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*A White Paper*

**NASA Virtual Environment Research,  
Applications, and Technology**

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James P. Jenkins, Ph.D.  
Co-Editors

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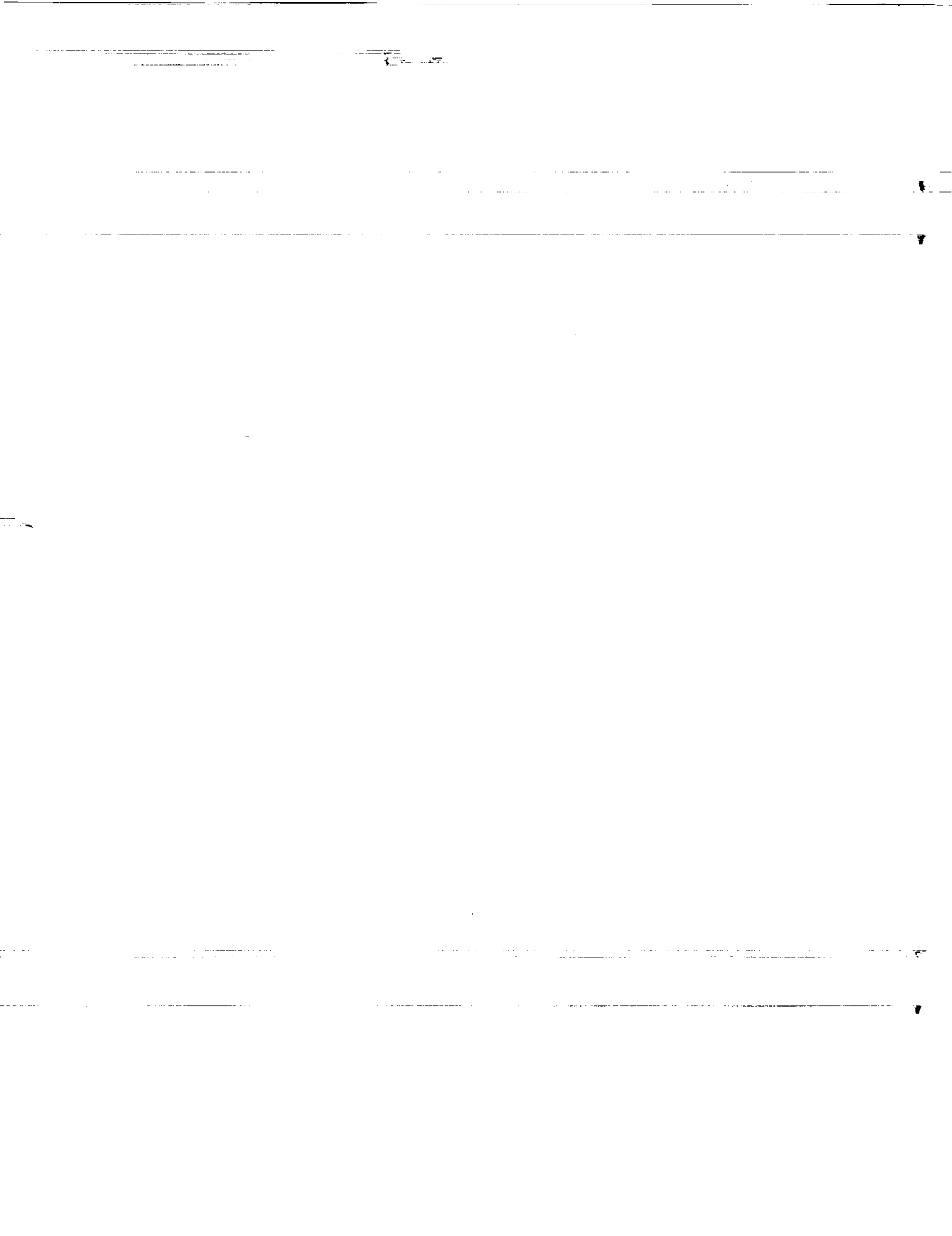
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# NASA Virtual Environment Research, Applications, and Technology

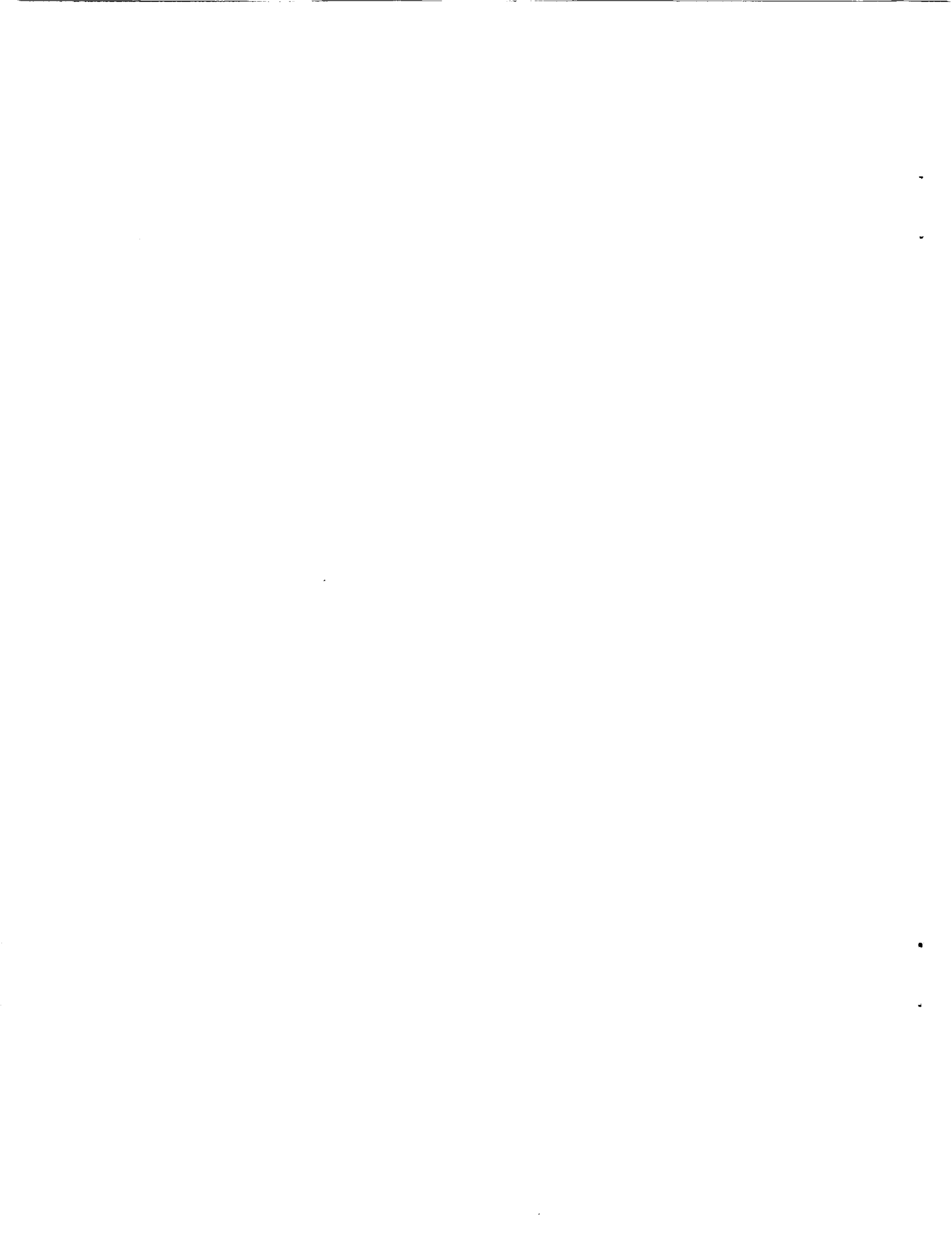
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# **NASA Virtual Environment Research, Applications, and Technology**

***Cynthia H. Null  
James P. Jenkins  
Co-Editors***

## **Executive Summary**

### **Introduction**

Research support for Virtual Environment technology development has been a part of NASA's human factors research program since 1985. Under the auspices of the Office of Aeronautics and Space Technology (OAST), initial funding was provided to the Aerospace Human Factors Research Division, Ames Research Center, which resulted in the origination of this technology. Since 1985, other Centers have begun using and developing this technology. At each research and space flight center, NASA missions have been major drivers of the technology.

This White Paper was the joint effort of all the Centers which have been involved in the development of technology and its applications to their unique missions. Appendix A is the list of those who have worked to prepare the document, directed by Dr. Cynthia H. Null, Ames Research Center, and Dr. James P. Jenkins, NASA Headquarters.

This White Paper describes the technology and its applications in NASA Centers (Chapters 1, 2 and 3), the potential roles it can take in NASA (Chapters 4 and 5), and a roadmap of the next 5 years (FY 1994-1998). The audience for this White Paper consists of managers, engineers, scientists and the general public with an interest in Virtual Environment technology. Those who read the paper will determine whether this roadmap, or others, are to be followed.

### **Summary of the Technology**

"Virtual reality is the human experience of perceiving and interacting through sensors and effectors with a synthetic (simulated) environment, and with simulated objects in it, as if they were real" (Virtual Reality Technology Report to the Office of Science and Technology Policy, Executive Office of the President).

Virtual reality is a unique method to achieve this simulation because of its capability to immerse and envelop the human user in the simulated environment. This definition engages the human experience and human interaction such that the human performance that results from immersion in the virtual reality benefits the human user. The technology needed to achieve virtual reality is called Virtual Environment Technology.

Virtual Environment 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 to detect human action, such as a head-mounted 6 degree of freedom position sensor; 2) effectors to influence the operators' senses, such as a stereoscopic display; 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.

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 applications, for example, Virtual Environments 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.

Virtual Environment technology is still in its infancy. However, there is great potential for this technology for NASA. Several NASA centers, following initial research and development at AMES in the Human Factors Division, are now investigating and developing Virtual Environment technology for specific NASA tasks and missions. The following outlines the different responsibilities by Center.

### **Center Activities in Virtual Environment**

#### **Ames Research Center**

- Responsible for human performance research relevant to developing Virtual Environment for NASA applications.
- Responsible for the development of human centered technology for aeronautics.

#### **Goddard Space Flight Center**

- Responsible for unmanned scientific studies and applications for unmanned space flight, in the areas of:
  - Space physics
  - Astrophysics
  - Earth sciences
  - Flight project support

#### **Jet Propulsion Laboratory**

- Responsible for research, development and applications for unmanned spacecraft, satellites and ground data systems.



**Johnson Space Flight Center**

- Responsible for manned space flight research, development, and applications.
- Responsible for astronaut training.

**Marshall Space Flight Center**

- Responsible for spacecraft design, structure, development and operations.

These centers have worked together to evaluate the current state of the technology, plan for future activities and to organize this report. This group makes the following comments and conclusions on Virtual Environment within NASA.

**Conclusions**

Since beginning research and technology development in 1985, NASA Centers have learned important lessons about the technology itself and the value it can provide in accomplishing the gamut of NASA's missions in aeronautics, science, and space.

1. Cost savings could be dramatic since Virtual Environment can potentially allow change to be made in a small way which can have a large effect; can potentially analyze situations with Virtual Environment with capabilities not heretofore available; can potentially analyze situations quicker and cheaper than with conventional methods; analyses can potentially be done which allow unique insights for investigators/scientists.
2. Networking is critically important to users of Virtual Environment because of the need to share data among many investigators.
3. Since model and database development are critical and time consuming for virtual world development, techniques for streaming this modeling are essential. Standardization, and maintenance are also critical and need to be address.
4. NASA recognizes the need for human performance validation and that human performance requirements drive the technology.
5. The productivity benefits of Virtual Environment will critically depend upon validated modeling of the specific task domain.
6. Challenging mission applications within NASA call for a responsive Virtual Environment technology. Typically, this is a high technology need. NASA has a leadership role in the technology development without depending upon the value of low-tech commercial development.
7. Virtual Environment is pervasive and the implications are extensive within NASA's many missions and research programs. NASA should be prepared to respond to such demands by supporting the technology.

