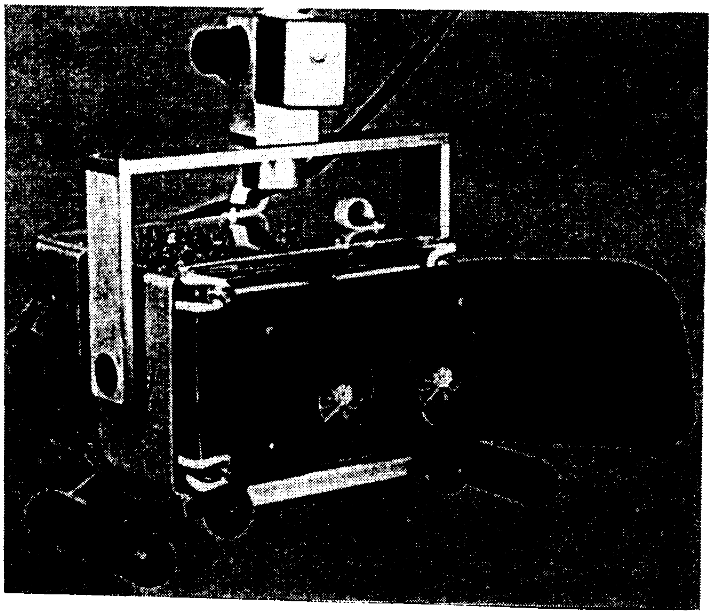

Figure 5. "Boom" mounted displays currently provide a solution to the poor resolution of head-mounted virtual environment displays. They can support heavier, high resolution monitors. This figure illustrates the first in a series of modern "boom"mounted stereo displays made since 1986 by Fake Space Technology.

A key missing element in many of the applications areas is a rigorous comparison of user performance with a virtual environment display contrasted with performance achieved with a well-designed, possibly stereoscopic panel mounted substitute. Such panel mounted alternative hardware formats are publicly viewable, available with high resolution, and currently generally cheaper than virtual environment systems. When such comparative studies are suggested, VE developers often complain that their systems are not yet ready for such testing.

There is clearly truth in this claim as most of the head-mounted visual displays systems cannot meet such basic specifications, such as the recommended number of scan lines per character of displayed text[36]. But unless such comparisons of alternative display format are made, the potential benefits of the new technology will never be known and the users and supporters of the development will have to wait indefinitely to learn whether the promised wonders will even practically materialize.

Never the less, some apparently economically successful applications have appeared. In Japan Matsushita Electric Works in Osaka has used the VPL EyePhone system as a successful marketing tool to help sell custom-designed kitchens and cabinetry. This application is an example of the "architectural walk-through" demonstrated by Prof. Brooks group at UNC[38].

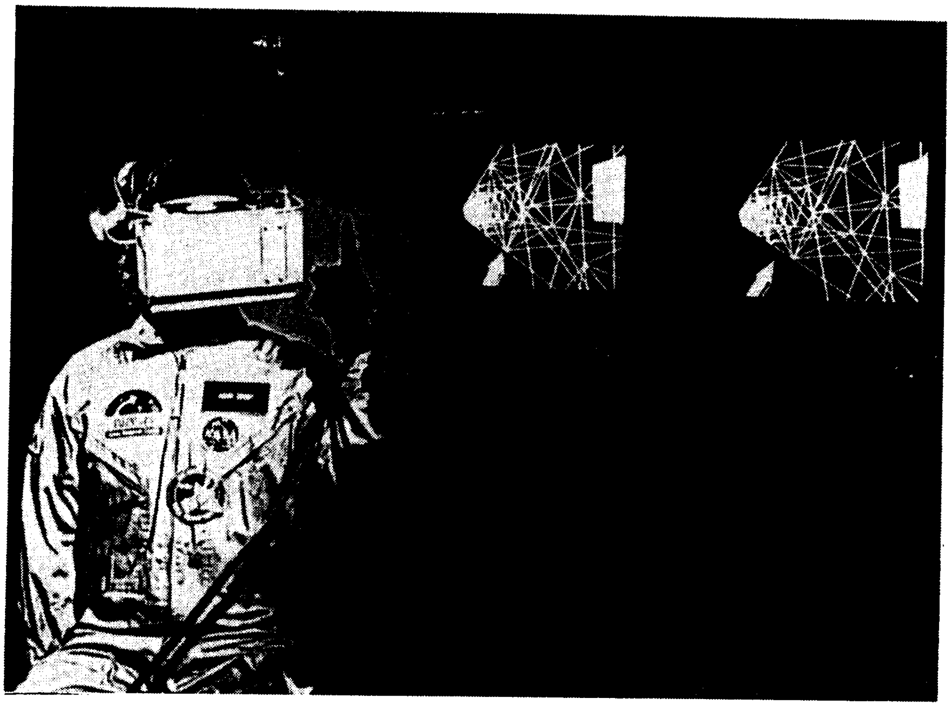

Figure 6. A virtual environment display used for a personal simulation of a hand-held maneuvering device used by an astronaut who may need to fly back to a space station after accidental separation.