8. Uses of Virtual Environment technology for human performance applied studies and critical descriptive research matches both applied mission needs as well as fundamental research needs.
9. Uses of Virtual Environment technology provide a flexible, relatively low-cost method for operational analysis, scientific studies, and critical discipline research.
10. Although Virtual Environment technology is evolutionary, building upon technologies such as simulation, computer graphics and so forth; implications for its use are revolutionary.
11. A well-documented, international interest and economic position of Virtual Environment technology exists. NASA has a well understood role in technology development and transfer. This transfer must be fostered if the US is to maintain its leadership position.
12. Current Virtual Environment systems generally do not have sufficient sensory-motor fidelity and human-machine interface design to deliver the performance necessary to achieve many of the above potential applications but foreseeable technical advances may change this situation within 1-3 years.

## **Detailed 5-year Virtual Environment Technology Plan**

The Outline which follows is a summary of the research at each Center which had FY 94 funding, as of April 1993, and plans for additional research which was "Unfunded" as of that date.

## Detailed 5-year Virtual Environment Technology Plan VE for Aeronautical Applications

Funded			Unfunded		
Year	Center	Milestone	Year	Center	Milestone
FY94	ARC	<ul style="list-style-type: none"> <li>Complete data collection for preliminary study investigating ATC use/acceptance of 3-D sound for situational awareness (using Convolvertron installed in the ATC lab at MVSRF).</li> </ul>			
FY94	ARC	<ul style="list-style-type: none"> <li>Complete baseline study of role of head-motion in enhancing localization accuracy using broadband (easily localized) stimuli.</li> </ul>			
FY94	ARC	<ul style="list-style-type: none"> <li>Publication of analysis of "tunnel" situation awareness experiment.</li> </ul>			
			FY94	ARC	<ul style="list-style-type: none"> <li>Assessment of "see-through" HUD for manufacturing.</li> </ul>
			FY94	ARC	<ul style="list-style-type: none"> <li>Development of full color, hires boom display for ATC &amp; manufacturing VE applications.</li> </ul>
			FY94	ARC	<ul style="list-style-type: none"> <li>Evaluate benefits of combining active-noise cancellation and 3D auditory speech display technologies for cockpit/ATC applications.</li> </ul>
			FY94	ARC	<ul style="list-style-type: none"> <li>Complete preliminary design of prototype hardware for large-scale simulation of reverberant environments (i.e., including both early reflections and late reverberation).</li> </ul>
FY95	ARC	<ul style="list-style-type: none"> <li>Complete study of role of head-motion in enhancing localization accuracy comparing speech and broadband stimuli.</li> </ul>			
			FY95	ARC	<ul style="list-style-type: none"> <li>Experimental assessment of 3 color boom in ATC environment.</li> </ul>
			FY95	ARC	<ul style="list-style-type: none"> <li>Demonstrate 3-D landing aids.</li> </ul>
			FY95	ARC	<ul style="list-style-type: none"> <li>Evaluate binaural speech intelligibility advantage using noise-canceling 3D auditory display in flight simulator.</li> </ul>

### VE for Aeronautical Applications

FY96	ARC	• Psychoacoustical investigations into enhancing vertical localization and minimizing confusion errors.	FY96	ARC	<ul style="list-style-type: none"> <li>• Design system for measuring HRTFs of aero personnel in the auditory lab and in arbitrary (noisy, reverberant) environments.</li> <li>• Demonstrate integrated visual and auditory landing aids.</li> <li>• Assessment boom display for CAD/CAM operation.</li> </ul>
FY97	ARC	• Psychoacoustical investigations into the synthesis of auditory distance.	FY97	ARC	<ul style="list-style-type: none"> <li>• Procure and integrate system for measuring HRTFs of aero personnel in the auditory lab.</li> <li>• Demonstrate integrated visual and auditory situation awareness display for Air Traffic Management.</li> <li>• Design of CAD/CAM system for VE.</li> </ul>
FY98	ARC	• Evaluate benefits of training / adaptation to spatial cues for auditory display users.	FY98	ARC	<ul style="list-style-type: none"> <li>• Design and evaluate advanced sonification display for aeronautical warning systems and situational awareness displays.</li> <li>• Testing of VE CAD/CAM tools in industrial environment for manufacturability and maintainability.</li> </ul>

### Visualization for Space Operations

Funded			Unfunded		
Year	Center	Milestone	Year	Center	Milestone
FY94	ARC	<ul style="list-style-type: none"> <li>Complete part-task perceptual studies at Ames to measure the enhanced speech intelligibility obtained with the spatial synthesis methods used in the communications prototype at KSC (funded by Ames DDF).</li> </ul>			
FY94	ARC	<ul style="list-style-type: none"> <li>Complete prototype hardware for simulation of reverberant environments based on data-reduction techniques applied to HR TFs (PCA model).</li> </ul>			
			FY94	ARC	<ul style="list-style-type: none"> <li>Testing of integrated optimizer with proximity operations planner.</li> </ul>
FY94	JPL	<ul style="list-style-type: none"> <li>Complete study of interactive, virtual windows for mission ops.</li> </ul>			
FY94	JPL	<ul style="list-style-type: none"> <li>Application of AI techniques to VEs.</li> </ul>			
			FY94	JPL	<ul style="list-style-type: none"> <li>Virtual teleconferencing for Cassini MOS.</li> </ul>
			FY94	JPL	<ul style="list-style-type: none"> <li>Virtual S/C design for early integration &amp; test.</li> </ul>
FY94	MSFC	<ul style="list-style-type: none"> <li>Macro-ergonomics: "real" and virtual control rooms (POCC,DCR).</li> </ul>			
FY94	MSFC	<ul style="list-style-type: none"> <li>Macro-ergonomics analyses of POIC/PCA layout/features.</li> </ul>			
FY94	MSFC	<ul style="list-style-type: none"> <li>Sensing And force-reflecting exoskelton (SAFiRE): hand.</li> </ul>			
FY94	MSFC	<ul style="list-style-type: none"> <li>Interactive virtual panels.</li> </ul>			
			FY94	MSFC	<ul style="list-style-type: none"> <li>"Transportable" VE system.</li> </ul>
			FY94	MSFC	<ul style="list-style-type: none"> <li>Stowage virtual Spacelab module.</li> </ul>
			FY94	MSFC	<ul style="list-style-type: none"> <li>Incorporate anthropometric model.</li> </ul>
			FY94	MSFC	<ul style="list-style-type: none"> <li>Incorporate physical model.</li> </ul>
			FY94	MSFC	<ul style="list-style-type: none"> <li>IGDS/EMS (Integrgraph) CAD file translation/conversion.</li> </ul>
			FY94	MSFC	<ul style="list-style-type: none"> <li>HFE for IML-2, SSFP WPO1/Payloads.</li> </ul>

### Visualization for Space Operations

FY95	ARC	<ul style="list-style-type: none"> <li>• Psychoacoustically evaluate prototype hardware for simulation of reverberant environments with PCA reduced HRTFs.</li> </ul>	FY95	ARC	<ul style="list-style-type: none"> <li>• Establish requirements for response-speed and visual fidelity based on field studies in space-analog environments and simulation.</li> <li>• Complete prototype hardware for large-scale simulation of reverberant environments.</li> <li>• Introduction of Navie planning tool into operations center.</li> <li>• Virtual DSOT cockpit.</li> <li>• Use of autonomous agents in mission ops.</li> <li>• Sensing And force-reflecting exoskelton (SAFiRE): arm.</li> <li>• IGDS/EMS (Integraph) CAD File immersion.</li> <li>• Enhanced virtual USML-2.</li> <li>• USML-2 Mission Support.</li> <li>• HFE for USML-2, SSFP WP01/Payloads.</li> <li>• Continue applications development/demonstration/validation.</li> <li>• Continue application driven system enhancements.</li> <li>• SL3 DDM unplanned IFM "virtualization".</li> </ul>
			FY95	ARC	
			FY95	ARC	
			FY95	JPL	
			FY95	JPL	
			FY95	MSFC	
			FY95	MSFC	
			FY95	MSFC	
			FY95	MSFC	
			FY95	MSFC	
			FY95	MSFC	
			FY95	MSFC	
			FY95	MSFC	
			FY95	MSFC	
			FY95	MSFC	
FY96	ARC	<ul style="list-style-type: none"> <li>• Redesign Convolver (Mark II) to take full advantage of PCA-based modeling, enable real time rendering of complex environments.</li> </ul>	FY96	ARC	<ul style="list-style-type: none"> <li>• Psychoacoustically evaluate prototype hardware for large-scale simulation of reverberant environments.</li> <li>• Demonstrate VE-based remote fault diagnosis.</li> <li>• Complete interactive prox ops optimizer command syntax.</li> </ul>
			FY96	ARC	
			FY96	ARC	

## Visualization for Space Operations

		FY96	JPL	<ul style="list-style-type: none"> <li>• Interactive mission design in a VE.</li> </ul>
		FY96	JPL	<ul style="list-style-type: none"> <li>• Multiview presentation of multidimensional data.</li> </ul>
		FY96	JPL	<ul style="list-style-type: none"> <li>• Upgrade mission ops workstations to include multimodal capabilities.</li> </ul>
		FY96	MSFC	<ul style="list-style-type: none"> <li>• Demonstrate SSF interior visualization for human engineering evaluations.</li> </ul>
FY97	ARC			<ul style="list-style-type: none"> <li>• Systematically evaluate psychoacoustic parameters of synthetic room models to maximize perceptual accuracy.</li> </ul>
		FY97	ARC	<ul style="list-style-type: none"> <li>• Demonstrate integration and visualization of operational-expertise database.</li> </ul>
		FY97	ARC	<ul style="list-style-type: none"> <li>• Demonstrate visualization of on-orbit lighting for STS/SSF EVA planning.</li> </ul>
		FY97	ARC	<ul style="list-style-type: none"> <li>• Upgrade VE workstation to include spatial auditory cues for conducting psychophysical studies of multimodal displays.</li> </ul>
		FY97	ARC	<ul style="list-style-type: none"> <li>• Use prox ops planner for real-time orbital planning.</li> </ul>
		FY97	JPL	<ul style="list-style-type: none"> <li>• Demonstrate virtual mission command and control centers.</li> </ul>
		FY97	JPL	<ul style="list-style-type: none"> <li>• Interactive environmental testing for S/C.</li> </ul>
FY98	ARC			<ul style="list-style-type: none"> <li>• Implement optimized synthetic room model into Convolutron for testing in applied contexts.</li> </ul>
		FY98	ARC	<ul style="list-style-type: none"> <li>• Demonstrate situation awareness for SSF exterior structure and attachments.</li> </ul>
		FY98	ARC	<ul style="list-style-type: none"> <li>• Demonstrated integrated visualization of mission planning with multiple controllers and automated advisory systems.</li> </ul>



### Visualization for Space Operations

			FY98	ARC	<ul style="list-style-type: none"> <li>• Implement sonification display within upgraded VE workstation.</li> </ul>
			FY98	ARC	<ul style="list-style-type: none"> <li>• Use prox ops planner for on-orbit maneuver planning.</li> </ul>
			FY98	JPL	<ul style="list-style-type: none"> <li>• Demonstrate virtual mission command and control centers.</li> </ul>
			FY98	JPL	<ul style="list-style-type: none"> <li>• Develop virtual instrument to support a spacecraft design model testbed.</li> </ul>

### Scientific Visualization

Funded			Unfunded		
Year	Center	Milestone	Year	Center	Milestone
FY94	ARC	<ul style="list-style-type: none"> <li>Conclude development of C-language-based digital terrain model (DTM) virtual reality system.</li> </ul>			
FY94	ARC	<ul style="list-style-type: none"> <li>Demonstrate visualization for integrating disparate data.</li> </ul>			
FY 94	GSFC	<ul style="list-style-type: none"> <li>Multi-user virtual environment utilizing Flow Analysis Software Toolkit (VE-FAST) with medium resolution and full color for Earth and space science research.</li> </ul>	FY94	ARC	<ul style="list-style-type: none"> <li>Publish object-oriented, ethnography-based analyses of "common core" user domains.</li> </ul>
FY94	JPL	<ul style="list-style-type: none"> <li>Conclude the development and beta testing of Surveyor, the interactive design tool for constructing animations.</li> </ul>			
FY94	JPL	<ul style="list-style-type: none"> <li>Implement interactive 3D animation.</li> </ul>			
FY94	JPL	<ul style="list-style-type: none"> <li>Complete global data sets for Venus.</li> </ul>			
FY94	JPL	<ul style="list-style-type: none"> <li>Create software to provide extrapolation and interpolation of atmospheric using velocity field measurement.</li> </ul>			
FY94	JPL	<ul style="list-style-type: none"> <li>Construct Viking global dataset for Mars.</li> </ul>			
FY94	JPL	<ul style="list-style-type: none"> <li>Create initial interactive planetary atlas for accessing terrestrial data sets.</li> </ul>			
			FY94	JPL	<ul style="list-style-type: none"> <li>Develop initial set of visualization tools for planetary operations.</li> </ul>
			FY95	ARC	<ul style="list-style-type: none"> <li>Publish object-oriented, ethnography-based designs for implementation of "common core" components of data visualization workstation.</li> </ul>
			FY95	ARC	<ul style="list-style-type: none"> <li>Publish object-oriented, ethnography-based analyses of "focus" user domain.</li> </ul>

### Scientific Visualization

FY 95	GSFC	VE-FAST with medium resolution and full color, with automatic animation along viewpaths.	FY95	JPL	<ul style="list-style-type: none"> <li>• Initial development of visualization tools to rapidly access and interactively explore massive, n-dimensional data bases.</li> <li>• Complete Viking global data set and begin incorporating Mars Observer data.</li> <li>• Complete high resolution global time dependent atmospheric data for Jupiter.</li> <li>• Initial development of tools and techniques to interactively build and manipulate complex scientific models and merge these models with data.</li> <li>• Complete 3D stereo photo CD production capability.</li> <li>• Initial development of mission/instrument/target body simulation capability including sensor image simulation, spacecraft trajectories, attitudes and planetary systems.</li> <li>• Enhanced visualization tools for planetary operations.</li> </ul>
			FY96	ARC	<ul style="list-style-type: none"> <li>• Demonstrate and publish implementation of "common core" components of data visualization workstation.</li> <li>• Demonstrate data-visualization workstation for EOS applications.</li> <li>• Publish object-oriented, ethnography-based designs for implementation of "focus" components of data visualization workstation.</li> </ul>
FY 96	GSFC	Distributed VE-FAST with medium resolution and full color.			

Scientific Visualization

			FY96	JPL	<ul style="list-style-type: none"> <li>• Complete full video resolution quicktime animation production capability.</li> </ul>
			FY96	JPL	<ul style="list-style-type: none"> <li>• Enhance development of visualization tools to rapidly access and interactively explore massive, n-dimensional data bases.</li> </ul>
			FY96	JPL	<ul style="list-style-type: none"> <li>• Create global data sets for moons of Uranus, Neptune and Jupiter from Voyager data sets.</li> </ul>
			FY96	JPL	<ul style="list-style-type: none"> <li>• Enhanced tools and techniques to interactively build and manipulate complex scientific models an merge these models with data.</li> </ul>
			FY96	JPL	<ul style="list-style-type: none"> <li>• Provide seamless animation for flight through atmospheres and over planetary surfaces which includes planetary curvature.</li> </ul>
			FY96	JPL	<ul style="list-style-type: none"> <li>• Enhanced mission/instrument/target body simulation capability including sensor image simulation, spacecraft trajectories, attitude and planetary systems.</li> </ul>
			FY96	JPL	<ul style="list-style-type: none"> <li>• Complete development of visualization for planetary operations.</li> </ul>
			FY97	ARC	<ul style="list-style-type: none"> <li>• Demonstrate and publish implementation of "focus" components of data visualization workstation.</li> </ul>
			FY97	ARC	<ul style="list-style-type: none"> <li>• Demonstrate network-based collaborative visual data analysis.</li> </ul>
			FY97	ARC	<ul style="list-style-type: none"> <li>• Publish object-oriented, ethnography-based analyses of alternative "focus" user domain.</li> </ul>
FY 97	GSFC	<ul style="list-style-type: none"> <li>• Distributed, parallelized VE-FAST with medium resolution and full color.</li> </ul>			

### Scientific Visualization

		FY97	JPL	<ul style="list-style-type: none"> <li>• Develop rings dynamics model for Saturn.</li> </ul>
		FY97	JPL	<ul style="list-style-type: none"> <li>• Add time dependent and frequency dependent access for interactive planetary atlas.</li> </ul>
		FY97	JPL	<ul style="list-style-type: none"> <li>• Complete global maps of Saturn satellite; use Galileo data to augment satellites of Jupiter.</li> </ul>
		FY97	JPL	<ul style="list-style-type: none"> <li>• Complete development of visualization tools to rapidly access and Interactively explore massive, n-dimensional data bases.</li> </ul>
		FY97	JPL	<ul style="list-style-type: none"> <li>• Complete interactive, manipulative techniques &amp; tools for complex scientific models &amp; data.</li> </ul>
		FY97	JPL	<ul style="list-style-type: none"> <li>• Develop visualization for energy flux for all spacecraft constructed after 1987.</li> </ul>
		FY98	ARC	<ul style="list-style-type: none"> <li>• Publish object-oriented, ethnography-based designs for implementation of alternative "focus" user domain.</li> </ul>
		FY98	ARC	<ul style="list-style-type: none"> <li>• Demonstrate implementation of alternative "focus" components of data visualization workstation and rapid reconfigurability.</li> </ul>
FY 98	GSFC			<ul style="list-style-type: none"> <li>• Distributed, parallelized VE-FAST with high resolution and full color.</li> </ul>
		FY98	JPL	<ul style="list-style-type: none"> <li>• Complete development of mission/instrument/target body simulation capability including sensor image simulation, S/C trajectories, attitudes and planetary systems.</li> </ul>
		FY98	JPL	<ul style="list-style-type: none"> <li>• Develop crater impact model with adjustable parameters for all terrestrial planets.</li> </ul>
		FY98	JPL	<ul style="list-style-type: none"> <li>• Incorporate Cassini data into global model for Saturnian satellites.</li> </ul>
		FY98	JPL	<ul style="list-style-type: none"> <li>• Generalized procedural models for simulation of natural phenomena such as crater formation, volcanic eruptions.</li> </ul>

### VE Control for Teleoperations/Telerobotics

Funded			Unfunded		
Year	Center	Milestone	Year	Center	Milestone
FY94	ARC	• Demonstrate VE interface for telerobotic planning and worksite visualization.			
FY94	ARC	• Determine dynamic & kinematic needs for kinesthetic feedback in VE.			
FY94	ARC	• Demonstrate shared human-computer control of remote robot.			
			FY94	ARC	• Measure kinetic fidelity of VE robotic simulation
			FY94	ARC	• Measurement of motion sickness side effects in VE.
FY95	ARC	• Develop high fidelity 6 dof, force reflecting manipulandum.			
			FY95	ARC	• Demonstrate wireless large-area tracking technology.
			FY95	JPL	• Demonstrate VE interface for deep space telerobotic missions.
FY96	ARC	• Develop dynamic modeling for real-time VE display.			
			FY96	ARC	• Demonstrate hierarchical gesture recognition capability.
			FY96	JPL	• Demonstrate VE interface for route planning.
			FY96	JPL	• Develop interface strategies to compensate for long round trip light times.

**VE Control for Teleoperations/Telerobotics**

FY97	ARC	• Assess fidelity of dynamically realistic VE.	FY97	ARC	• Demonstrate variable virtual physics for optimizing human performance.
			FY98	ARC	• Field testing of high fidelity dynamically accurate VE.
			FY98	ARC	• Evaluate performance of ultiple operators in multiple simultaneous virtual environments.*

## Training Systems

Funded			Unfunded		
Year	Center	Milestone	Year	Center	Milestone
			FY94	ARC	<ul style="list-style-type: none"> <li>• VE developed to train cable layout &amp; assembly task.</li> </ul>
			FY94	JPL	<ul style="list-style-type: none"> <li>• Spacecraft integration training in a VE.</li> </ul>
FY94	JSC	<ul style="list-style-type: none"> <li>• Proof-of-concept demonstration of VE for shuttle/station training for one astronaut.</li> </ul>			
FY94	JSC	<ul style="list-style-type: none"> <li>• Real-time, routine sharing of VE between two distant sites.</li> </ul>			
FY94	JSC	<ul style="list-style-type: none"> <li>• Temperature/tactile feedback.</li> </ul>			
FY94	JSC	<ul style="list-style-type: none"> <li>• Initiate development of tools for building VE-based training systems.</li> </ul>			
			FY94	JSC	<ul style="list-style-type: none"> <li>• Proof-of-concept demonstration of VE for shuttle/station training for two astronauts.</li> </ul>
			FY94	JSC	<ul style="list-style-type: none"> <li>• Real-time routine sharing of VE between three to five distant sites.</li> </ul>
			FY94	JSC	<ul style="list-style-type: none"> <li>• Temperature/tactile/force feedback.</li> </ul>
			FY94	MSFC	<ul style="list-style-type: none"> <li>• VE orbital mechanics trainer.</li> </ul>
			FY94	MSFC	<ul style="list-style-type: none"> <li>• Familiarization training virtual spacelab module.</li> </ul>
			FY94	MSFC	<ul style="list-style-type: none"> <li>• Science/payload system VE training.</li> </ul>
			FY94	MSFC	<ul style="list-style-type: none"> <li>• USML-2 Familiarization training in virtual spacelab module.</li> </ul>
			FY94	MSFC	<ul style="list-style-type: none"> <li>• SAFiRE/IML-2 glovebox ops trainer.</li> </ul>
			FY94	MSFC	<ul style="list-style-type: none"> <li>• IML-2 virtual panels trainer.</li> </ul>



### Training Systems

FY95	ARC	<ul style="list-style-type: none"> <li>• Calibration testing of wide area tracker &amp; environment model validation.</li> </ul>	FY95	JPL	<ul style="list-style-type: none"> <li>• Sequence planning &amp; design training in distributed VE.</li> <li>• VE training of mission controllers.</li> </ul>
FY95	JSC	<ul style="list-style-type: none"> <li>• Integration of intelligent computer-aided training (ICAT) with VE for autonomous training for one astronaut.</li> </ul>	FY95	JPL	
FY95	JSC	<ul style="list-style-type: none"> <li>• Real-time routine sharing of VE between three to five distant sites.</li> </ul>			
FY95	JSC	<ul style="list-style-type: none"> <li>• Continue development of tools for building VE-based training systems.</li> </ul>	FY95	JSC	<ul style="list-style-type: none"> <li>• Integration of ICAT with VE for autonomous training of multiple astronauts.</li> </ul>
			FY95	JSC	<ul style="list-style-type: none"> <li>• Complete development of tools for building VE-based training systems.</li> </ul>
			FY95	JSC	<ul style="list-style-type: none"> <li>• Obtain portable hardware.</li> </ul>
			FY95	MSFC	<ul style="list-style-type: none"> <li>• USML-2 stowage reconfiguration trainer.</li> </ul>
			FY95	MSFC	<ul style="list-style-type: none"> <li>• USML-2 science/payload system trainer.</li> </ul>
			FY95	MSFC	<ul style="list-style-type: none"> <li>• USML-2 transportable VE trainer.</li> </ul>
			FY95	MSFC	<ul style="list-style-type: none"> <li>• Continue expansion of applications &amp; utilization; H/W, ops development &amp; support, &amp; training (Payload Operations, Science).</li> </ul>
			FY96	ARC	<ul style="list-style-type: none"> <li>• Evaluate VE application to in-space assembly.</li> </ul>
FY96	JSC	<ul style="list-style-type: none"> <li>• Integration of ICAT with VE for autonomous training of multiple astronauts.</li> </ul>			
FY96	JSC	<ul style="list-style-type: none"> <li>• Complete development of tools for building VE-based training systems.</li> </ul>			
FY96	JSC	<ul style="list-style-type: none"> <li>• Portable hardware.</li> </ul>			