Also "virtual reality" video games have been distributed by a British company called W Industries under the name of Virtuality and may be commercially successful. But commercial success of companies working in this field is certainly not guaranteed due to rapidly changing technical factors, i.e. the availability of better display technologies, and the possibility a large manufacturer, i.e. Sony[39] might enter the market. Most of the manufacturers in the U.S. are small startups and VPL, once acknowledged as the industry leader, has essentially gone bankrupt due to overextension[28]. The ease with which a developer may lose focus when working in this area may be a characteristic of the technology itself. Being a communications medium virtual environments appear to be useful for practically everything.

This apparent strength is in reality a significant weakness. Technologies derive their strength not from their generality but from their uniqueness. That which makes them truly useful is that which makes them distinct[40]. Aircraft simulators are not useful because they can simulate a generic aircraft, but because they can simulate a Boeing 747SP. However, as mentioned earlier, such specific simulation is achieved only after considerable engineering development and human factors tuning and testing. As similar efforts are brought to other potential application areas, virtual environment displays will move from the demo room to the desk-top. Cost reductions will accompany enlarged markets and the number of economically viable applications will grow as compact, personal simulators are customized to solve specific tasks. As major corporations enter the head-mounted display market and promise to radically lower the cost of a display[41], a variety of new applications may be explored.

It must, however, be said, the VE industry has not yet found its "VISICALC" -- the "spreadsheet" application whose invention created the microcomputer industry because thousands of potential users recognized in it an accessible, new, affordable tool that enabled them to do their existing jobs better and to imagine solutions to previously intractable problems.

Finding a "Visicalc"-like" application which would underscore obvious benefits from virtual environment displays is especially important because their use also brings risks and costs.

Like the flight simulators which were their predecessors, extended time in virtual environments can produce nausea and altered visual and visuomotor coordination. These aftereffects can interfere with automobile driving and other aspects of normal life in the physical environment to which all users must ultimately return. Life in virtual environments may, indeed, also have social aftereffects, especially if the high level of violence in existing video games is transferred into this new medium. Consequently, the design of virtual environments may provide not only technical, but also social and possibly political challenges as well.