### Training Systems

		FY96	JSC	<ul style="list-style-type: none"> <li>Development test objective flown to demonstrate VE on-board.</li> <li>Deliver complete training system or generic EVA and payload interaction.</li> </ul>
		FY96	JSC	
		FY97	ARC	<ul style="list-style-type: none"> <li>Measurement of productivity effects of VE training in aircraft system assembly.</li> </ul>
FY97	JSC			<ul style="list-style-type: none"> <li>Development test objective flown to demonstrate VE on-board.</li> </ul>
FY97	JSC			<ul style="list-style-type: none"> <li>Deliver complete training system for generic EVA and payload Interaction.</li> </ul>
		FY97	JSC	<ul style="list-style-type: none"> <li>Initiate training for space station crew using distributed VE.</li> </ul>
		FY97	JSC	<ul style="list-style-type: none"> <li>Deliver complete system for on-board VE training.</li> </ul>
		FY98	ARC	<ul style="list-style-type: none"> <li>Offsite generation of VE environments for manufacturing.</li> </ul>
FY98	JSC			<ul style="list-style-type: none"> <li>Initiate training for space station crew using distributed VE.</li> </ul>
FY98	JSC			<ul style="list-style-type: none"> <li>Deliver complete system for on-board VE training.</li> </ul>
		FY98	JSC	<ul style="list-style-type: none"> <li>Demonstrate shared VE between on-orbit environment and ground facilities for remote coaching and aiding.</li> </ul>

# Chapter 1: Introduction

## Virtual Environments: Definition

### 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 to detect human action, such as a head-mounted 6 degree of freedom position sensor; 2) effectors to influence the operators' senses, such as a stereoscopic display; 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. Terms like "virtual worlds" or "virtual environment" seem preferable since they are linguistically conservative and may be related to existing well established terms such as a virtual image (Ellis, 1991).

### Why are virtual environments useful?

#### Virtual environments are communications media

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 applications, for example, virtual environments 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.

#### Communications media have multiple uses.

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 multiple, coordinated, real-time foci of control in an environment. Tasks that involve manipulation of objects in complex visual environments and also require frequent, concurrent changes in viewing position, for example, laparoscopic surgery (Green, Satava, John-Hill, & Simon, 1992) are tasks that are naturally suited for virtual environment displays. Other tasks that may be mapped into this format are also may uniquely benefit.

### How are virtual environments made?

The display technology works by developing a real-time, interactive, personal simulation (Foley, 1987) of the content, geometry, and dynamics of a work environment directly analogous to that used for traditional vehicle simulation (Cardullo, 1993; Rolfe, & Staples, 1986). But the 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 and not 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?

### Precursors in telerobotics and computer graphics

Components of virtual environment display technology have been under development since the early 1960. Philco and Argonne National Laboratory work on telepresence displays (Comeau, & Brian, 1961; Goertz, 1964; Goertz, Mingesz, Potts, & Lindberg, 1965). More recent work has been associated with the development of computer graphics systems through the pioneering work of Ivan Sutherland (Myers, & Sutherland, 1968; Sutherland, 1965; Sutherland, 1970) at Harvard and Utah. As an outgrowth of the association with computer graphics development, virtual environment development has been most intensively pursued by aircraft simulation groups (CAE Electronics, 1991; British Aerospace, 1993) interested in alternative display systems to expensive projection dome systems. 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 Pimentel, & Teixeira, 1993, for a review).

### NASA application areas

Because of the broad potential applicability, a number of NASA centers have followed NASA Ames' lead. In 1985 in the Aerospace Human Factors Research Division at Ames, Michael McGreevy and James Humphries assembled the first low cost virtual environment system. Many of the programs following this initial development have been pursued under the aegis of a number of different programmatic titles, for example teleoperations, telerobotics, 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. In fact, research in these disciplines provides much useful design information for the engineering of virtual environment displays (Ellis, Kaiser, and Grunwald, 1993).

## Who conducts virtual environment research and development?

### Users and developers

Scientists and developers and those with nonprofessional interests 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 route planning and operation of undersea robot vehicles.

The distinction between these two groups is not always clear as many of the users often have overestimated the actual capabilities of existing systems. Though they may consider themselves to be users, they are actually developers who need to significantly improve the technology for their specific tasks. Unfortunately, because their expertise is primarily in a task domain, they are unaware of the man-machine interface principles needed to select and integrate appropriate equipment to enable them to efficiently achieve practical goals. Consequently, the product from this kind of development may be a "conceptual demo" which suggests possible applications but which itself is not practically useful. For example, the field use of a helmet mounted display developed for remote teleoperation of an underwater vehicle to be used for research in Antarctica proved difficult due to the limitations in the visual quality of the images it could present (Stoker, 1993).

### Semi-popular semi-technical interests

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 more or less annual 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 technical and intellectual content of the programs at these meetings is underscored by a remark by Robert Jacobson, one of the more enthusiastic proponents of "virtual reality" in which virtual reality was claimed at the 1992 Meckler VR Conference in San Jose to be a very special field, "it's a field where there are no experts, and everyone can be one!"

### **Role of vehicle simulation technologists**

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 usable 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 (Furness, 1986; Barrette, et al., 1990).

### **Professional organizations interested in research agendas**

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 (Bishop, 1992), the Engineering Foundation (Durlach, Sheridan, & Ellis, 1991), and NASA (NASA, 1991) and Office of Naval Research (Forthcoming, May 1993). These meetings have been and are continuing to be called to help establish national agendas for research.

## **When will virtual environments be available?**

### **Vehicle simulators are available now.**

Virtual environments have been commercially available as flight simulators, for example CAE fiberoptic helmet mounted display (Barrette, et al., 1990), 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. (Division Limited, 1993; W Industries Ltd., 1993; FakeSpace; Virtual Research, 1993; Sense8 Corporation, 1993; Leep Systems, 1993; Virtual Reality Group, 1993). The market for the cheaper virtual environment systems has generally tolerated much poor performance and manufacturing quality than the flight simulator market. However, poor performance and reliability appears to have been partially responsible for the fall of the former market leader, the now dissolved VPL Research (Hamit, 1993).

### **Cheaper head-mounted systems are sufficient only for video demos**

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 (Zimmerman, Lanier, Blanchard, Bryson, & Harvil, 1987), 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 (Zimmerman, 1992).

### **Marketing problems**

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 Antarctic (Stoker, 1993). 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 (Cardullo, 1993), a requirement frequently underestimated by those suggesting extensions of personal simulators into other domains.

### **Required demonstrations of utility**

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 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 with respect to the head-referenced displays that both use. Such head-referenced 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* (Bradley, 1967). Since the key innovations of the display technology are human interface issues, the reasons for the failure for earlier diffusion 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 limitation on the viewer technology are strikingly contemporary yet date from the 1960's. Goertz's discussion about why a 1000 line TV system is at least 165 times poorer than the human eye, even disregarding the great difference in available contrast ratios, is especially revealing (Goertz, et al., 1965).

**Technical solutions to the resolution problem.** Advances in boom-mounted displays (McDowall, Bolas, Pieper, Fisher, & Humphries, 1990), improved interfacing techniques, and 6 dof tracker characterizations (Adelstein, Johnston, & Ellis, 1992) 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 potentially can provide a compact format for personal training simulators of hand-held systems such as Hand Held Maneuvering Units for use in space (Brody, Jacoby, & Ellis, 1992) or Stinger anti-aircraft missile launchers (Jense, & Kuijper, 1993), but even these applications are still essentially conceptual demonstrations awaiting further improvements in the inexpensive virtual environment systems.

**Demonstration of real utility: comparison to panel mounted formats.** 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 (Weintraub, & Ensing, 1992). 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.

**Some commercial applications.** 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 (Airey, Rohlf, & Brooks, 1990). 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 (Anonymous, 1993), 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 (Hamit, 1993). 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.

**Sources of technological strength.** 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 (Basalla, 1988). 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 (Anonymous, 1993), 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 as lasting aftereffects which can interfere with automobile driving and other aspects of normal life in the physical environment to which all users must ultimately return.

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# **Chapter 2: State of Knowledge, State of Technology, Limitations, Research Needs, and Implications for System Requirements**

A Virtual Environment (VE) is an interface media. Therefore, human performance is one of the important considerations in defining requirements for a VE. In this section, we consider visual, auditory, haptic and vestibular perception. Briefly the state of research knowledge relevant to VE is presented. Research to provide the knowledge needed to more fully define the requirements for a VE system are outlined. The implications the state of research knowledge has for VE systems requirements are specified.

## **Chapter Organization**

### **Vision and Visual Perception**

- Visual Image: Luminance, Contour, and Color on the Retina

- Visual Scene: Segregated Interpretation of Images

- Visual World: Spatial Interpretations of Scenes

- Head-Mounted/Head-Referenced Displays

### **Spatial Perception and Orientation**

#### **Visual-Vestibular Research and Motion Sickness**

### **Haptic Interfaces**

- Haptic Perception

- Haptic Interface Design and Control

- Gesture Recognition

### **Audition and Virtual Acoustic Displays**

- Improving Human Performance

- Issues for Audio Communications

- Spatial Orientation and Situational Awareness

- Synthesizing Non-Spatial Auditory Icons

- Issues for Hardware/Software Development

### **Overall System Issues**

- Host Computers

- Networks

- Models, Imagery, and Other Data

- Software Tools

- Domain Analysis and Design

- Spatial Position/Orientation Trackers

## Vision and Visual Perception

### Background

Vision dominates performance and perception in a VE. This key role has 3 aspects: characteristics of the visual image, structure of the visual scene, and visual consequences of interaction with the scene.

### Visual Image: Luminance, Contour, and Color On The Retina

#### State of Knowledge / Technology

Visual image properties are well understood from previous applications in flight simulation and the design of optical displays including HUDs, photographic or video displays. Flight simulation displays have higher information bandwidth than those currently used in VE. Significantly, known visibility requirements for text on HUD displays are not satisfied by most VE helmet displays. The specific trade-offs between the purely visual parameters that could be made for improved design of VE displays are not in general known or demonstrated for target tasks. For example, because of the binocular overlap between the left and right eye images need not be complete, monocular fields exceeding 60° may only rarely be required.

#### Research Needs

Display resolution: Precision visual tasks will require better image properties of small CRT display systems providing daytime luminance levels. Visual performance needs to be assessed with parameters likely to be provided by future display systems which may use nonstandard pixel layouts, variable field resolution, and field magnification to optimize allocation of computer graphics processing. For example, the benefits of inserting higher resolution imagery into the central visual field need to be explored.

Stereoscopic properties, for example characteristics of display separation, need to be studied to measure likely visual fatigue with protracted use. Trade offs between the binocular overlap between the left and right eye images and total field of view need investigation.

Trade off studies between visual image parameters, field of view, resolution, stereo disparity, color gamut, need to be conducted in task environments since in existing systems provision of full fidelity of all parameters is impossible. Trade off studies using "boom" mounted displays -- which can provide much higher resolution, but are much harder to move naturally -- are needed to establish specific visual requirements for NASA tasks and measure depth and direction sensitivity, discriminability and bias, as well as target recognition and detection.

Research should be conducted to examine the use of synesthetic stimuli that, for example, transform a visual signal such as the brightness into an auditory or tactile signal. VE provides enormous flexibility for such studies and should be exploited to develop new communication channels for sensory stimuli.

#### VE System Requirements

Resolution:	2-3'/pixel in central 20° field; Many manufacturers specify display resolution of their devices, but practical testing has indicated in the Ames lab that the displays do not meet the published specifications, Standardized testing is needed.
Field of view:	Total field of view >60°.
Magnification factor:	1, but zoom lens compensation for poor resolution is needed, Visual disturbances due to zoom need to be determined.
Binocular overlap:	20-30°, trade off of binocular overlap; total field of view needs further study.
Disparity range:	unknown; magnification aggravates fatigue; countermeasures need study.

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## Visual Scene: Segregated Interpretation of Images

### State of Knowledge

Visual images are perceived to be segregated into subparts based on image processing rules that are not completely understood, but which collect visual attributes such as color and shape and segregate the image into regions. This segregation is accomplished by both simultaneous and serial information processing. VE displays must have sufficient fidelity to allow this processing to take place. Most existing displays do not provide sufficient visual fidelity for these processes to take place normally.

### Research Needs

Since VE will only be able to present somewhat degraded low level visual cues such as contrast and stereopsis, the capacity for viewers break camouflage -- to segregate foreground from background -- is likely to be less than that with natural images from real environments. Accordingly, visual segregation with degraded image quality and dynamics should be studied and enhancements to overcome difficulties should be developed. This is an area where knowledge of texture perception can be used to help control the visual clutter in images.

Specific trade offs of image properties may be studied to improve image segregation, for example color coding can be used to substitute for poor stereoscopic characteristics which normally reveal concealed objects.

Studies of use of other sensory modalities to assist image segregation should be conducted so as to improve the VE user's sense of the spatial and control context in which they find themselves. Knowledge of context can improve the users' ability to segregate a noisy or imperfect visual image.

### VE System Requirements

Visual resolution needs to be increased to levels approaching that of a standard desktop CRT such as a Macintosh monitor so a wide variety of textures can be presented.

Visual textures, the integrated spatial distribution of contour and shading across the visual image, needs to be quantified and computational models are needed to predict their visibility in VE displays systems.

Visual clutter: visual textures that can assist image segregation in VE displays which fail to meet known visual performance specifications for other tasks need to be identified.

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## Visual World: Spatial Interpretations of Scenes

### State of Knowledge

Segregated visual scenes are normally interpreted as an external world populated by actors and objects located in space. The spatial interpretation of visual images is highly dependent upon the moving properties of the image, in particular those motions that are consequences of the observer himself. The patterns of image motion that are associated with observers' movements provide much of the necessary information for guidance through a cluttered environment and have provided the basis identifying the visual cues to motion, space and causality. In this field, researchers have investigated the natural linkages established between properties of image, or object motion, object position and orientation and complex normal behaviors such as walking, perception of self-motion, object avoidance or manipulative interaction. Computation models of the spatially related behaviors in the visual world have been developed to assist the visual design of vehicle simulators.

Visual information is not only important for local navigation and perception of self-motion while traversing an environment but also for global path planning and route selection. Visual orientation is also important for more integrated tasks in which subjects use visual aids such as maps to maintain their internal representation of the surrounding space and assist planning of future activities.

### Research Needs

Models used to predict phenomena in the visual world, such asvection, illusory self-motion due purely to visual stimulation, need to be applied to the VE. Most previous work is relevant to simulators that are entered rather than worn. Experimental studies checking model predictions are needed.

Subjective and objective operator reactions to approximated kinematic and dynamic models of synthetic environments. How far can a simulation deviate from correct physical modeling and still appear to be realistic?

Visual stimuli that induce apparent self-motion should be evaluated for integration into VE displays designed to create apparent movement through virtual spaces.

Since visual textures are a major cue to purely visual spatial perception, the ability of users to make purely visual texture based spatial judgements should be investigated and enhanced by necessary image processing to overcome deficiencies in visual displays.

Since imperfect and slow dynamics of VEs can lead to significant difficulties for users to main their spatial orientation within a simulated larger environment, sensitivity studies of visual disorientation are needed. Orientation aids to compensate for these difficulties should be developed to allow developers to simulate highly detailed real environments when such detailed simulation is required. These aids should assist users switch between ego and exocentric frames of reference which will be needed for efficient interpretation and control of objects in the simulated environment.

### VE System Requirements

Reference tasks need to be identified to determine if the visual world is presented with adequate fidelity so as to allow the viewer to perceive causal interactions between actors and objects.

These standardized tasks are similar to those used to obtain FAA qualification for a flight simulator, but have not been identified for VE applications in other areas.

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## Head-Mounted / Head-Referenced Displays

### State of Technology

A VE display is a visually dominated device. Though other sensory modalities may contribute essential information, the illusion of being at another location is primarily visual. VE visual displays have primarily been head-mounted stereoscopic devices which only can present a visual image with sufficient field of view, resolution, color gamut, luminance and dynamic fidelity with great difficulty and expense, e.g., the CAE Fiber optic helmet mounted display (FOHMD). While helmet mounted displays are inherently somewhat obtrusive they can be more flexible and less expensive than alternative back-projection systems e.g., the "CAVE" of University of Illinois. In fact, the FOHMD was designed as a cost-effective alternative to a dome projection flight simulator. Experience with existing VE helmets as well as current ergonomic and human factors knowledge all support the fact that VE head-mounted display technology in general fails to meet minimum requirements of image quality, weight, and packaging to allow VE operators to use the displays for long periods of useful work.

Alternative head-referenced displays have been developed to solve the weight and resolution problems, originally by Ray Goertz but more recently by FakeSpace Labs. These displays involve a using boom mounted CRT to present the visual image generated for the VE. Since the boom can carry the CRT and optics weight, much improved imagery can be provided by higher resolution monitors and optics that in other formats would be too head to use. These types of displays may either be actively controlled like a submarine's periscope or may be made to passively track the head of the user. Though in either case the resulting display system is more cumbersome than a head-mounted one, it can deliver the required visual performance for useful work. The added inertia and mounting linkage, however, interferes with the illusion of being directly present in a VE.

### Research Needs

Systematic comparison of panel-mounted, head referenced and head mounted formats need to be made to determine which applications require which format. Those that can usefully adopt head-referenced boom displays are those for near term products.

Advances in miniaturization of high definition video displays needs to be encouraged since the lack of a small (1") high-definition monitor with greater than 1000 X 1000 line resolution complicates the presentation of a visual image with needed resolution.

Alternative optical techniques for providing high resolution imagery should be investigated, i.e. fiber optics, relay lenses, video mixing systems.

Techniques for correcting for the inertia and cumbersome linkages in boom mounts for head-referenced displays should be investigated. Minimum kinematic fidelity requirements for display mounts should be established.

High resolution electronic image and video standards need to be established to provide a technological infrastructure that will encourage the development of display technology utilized by VE.

### VE System Requirements

(See visual display requirements)

### References

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## Spatial Perception and Orientation

### Background

Coordinated presentation of stimuli in different sensory modalities enhances the illusion that an observer is in a virtual space. There are 4 factors influencing this illusion: 1) The match of synthetic sensory stimuli to natural stimuli, 2) The correlation of changes in all spatially dependent stimuli, 3) The naturalness and completeness of motor interactions, and 4) the normal correlation of movement and its sensory consequences. The completeness of the illusion can measure overall VE simulation fidelity.

### State of Knowledge

Spatially related physiological reflexes in VE are well described by standard biomedical techniques. Some reflexes, such as, the vestibular-ocular reflex, postural balance reflexes, and the looming reflex, may be used to provide objective measures of the extent to which inhabitants of a VE behave as if they were in a real environment. More complex psychological responses to being present in a space also can measure the immersion illusion, i.e. apparent location of the horizon in a variety of reference frames, the spontaneous avoidance of "visual cliffs" or the presence of environmentally induced circular and linear vection (self-motion). The correlated sensory stimulation associated with natural movement combine synergistically to improve the sense of spatial immersion and provoke the above spatial responses

Inhabitants of physical space are generally sufficiently well adapted so that spatial tasks may be successfully accomplished. For example, the egocentric direction of target may be determined so that they may be manipulated or moved toward in a coordinated manner. Subjective measures of direction and depth, that have been studied in physical environments, may be adapted for studies in VEs to measure their spatial fidelity. Static measures include accuracy of perceived egocentric direction and apparent depth. Dynamic measures include 3D tracking, pick and place tasks, and reports of perceived of egocentric and exocentric motion.

The essential character of the immersing spatial illusion provided by a VE is its interactivity. Similar interactivity, present with usual human-computer interfaces, has been the object of many "useability" studies. These provide models for parallel issues in VE and 3D generalizations of 2D graphics interfaces.

### Research Needs

Spatially related physiological and psychological responses need to be validated as measures of simulation fidelity in VE

Engineering demonstration environments should be developed to allow formal comparison of performance with VE interfaces to spatial data with well-designed panel-mounted alternatives. Existing panel-mounted displays may provide faster and cheaper interfaces for some spatial tasks. Exactly which types of spatial tasks can uniquely benefit from the VE interface need to be determined. This determination can be accomplished by analysis of task-specific, spatially oriented behavior in the field and laboratory analysis of how the target task may be more efficiently accomplished with VE technology.

Applied tasks such as aspects of satellite servicing with a hand-held orbital maneuvering system need to be developed to determine if VE can provide a useful simulation and training capacity for the task in question. This type of performance measure is similar to the acceptance testing done for flight simulators.

Synergistic combinations of stimuli, such as vision and correlated sound, need to be used to improve the overall spatial response to the stimuli which would otherwise be incomplete due to known imperfections into the VE display technology. Studies should be conducted to investigate the potential of substituting information from one sense for that in another, such as visual or auditory presentation of force.

### VE System Requirements

Simulation fidelity requirements for VE applications depend upon the specific task environment but should all the VE user to be spatially oriented at least as well as in the corresponding real environment, but if the VE user is not better oriented in the VE than he could be in the real environment, the VE systems would have failed to provide its potential benefit. Existing simulation fidelity requirements for flight simulators may provide initial guesses of what VE requirements are for personal simulators that are worn.

### References

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## Visual-Vestibular Research and Motion Sickness

### Background

Human locomotion and movement involve a dynamic sensory-motor adaption to the background gravity on Earth. Disruptions of the normal patterns of sensory feedback from vision, vestibular sense, touch, somatosensation, proprioception combined with motor corollary during locomotion and other coordinated movements. In particular visual-vestibular conflict can arise from several sources and can cause serious performance degradation as well as motion sickness.

### State of Knowledge

Visual motion displays can cause malaise similar to simulator sickness where visually-induced vection contradicts the vestibular system which signals that the head/body is not moving. Conversely, feedback delays or inaccurate signals from head trackers cause the display to be updated inaccurately so that vestibular system signals self-motion while the visual system does not. Distortions, low-resolution, and small fields-of-view in the visual display can also create visual-vestibular conflicts. The ability to generate arbitrary vehicle motions in VE may also cause unanticipated sickness. Adaptation to VE can cause post-VE malaise, sickness or even perceptual errors with potentially disastrous safety consequences.

Serious performance errors often occur in present state of the art VEs. Spatial calibration is generally empirical as the many sources of error are not well quantified (eg. simulated eye separation, display distortions) that can cause reaching errors and other sensorimotor dysfunction. Sensorimotor control is difficult and error-prone in systems with low resolution and long temporal delays.