References

1. Ellis, S. R. "Nature and origins of virtual environments: a bibliographical essay", *Computer Systems in Engineering*, Vol. 2, 1991, pp. 321-347.
2. Green, P., Satava, R., JohnHill & Simon, I. "Telepresence: advanced teleoperator technology for minimally invasive surgery," *Surgical Endoscopy*, 6 1992, pp. 62-67 .
3. Foley, J.D. "Interfaces for advanced computing", *Scientific American*, 257, 1987, pp. 126-135.
4. Cardullo, F. Flight Simulation Update 1993, Watson School of Continuing Education, SUNY Binghamton, Binghamton, New York, 1993.
5. Rolfe, J.M. & Staples, K.J. *Flight simulation* , Cambridge University Press, London, 1986.
6. Comeau, C.P. & Brian, J.S. "Headsight television system provides remote surveillance," *Electronics*,, November 10, 1961, pp. 86-90.
7. Goertz, R.C. "Manipulator system development at ANL. Proceedings of the 12th RSTD Conference", Argonne National Laboratory, 1964, pp. 117-136.
8. Goertz, R.C., Mingesz, S., Potts, C. & Lindberg, J. "An experimental head-controlled television to provide viewing for a manipulator operator," Proceedings of the 13th Remote Systems Technology Conference, Argonne National Laboratory, 1965, pp. 57-60.
9. Myers, T.H. & Sutherland, I.E. "On the design of display processors," *Communications of the ACM*, 11, 6, 1968, pp. 410-414.
10. Sutherland, I.E. "The ultimate computer display," *International Federation of Information Processing*, 2, 1965, p. 506.
11. Sutherland, I.E. "Computer Displays," *Scientific American*, 222, 6, 1970, pp. 56-81.
12. CAE Electronics. Product literature , CAE Electronics, Montréal, Canada, 1991.
13. British Aerospace. British Aerospace, Military Aircraft, Ltd., Brough, UK, 1993.
14. Pimentel, K. & Teixeira, K. *Virtual reality: through the new looking glass* Windcrest/Intel/McGraw- Hill, New York, 1993.
15. NASA. White Paper on Virtual Environment Research and Technology , NASA Headquarters, Washington D. C., 1993.
16. Tachi, S., Hirohiko, A., & Maeda, T. (1989 May 21-24). Development of anthropomorphic tele-existence slave robot. Proceedings of the International Conference on Advanced Mechatronics. Toyko. 385-390.
17. Furness, T.A. "The supercockpit and its human factors challenges," *Proceedings of the 30th Annual Meeting of the Human Factors Society*, Human Factors Society, Santa Barbara, CA, 1986, pp.48-52, .
18. Barrette, R., *et al.* Flight simulation advanced wide FOV helmet mounted infinity display , AFHRL-TR-89-36, Air Force Human Resources Laboratory, WPAFB, 1990.
19. Bishop, G., Bricken, W., Brooks, F. P., Brown, M., Burbeck, C., Durlach, N., Ellis, S. R., Fuchs, H., Green, M., Lackner, J., McNiell, M., Moshell, M., Rausch, R., Robinett, W., Scrinivasan, M. A., Sutherland, I., Urban, R., Wenzel, E. "Research in Virtual Environments: report of an NSF Workshop, March 23-24,1992, Chapel Hill, NC, " *Computer Graphics*, 26, 3, 1992, pp.154-177.
20. Durlach, N.I., Sheridan, T.B. & Ellis, S.R. Human machine interfaces for teleoperators and virtual environments, NASA CP 91035, Ames Research Center, Moffett Field CA., 1991.
21. NASA. Virtual Reality Workshop; Jackson Hole, WY, 1991.
22. Division Limited. Company literature , Division Limited, 19 Apex Court, Woodlands,, Almondsbury, Bristol BS12 4JT, UK, 1993.
23. W Industries Ltd. Company literature, W Industries Ltd. , 3 Oswin Road , Brailsford Industrial Park, Leicester UK, LE3 1HR, 1993.
24. Virtual Research. Company literature, Virtual Research, 1313 Socorro Ave, Sunnyvale CA, 94089, 1993.
25. Sense8 Corporation. Company Literature , Sense8 Corporation, 4000 Bridgeway, Saucilito, CA, 95965, 1993.
26. Leep Systems. Company literature, Leep Systems, 241 Crescent Street, Waltham, Massachusetts, 02154, 1993.
27. Virtual Reality Group. Company literature, Virtual Reality Group, Advanced Technology Systems, 800 Follin Lane Suite 270, Vienna, VA, 22180, 1993.
28. Hamit, F. "Profile of a wayward dream: the collapse of VPL Research," *Silicon Graphics World*, 3, 2, 1993, pp. 1, 11-15.
29. Zimmerman, T., Lanier, J., Blanchard, C., Bryson, S. & Harvil, Y. "A hand gesture interface device," *Proceedings of the CHI and GI* ACM, 1987 pp. 189-192
30. Zimmerman, T. Personal communication (1992).
31. Bradley, W.E. "Telefactor control of space operations," *Aeronautics and Astronautics*,, 1967, May, pp. 32-38. .
32. McDowall, I.E., Bolas, M., Pieper, S., Fisher, S.S. & Humphries, J. Implementation and integration of a counterbalanced CRT-base stereoscopic display for

interactive viewpoint control in virtual environment applications. SPIE, Bellingham Wash., 1990.
33. Levit, C., & Bryson, S. A virtual environment for the exploration of three dimensional steady flows. SPIE 1457, 1991.
34. Adelstein, B.D., Johnston, E.R. & Ellis, S.R. "A testbed for characterizing the response of virtual environment spatial sensors," Proceedings of UIST '92, ACM, 1992, pp. 15-22.
35. Brody, A.R., Richard Jacoby & Ellis, S.R. "Extravehicular activity self rescue using a hand held thruster," *Journal of Spacecraft and Rockets,* 29, 1992, pp. 842-848.
36. Jense, G.J. & Kuijper, F. Applying virtual environments to training and simulation. Proceedings of the Applied Vision Association Meeting, AVA, 1993.
37. Weintraub, D.J. & Ensing, M. *Human factors issues in head-up display design: the book of HUD* , CSERIAC, Wright Patternson AFB, Ohio, 1992.
38. Airey, J.M., Rohlf, J.H. & Brooks Jr, F. "Towards image realism with interactive update rates in complex virtual building environments," *Computer Graphics,* 24, 1990, pp. 41-50.
39. Annonymous. "New Products: Sony head-mounted television," *Information Display,* February, 1993, p. 22.
40. Basalla, G. *The evolution of technology* , Cambridge University Press, New York, 1988.
41. Fisher, S.S., McGreevy, M., Humphries, J. & Robinett, W. "Virtual Environment Display System, " *ACM 1986 Workshop on 3D Interactive Graphics,* ACM, October 23-24, 1986.