### Research Needs

Future VE development will require predictive models of human motion sickness. For example, given a particular combination of visual, vestibular, and other stimuli, what is the probability of getting sick? After what length of time? What types of visual and vestibular stimuli cause motion sickness? In particular, what types of visual-vestibular conflicts are tolerable and which are not (e.g., minimum head position update rate)? These models should also provide a better understanding of what types of stimuli could be provided to counteract motion sickness (e.g., tread mill or other devices to simulate actual motion stimuli).

Countermeasures to motion sickness in VE should be studied using existing drug treatments but extending to specifically designed training environment which could be presented as VE. VE should be explored as an adaptation environment for existing forms of motion, simulation, and space sickness.

Effective VE design will also require predictive models of human performance in 3D perceptual tasks that provide an understanding of the minimum visual-vestibular information necessary for accurate self-motion perception and the maximum adequate for asymptotic performance. For example, how do visual, vestibular, and other stimuli combine to generate accurate performance? What visual parameters are necessary for accurate performance? Will an additional minimal vestibular stimulus enhance performance over visual stimuli alone? What is the minimum amount of information necessary to generate asymptotic performance? What are the information-performance trade-offs? What information is unnecessary so that computation or data storage resources are not wasted? In addition to enhanced visual display and head tracking methodologies, clever use of vestibular and other stimuli may be fruitful and need evaluation.

### VE System Requirements

High spatial and temporal resolution visual display with accurate and fast head tracking. are required. Adequate visual spatial and temporal resolution will be necessary to minimize visual-vestibular conflict. The exact parametric values are at present unknown and will require empirical measurement and model development. In addition, effective countermeasures within the VE design will be necessary to avoid or eliminate either sickness either before or after VE work. VE should incorporate hardware to aid normal visual-vestibular correlations during movement such as, motion platforms and treadmills.

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## Haptic Perception

### Background

Human haptic perception requires the active integration of information on touch from the surface of the skin as sensed by tactile receptors with information on limb displacements, velocities, and forces as detected by joint, muscle, and tendon receptors. When integrated together, stimuli to these various sense organs contribute to the overall "feel" of the material properties (e.g., shape, hardness, weight, etc.) of real objects when we physically interact with a real environment. A haptic VE strives to emulate these real mechanical characteristics by stimulating these sense organs. Applications of interest for NASA include telemanipulation and force reflection for fly-by-wire aircraft.

### State of Knowledge

Haptic interface research at laboratories in the US and other countries has focused separately either on the tactile sense alone through stimulation of the skin, or on the whole-limb displacement, velocity, and force sense of mechanical dynamics when coupled to electromechanically powered joystick and exoskeleton devices. The physiology of both cutaneous and musculoskeletal haptic sensory organs and the psychophysics of tactile perception have received considerable research attention over the last several decades. By comparison, until very recently, human perception of dynamic mechanical characteristics has seen relatively little work beyond basic studies of kinesthesia (perception of limb displacement) and static force discrimination. Several research groups are beginning to investigate temporal and spatial psychophysical discriminants of simple impedances (i.e., springs, dampers, inertias), forces, and displacements [1, 2, 3]. Among their goals is to contribute to quantitative design guidelines for future haptic interfaces.

### Research Needs

The most pressing research problems are in the areas that will lead to quantitative performance specifications and combined human-system models for haptic interfaces. Research into the psychophysics of haptic perception must be developed to include the aspects relevant to spatial and temporal whole-limb sensation of mechanical properties beyond those derived purely for the sense of touch. A necessary first step is research on the perceptual dynamic range and resolution requirements for simple mechanical quantities such as displacements, velocities, forces, and impedances.

A related issue is how the intrinsic mechanical properties of the haptic interface hardware alter human perception of those basic quantities. Similarly, basic computer control parameters such as update rate and temporal latencies that arise in modulating haptic interface mechanical output (parallel to CRT refresh and persistence) must be examined.

Research that can be carried out at NASA encompasses basic psychophysical experimentation that depends on high performance haptic research apparatus as well as psychophysical and related human performance studies involving multisensory interfaces to augment haptic display capabilities.

### VE System Requirements

An understanding of the type and detail of dynamic mechanical information from the environment that humans can integrate will lead to appropriate design specifications for general and application-specific haptic systems as well as individual actuator and sensor components. Psychophysical research will also lead to quantitative models of human haptic perception that are vital to effective control algorithm design and analysis (see section on Haptic Interface Design and Control).

Quantitative design specifications are needed to guide technological goals for future haptic interfaces—both to drive the market to achieve these goals and to ensure that effort is not expended to unnecessarily exceed these specifications.

### References

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## Haptic Interface Design and Control

### Background

Unlike visual or auditory VE displays, haptic interface hardware typically transfers information to the same body part that delivers the human operator's (e.g., manual) response. Consequently, a distinguishing attribute of the haptic display is that the transfer of information back-and-forth between the human operator and the VE entails mechanical power exchange through the interface and attached human's limb segments [1]. The implication is that the modulation of the mechanical characteristics of the haptic interface by computer control and the mechanical characteristics of the human limb under the human's control will alter mechanical power flow and hence affect information transfer. Thus, the development of effective haptic displays for VEs will depend on a thorough understanding of the effects of interface and limb mechanical impedance on human sensory input capabilities.

### State of Knowledge / Research Needs

One area requiring research is control algorithms for haptic displays. Much of the control research has benefited from recent analytic tools for robust stable telemanipulator control [2]. Research into the requirements for stable interface behavior is one prerequisite for acceptable haptic presentation quality. Thus far, though, this work has not been applied for the purpose of human sensory interaction at frequencies beyond the bandwidth of manual output.

A second line of research must be directed to the development of hardware subcomponents with appropriate performance capabilities for use in haptic interface systems. Several academic and commercial groups have concentrated on the construction of general purpose and application-specific haptic interface hardware. Due in part to the lack of comprehensive objective design specifications to help develop the market, a shortcoming encountered in many of these devices has been the lack of suitable, commercially-available actuators and sensors on which to base their designs. The most successful future designs will benefit from research into radically different sensor and actuator concepts that will be geared specifically toward haptic interface applications.

### VE System Requirements

General performance specifications for haptic VE applications are listed below. The type of application—whether the intended use is dominated by purely tactile or whole-limb kinesthetic and force information display—should be the major consideration in developing quantitative specifications for haptic displays. It is important to note that, especially for the limb sense of dynamics, little experimental data is available at this stage to develop these specifications.

Motion resolution:	Minimum relative displacements for output to human is on the scale of $1\ \mu\text{m}$ for tactile perception and 0.1 mm and greater for purely kinesthetic applications.
Motion range:	Application specific. Depends on which body segments are coupled to the interface.
Force range:	Application specific. The interface may need to be strong enough to resist all human motion: ~1000 Newton (225 lb) maximum for the arm at 0 Hz and trailing off to ~25 Newton between 3-10 Hz when the arm is braced in a stationary posture.
Frequency range:	Not fully known—the subject of psychophysical research. The interface must track limb output with negligible lag, implying a minimum analog bandwidth of 50 Hz and computer control update rates of at least 1 KHz. Muscle velocity receptors are sensitive to vibrations of 200+ Hz; skin receptors to frequencies as high as ~5 KHz.
Impedance range:	Equivalent to resistance to motion. Unknown—requirements need to be determined from extensive psychophysical research. Ideally—though not practically—impedance should span from zero to infinity. Zero impedance would make the interface feel completely "invisible", while infinite impedance would make an interface feel absolutely rigid.

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## Gesture Recognition

### State of Knowledge/Technology

Gesture is purposeful bodily movement, which includes locomotion and manipulation, as well as movement which can express or emphasize ideas, emotions, etc., or convey a state of mind or intention. This includes speech, whether verbalized or signed. Gesture has always been essential to user-computer interfaces and to user-environment interactions. Typing a command on Unix, moving a mouse to position a cursor, or pointing in the direction one wishes to fly in a VE are all gestures. Walking to go from room to room, reaching for and turning a door handle, traversing a new path in the mountains, or picking up a rock on the moon all require gesture.

The ability of a system to recognize gestures, whether of keystrokes, mouse positions, hand shapes, or paces, determines the ability of the user to communicate with the system via gesture. With VEs, the gestures used in the real world can equally apply in a computed one, but recognition of such gestures is currently very limited. The most fundamental VE gesture may be the turning of the head, which has been used to control the computed view to be presented in head mounted displays. Most gestures in VEs to date have, however, been primitive, as when arbitrary hand shapes have been non-intuitively mapped to commands such as "hide menu". Currently, voice is thought by some to be one of the most useful complex verbal commands in VE, since it leaves the hands free to grasp objects, and can be used to issue complex verbal commands without the use of a keyboard, menus, or buttons. Natural gestures, those used in the real world, have not yet been studied to any great extent with respect to their potential as elements of communication with computers. Instead, manipulative gesture interactions have been limited to pointing in directions or at menu selections, making grab gestures to pick up massless virtual objects, and pointing and firing weapons (although one inspired VE encourages users to touch the hearts of angels!). Walking in VEs is currently limited to a radius of 30 inches for many trackers, or can be done on a treadmill. Large area trackers are not yet available. Replication of gesture interactions with real environments is far from being available in virtual ones, and exploitation of virtual gesture interactions has not yet occurred.

### Research Needs

Human performance research is needed to provide an integrated theoretical framework for the use of gesture to interact with VE systems.

Given that VEs can potentially utilize all possible gestures, human performance research is needed to derive maps of "VE gesture space" for real world applications.

Joint human performance and computer science research is needed to develop gesture recognition systems capable of recognizing natural, dynamic gestures of all kinds.

### VE System Requirements

VE system gesture recognizers must not impose encoded gestures upon users.

Gestures recognized by VE systems must be derived from the target user domains, and intuitively understood by user domain experts.

Gestures learned on other systems, especially desktop workstations, must be considered as useful for VE systems until proven otherwise. Conversely, user difficulty with current technology workstations, such as wrist pain with keyboards or spatial ambiguities in complex data, must be factored into VE gesture interface designs.

## Virtual Acoustic Displays: Improving Human Performance

### Background

The synthesis technique used in spatial auditory displays involves the digital generation of stimuli using Head-Related Transfer Functions (HRTFs) measured in the ear canals of individual subjects in an anechoic (non-reverberant) environment. In most current systems, from one to four moving or static sources can be simulated (with varying degrees of fidelity) by filtering incoming signals with HRTF-based digital filters chosen according to the output of a head-tracking device. Motion trajectories and static locations at greater resolutions than the empirical data are generally simulated either by switching, or more preferably, by interpolating between the measured HRTFs. In some systems, a crude distance cue can be provided via real-time scaling of amplitude.

While current spatial auditory displays have proven benefits, they have only been partially perceptually-validated in terms of localization accuracy and realism. Further, their potential can be significantly enhanced by advances in hardware and software design driven by evaluations of human perceptual performance.

### Status of Knowledge

To date, several primary areas have been identified for improving human performance. These include: (1) simulation of acoustical environmental cues to enhance distance perception and reduce perceptual errors like front-back confusions; (2) simulation of acoustical cues induced by head and source-movements (e.g., via tracking devices) (3) understanding individual differences in HRTFs and identification of perceptually-relevant methods for modeling HRTFs to overcome such effects; (4) the use of feedback/training and super localization techniques to examine adaptation to auditory displays over time. Recently, NASA-funded studies have demonstrated the perceptual consequences of individual differences, the potential of using modeled HRTFs in place of measured HRTFs, and the usefulness of reverberation simulation to mitigate externalization errors. Less work has been done in the areas of training/adaptation and the potential benefits of dynamic motion cues.

### Research Needs

Critical features of reverberant environments (synthesis of early and late reverberation) must be parameterized in order to develop more powerful interactive, real-time hardware / software systems. For example, the number of early reflections that must be simulated to ensure realistic localization is unknown. Also, since the acoustic image gets larger (and therefore harder to localize) with increasingly reverberant environments, the trade-off between localization accuracy and realism must be determined.

In dealing with individual differences, several approaches are possible, including use of non-personalized HRTFs from people known to be good localizers, statistically-based models of HRTFs using techniques like principal components analyses, and structural models of HRTFs based on the physical shape of the ear/body structures. Such techniques can potentially drastically reduce the computational overhead during spatial synthesis. However, perceptual validation studies are necessary to ensure that localization accuracy remains acceptable in all of these cases before implementation in a hardware system.

Simulation of dynamic cues from both head and source-motion implies special problems for hardware and software development, including determining required update rates and methods for interpolating between measured or modeled HRTFs; these need to be evaluated in perceptual studies to determine the optimal methods and hardware specifications.

Finally, most current studies use relatively naive subjects and may be underestimating users' ability to localize virtual sources. Studies are needed to examine the localization ability of trained subjects since users of VE systems are likely to be highly-trained in many applications. Super localization or the artificial enhancement of localization cues that is made possible by a virtual system may also be of use.

### VE System Requirements

Reverberation synthesis:	Determination of perceptually-relevant cues.
Individual differences:	Design HRTFs useful for the general population.
Dynamic cue simulation:	Develop and evaluate interpolation and sound movement algorithms.
Training & super localization:	Measure how human performance with virtual acoustic display improves with training and/or additional cues to enhance localization.

## Virtual Acoustic Displays: Issues for Audio Communications

### Background

A 3-D auditory display can provide a listener with the sound source separation that occurs in normal, binaural hearing. Radio communication personnel (e.g., those in shuttle launch operations) must frequently monitor more than one communication stream simultaneously, over a single earpiece. This combination of signals at one ear leads to difficulties in segregating sources, and requires a desired signal to be transmitted louder than would be necessary with two ears for an equivalent level of intelligibility. This is also true for a single communication source heard against background noise. Louder levels result in increased fatigue during long-term exposure, thereby diminishing safety.

The 3-D auditory display separates input radio communication streams as if they were actual sound sources heard in a real room from different places. The importance of harnessing this binaural advantage has been recognized in, e.g., hearing aid development, but practical implementation within radio communication systems has been lacking.

### State of Knowledge / Technology

Methods for implementing 3-D sound displays using computer platforms such as the IBM-PC have been under development since the 1980s. However, these systems are too cumbersome for most aeronautical and space applications. Recently, a self-contained device with non-volatile, interchangeable memory was developed at Ames for use at Kennedy Space Center that spatializes four sources. An intelligibility gain of 6-7 dB was measured for identification of call signs against a background of multiple speaking voices.

### Research Needs

While studies have been conducted that evaluate the optimal position of one signal vs. noise, additional studies aimed at understanding perceptual segregation are needed to determine the optimal positioning of multiple sources, and the relationship between number of sources and intelligibility. Another need involves hardware/firmware requirements. Some progress has been made in simplifying spatial cues so that smaller, faster firmware/hardware can be developed. However, additional miniaturization (from 19" x 22" x 2") is desirable for some applications. Hardware development for concurrent radio/telephone interfaces is also desirable. Perceptual studies on the relationship between available frequency response from the particular communication system used and the effectiveness of the technique are necessary. Finally, determining the optimal set of headphones/headsets for a given application is a fundamental requirement. This could include combining this technology with active noise reduction techniques.

### VE System Requirements

HRTFs:	A limited set of HRTFs usable for the intended user or group, optimized around (1) usable communication frequency response, and (2) positions most useful for increasing intelligibility. While only a limited set of HRTFs are needed, obviating the need for computer interface, these should be interchangeable rather than hard-wired.
Communication system interface:	Isolated (low-cross talk) sources must be obtained from the interface, with consideration of incoming frequency response. "Fail-safe" design necessary for operational use. User ability to control levels, distribution of sources, and talk-back. When necessary, ability to take radio, telephone, warning system, active noise cancellation, and situational awareness audio simultaneously.
Headset:	Stereo headsets that are acceptable to communication personnel, and that allow simultaneous monitoring of surrounding ambient conversations, while (possibly) equipped with active noise cancellation technology.

## Virtual Acoustic Displays: Spatial Orientation and Situational Awareness

### Background

The auditory system as an alternative or supplementary information channel for situational awareness -- the identification and localization of external objects -- has great potential in both virtual reality and head-up applications. In contexts where considerable demand is made on the visual modality, spatial hearing via 3-D sound displays allows either additional channels of information to be conveyed, or acts as a positive "redundant" source of information to a visual display to reduce the potential of error.

### State of Knowledge / Technology

Methods for measuring the head related transfer functions (HRTFs) necessary for 3-D sound simulation have been under development since the 1970s. Measurement techniques are time consuming and usually require anechoic environments. Data on perceptual performance related to the use of 3-D sound for situational awareness has only begun since the mid-1980s. This research has shown that judgments of the location of virtual sound sources are reasonably close to judgments made in normal hearing, except for greater magnitude of reversals and distance errors (see "needs", below). The usefulness of these cues in current situational awareness implementations have been already demonstrated at Ames; e.g., a 3-D auditory TCAS display significantly reduced head-up target acquisition time in a flight simulator study.

### Research Needs

Current results show a higher magnitude of perceptual errors with simulated 3D sound, compared to real-world spatial hearing. This includes image reversals (front-back or back-front) and distance errors, including hearing sound within the head. Other perceptual errors sometimes show up in the form of overly high azimuth misestimation for certain positions, and inability to process vertical cues. These needs are being currently addressed by research into (1) a more complete representation of the acoustic environment via reverberation cues, (2) the use of head-tracker interfaces for simulating head-movement, (3) HRTFs that are perceptually validated for a large proportion of the general population, and (4) methods for quickly measuring "custom" HRTFs.

Another need involves hardware/firmware requirements. Some progress has been made in simplifying cues so that smaller, faster firmware/hardware can be developed. Two recent studies suggest that simplified HRTFs are as perceptually salient as actual measurements. However, an important need is to derive, then simplify, the methods for determining essential localization cues that would be useful for the general population, or for a particular individual.

### VE System Requirements

Perceptual validation:	A set of HRTFs usable for the intended user or group; knowledge of the potential localization error with the intended sound source. This includes knowledge of azimuth/elevation error, reversals, etc.
Head tracking, interpolated HRTFs:	Necessary depending on the particular application. Method for interpolation must be evaluated.
Auditory cue set:	The signals to be input to the display should be designed to be easily localizable: fast attack transient envelope, broad band spectrum.
Reverberation synthesis:	Necessary for externalizing sound sources; could potentially mitigate front-back errors.
Coordination with visual modality:	Requires further investigation- possible exaggeration of auditory space in relation to visual space may be necessary.

## Virtual Acoustic Displays: Synthesizing Non-Spatial Auditory Cues

### Background

While spatial cues are clearly a critical aspect of virtual acoustic displays, very little attention has been devoted to what the inputs to spatial sound systems must be. Non-speech sounds can provide a rich display medium if they are carefully designed with human perceptual abilities in mind. Just as a movie with sound is much more compelling and informationally-rich than a silent film, so will a VE be enhanced by an appropriate "sound track" to the task at hand.

One can conceive of the audible world as a collection of acoustic "objects". In addition to spatial location, acoustic features such as temporal onsets and offsets, timbre, pitch, intensity, and rhythm, can specify the identities of acoustic objects and convey meaning about discrete events (auditory icons representing object collisions or feedback for dataglove gesture-recognition), ongoing actions (data sonification/representation of airflow in a virtual wind tunnel), and their relationships to one another. The ideal synthesis device would be able to (1) flexibly generate the entire continuum of acoustic features for multiple, simultaneous sources, and (2) continuously modulate acoustic parameters associated with these sounds in real-time in response to ongoing events.

### State of Knowledge / Technology

Some basic principles for design and synthesis of non-spatial acoustic features can be gleaned from the fields of music, psychoacoustics, and higher-level cognitive studies of perceptual organization. Recently, a few studies have addressed methods for analytically modeling environmental sounds such as propellor cavitation, breaking or bouncing objects, and walking sounds, and structurally-based models of source characteristics like radiation patterns.

Current devices available for generating nonspeech sounds are based almost exclusively on MIDI (Musical Instrument Digital Interface) technology and tend to fall into two general categories; "samplers", which digitally store sounds for later real-time playback, and "synthesizers", which rely on analog or digital sound generation techniques originally developed for imitating musical instruments. With samplers, many different sounds can be reproduced (nearly) exactly, but substantial effort and storage media are required for accurately pre-recording sounds and there is usually limited real-time control of acoustic parameters. Synthesizers are more flexible in the type of real-time control available but less general in terms of the variety of sound qualities that can be generated. Potential disadvantages of both are that they are not specifically designed for information display and require specialized knowledge of musical/production techniques. A few systems using off-the-shelf devices have been integrated with spatial sound for VEs and some designers are developing systems for data visualization or "sonification".

### Needs

Sound-generation technologies specifically aimed at information display, including generalizable, analytical and structural models of source characteristics, need to be developed. More critical need is for research into lower-level sensory and higher-level cognitive factors that allow humans to organize the intermixed streams of sound that make up the acoustic world into individual, comprehensible objects. For example, there is little or no research available on how humans identify, segregate, and localize more than two simultaneous sources. Also, seemingly independent acoustic features/parameters like pitch and intensity can interact in unexpected ways so that what was intended to be two sound sources can appear to be a single source. Understanding of such effects is critical for designing and using synthesis devices.

### VE System Requirements

Number of sources	7 +/-2 simultaneous sources--short-term memory probably limits the number of sources that can be processed at once by human users.
Multiple-source perception	largely unknown; perceptual and cognitive studies needed to provide design guidelines.
Flexible synthesis techniques:	not yet available; initially "hybrid" sampler/synthesizer systems designed for information display can be built; generalizable, analytical models of source characteristics need to be developed.
Real-time parameter modulation:	> 31.25 Kbs; MIDI baud rate inadequate for multiple-source control; required speed and number of parameters depends on perceptual research outcome.

## Virtual Acoustic Displays: Issues for Hardware/Software Development

### Issue

The primary issues for improved 3-D auditory displays lies in digital signal processing (DSP) hardware and software, and headphone and head-tracking interfaces. Issues related to the head-related transfer function (HRTF), the key data component to the simulation, are particularly relevant.

### Status

Two primary hardware devices have been developed through Ames to date. The first is the Crystal River Engineering *Convolutron* family of devices, which are used primarily for situational awareness and psychophysical research. These are characterized by (1) utilization of a host computer platform, (2) capability of spatializing multiple inputs to anywhere in 3D space, albeit with concurrent degradation of HRTF with increasing number of sources; (3) capacity for interpolation; (4) *Polhemus* head tracker interface; (5) analog input and output. The second device, an Ames prototype, is designed for radio communications; it uses no head tracking interface or host computer, and is not capable of more than 4 (selectable) fixed spatial positions.

### Needs

Since the DSP capability of any device is finite, research into how to reduce the amount of data used to represent HRTFs used is very important for (1) designing less expensive virtual acoustic displays, and (2) allowing for allocation of DSP resources to issues such as simulation of reverberant environments (critical for source externalization and overall veridicality). For example, reverberation simulation currently requires large scale, expensive hardware, and is designed to approximate physical parameters. However, research into identifying the perceptually salient features of reverberation will most likely allow relaxation of the of physical modeling parameters, thereby freeing DSP resources for other chores. Increasing DSP resources also allows for the possibility of including "custom tailoring" routines into virtual acoustic displays, such that users could either 1) alter a display to their preferences for optimal localization, or 2) allow measurement and storage of individual HRTFs. The latter will be facilitated by redesigning systems around floating point signal processing chips, rather than the fixed point chips currently in use.

The nature of communication and simulation systems will become increasingly digital in all aspects, including fiber optic transmission, all-digital mixing and processing, and digital interconnectivity-- analog interfaces will exist only at the terminus point of the system. Hence, it is essential that existing devices be modified in the future to accommodate the range of digital interfaces currently in use (e.g., AES-EBU). This also will require enhancement of devices to take full advantage of the > 90 dB signal/noise ratio available on 16-bit digital audio systems. Interface connectivity will also require redesign as tracker technology, which is currently in its infancy, develops and offers new methods of transmission. The trackers themselves suffer from magnetic field distortion, cumbersomeness, and speed; more often than not, the weak link of a virtual acoustic display is the interface between tracker technology and sound spatialization software. Hence, virtual acoustic displays shall require modification as better trackers are developed. For communication system displays, size and portability are important considerations for applications such as manned space missions; research into miniaturization and reducing power supply demands are essential. Size is also a consideration in applications such as test director consoles. Finally, research into stereo headsets acceptable to communication personnel may be necessary

### VE System Requirements

DSP platform:	Should allow (1) data reduced HRTFs; (2) reverberation simulation; (3) HRTF measurement capability; (4) real-time floating-point DSP.
miniaturization	Size and power requirements should be minimized.
system interface:	Non-cumbersome head trackers; allowance for digital I/O; stereo headsets usable by communication personnel; means for customizing HRTFs.

## Host Computers

### State of Knowledge/Technology

Current VE host computers range from relatively inexpensive personal computers, with add-on graphics and video boards, to expensive, high performance graphics workstations. Most VE's are currently built with polygons, so transformation of polygons is the dominant processing capability. The use of texture maps adds visual detail at less computational cost than reliance upon polygons alone, so system support for texture maps is increasing. A high-end system can produce 7000 small, anti-aliased, textured polygons per graphics pipeline at 30 Hz. This system can provide 380 128 x 128 simultaneous textures, with a maximum texture size of 1024 by 1024 texture elements. Renderers are designed to fill workstation screens with images of uniform resolution. Pipelined graphics systems with their inherent latency (e.g. 50 milliseconds on one high-end system) dominate the scene, but efforts to reduce this latency are making some progress in graphics hardware architecture research labs. Parallelism in most VE host computers is limited to, at most, a few parallel processors, but new highly parallel graphics architectures are being developed. Massively parallel processors (MPPs), currently the domain of supercomputers (sustained processing rates of a trillion floating point operations per second are expected by the year 2000), are being applied a few very high-end (and very costly) VE systems. Although much is being written about fully integrating video and audio into information systems of all kinds, including VEs, this effort is far from reaching its goals. Further, image processing systems and graphics systems, which are slowly coming together in medical VE systems, still remain far apart in design, emphasis, and interactivity.

### Research Needs

Human performance research is needed to characterize, to the greatest extent possible, the parallelism inherent in user-environment-system interactions, for all target applications, in order to map the problem to the MPP-based VEs of the near future.

Human performance research is needed to determine the texture map sizes necessary to support user visual/informational requirements for applications that will benefit from VE. For example, virtual planetary exploration requires texture maps that are much larger than those provided by current systems. Analysis of the use of texture maps to support planetary exploration systems and users, and similar analyses in other applications, will provide essential guidance to VE system architects.

Human performance research is needed to determine the types of data required for human visualization of complex systems and phenomena, and the relationships among those data types, in each application domain of interest, as guidance for the design of multimedia VE architectures.

### VE System Requirements

Systems must provide a capability to texture map planet sized objects at centimeter resolution, if not by brute force of massive memory, then by means which give the user the appearance of continuous mapping in real-time.

In order to effectively utilize the hundreds and even thousands of parallel processors of MPPs for VE, toolkits based on human performance research must be developed that can extract the parallelism inherent in VE applications.

Renderers must be specifically optimized for use with head mounted displays for VE systems. For example, rendering based on human vision would put more detail in the center of the image and less toward the periphery. When there is no eye-tracking, a "pseudo-fovea" of plus or minus 15 degrees containing high detail, with a fall off of detail toward the periphery, would be appropriate to support HMD use. This is so because humans typically make eye movements of plus or minus 15 degrees from straight ahead, and will typically turn their heads as necessary in order to look beyond that. Thus, rendering to support HMDs is very different than that to support desktop workstations, and must be optimized accordingly.

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## Networks

### State of Knowledge/Technology

Local area networks (LANs) and wide area networks (WANs) are becoming increasingly central to computing and communications, and there is much research being done to increase network capability and accessibility. Distributed and shared VEs, being developed in research labs, will benefit from high speed networks. The Broadband Integrated Service Digital Network (B-ISDN), an emerging telecommunications standard, will provide user-to-user bandwidths of 10's of millions of bytes per second, with total bandwidths of perhaps hundreds of billions of bytes per second. Access to Internet, the world's largest computer network, is rapidly increasing. While shared quasi-VE's via Internet do not provide a sense of presence, the information sharing capability provided by Internet is already providing forums for discussions and announcements regarding VE ("virtual communities in cyberspace"), and collections of free VE models and toolkits. Despite these pioneering efforts, use of networks for collaborative sharing in support of VE is largely underdeveloped.

While raw speed and interconnectivity of networks are increasing, to the benefit of VE research and development, some difficult organizational and social issues are similarly on the rise. The openness of Internet raises competitiveness issues that cause concern to some. For example, some institutions which are unaccustomed to, or uncomfortable with, the implications of widespread network communications are actively discouraging information sharing on Internet. As access to network resources is increasing, many fundamental social issues are also being raised (e.g. copyrights, rights to information access, protections of privacy). For example, research into practical matters of dealing with the information glut, such as through the use of information filters, is based in part on modeling or profiling the interests and access patterns of users. As distributed VEs enable complex user behaviors or highly targeted data searches, access to user interaction profiles will have vast implications for marketing, privacy, and security.

### Research Needs

Human performance research is needed to determine the network performance requirements, and the implications of communication latencies, for a wide variety of VE capabilities and applications, including both distributed VEs and network-supported VEs.

The lessons learned from research on SimNet (the DOD's distributed battle simulation system) and its successors, as well as from the current research in networking heterogeneous military simulators, need to be made readily available to the VE community. This will greatly benefit the utilization of available and future network capability for application to general purpose VEs, and foster commercial development.

### VE System Requirements

Network-based VE systems require network bandwidths sufficient for establishing a sense of presence created from all essential forms of user domain data, including digital models, static and dynamic imagery, voice, etc., for a wide variety of applications.

VE resources such as models, worlds, toolkits, need to be distributed via large area networks.

Policies of participating institutions regarding access to and use of networks for VE need to be brought into alignment with technological capabilities.

Social issues of networks and VEs must be widely discussed and debated, consensus must be reached, system-safeguards must be implemented, and regulations must be legislated.

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## Models, Imagery, and Other Data

### State of Knowledge/Technology

Virtual environments are currently built of digital models of things and phenomena, along with means to represent them to human perception. A room, for example, can be represented as a collection of numerically defined geometric shapes. The wind over a wing can be indicated as string-like objects consisting of short line segments whose endpoints have numerical coordinates. A photo can be texture-mapped onto a shape, or a sound associated with an object behavior. Users themselves could be extensively modeled within a VE, although only very limited user modeling is currently done. Use of data from various disciplines, such as planetary exploration, computational chemistry, anatomy, and fluid dynamics provides some very realistic models, though these are not always well suited to VEs. Models created explicitly for VEs, however, are typically primitive, "hand crafted", and far from comprehensive in their representation of the thing or phenomenon modeled. One reason for this is that the limits of available computing power and the need for an acceptable update rates combine to limit the model complexity that can be presented. Another reason for the current limitations of VE models is that object/environment scanning and computer aided design tools for VE are underdeveloped. The integration of the many kinds and formats of models, imagery, and data is hampered by the large number of incompatible formats. Although some small companies have begun to provide "3D clip objects", analogous to 2D clip art, there is no significant marketplace of virtual objects. Some objects and data appropriate for VEs are available for free on Internet. Representation and processing of the behaviors and other non-geometric characteristics of digital entities in VEs are currently underdeveloped.

### Research Needs

Human performance research is needed to understand user domain requirements for utilizing models/data. This would provide, for example, an understanding of how large terrain models must be subdivided. It would also guide the development of methods for real-time traversal of virtual terrain that involves multiple data files. This research would also provide an understanding of how disparate forms of data are related to each other by the user in each of the studied user domains.

Artificial intelligence research is needed to enable automated scanning of physical environments, automated differentiation of individual objects, intelligent attribution of object characteristics and behaviors, and automatic archiving.

Computer graphics research is needed that will enable virtual objects to show the effects of use over time, such as wear, and modifications comparable to those available with real world objects. Research is also needed to enable these and all other VE model characteristics to be modifiable in real-time.

### VE System Requirements

Tools and techniques are needed that can rapidly digitize environments and intelligently differentiate individual objects.

Readily accessible collections of hierarchical geometric and behavioral models are needed. These collections should be accessible via network. It should be possible to add new models easily and to search the archive rapidly for models needed by specific applications. Methods and systems are needed to enable archival objects to be modified, customized, and personalized.

Standards are needed among model formats to enable sharing and to eliminate expensive, ad hoc model development.

Models must have capacity for individualization, and the unique marks of use over time.

It should be possible to integrate all forms of data and models, for example, to map live or recorded video with sound onto polygons within a VE.

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## Software Tools

### State of Knowledge/Technology

Several toolkits are available for the creation and management of VEs. High-end tools such as SGI's Performer help with real-time simulation by providing a library for optimizing rendering functions, efficient graphics state control, and other functions. Performer also provides a visual simulation application development environment which provides multichannel and multipipeline capability; parallel simulation, intersection, cull, and draw processes; hierarchical scene graph construction and real-time editing; system stress and load management; level of detail model switching; fixed frame rate capability; and other features.

University and commercial toolkits are becoming available to support "virtual world creation", including Minimal Reality (MR) Toolkit from University of Alberta, WorldToolKit from Sense8, Cyberspace Development Kit from AutoDesk, and the IBM Virtual Reality Toolkit. These help to manage the various input/output devices, graphical objects, object interactions, and views. Some, like the IBM system, support distributed VEs.

3D "widget" toolkits are being developed in a few university research labs so as to go beyond 2D buttons, sliders, and other window-oriented control devices. The 3D widgets are intended to better support the virtual reality paradigm.

Computer aided software engineering (CASE) tools are commercially available to automate some of the manual activities of software engineering, to support adopted methodologies, and to improve quality and reliability. CASE tools are not yet widely used, however, and there are none specifically for VE. CASE tools require significant training, and there is no hard data indicating that they improve productivity. Since software development is so costly and complex, however, tools that improve the development process have significant appeal, and are undergoing intense development.

### Research Needs

Human performance research is needed that will serve to guide the development of user domain-based toolkits. Such research would include analysis of the commonalities among related user applications. In addition, joint human performance and computer science research will be needed to integrate graphical toolkits and user domain toolkits.

Human performance research is needed to advance content analysis of domain documentation, including voice transcripts, post-mission debriefings, formal reports, photographs, maps, and all other forms of domain data. This will provide guidance for the design of computer aided, object-oriented analysis toolkits to support the creation of application-oriented VEs.

### VE System Requirements

Using available toolkits, and network accessible geometric, behavioral, and user domain models, a knowledgeable individual should be able to create a useful prototype of an application-based VE in one week. A team of graphics and user domain analysts should be able to refine the VE for initial use by domain users within a month. It should be possible to complete a final production system within 60 days. Further, it should be possible to make the necessary modifications to meet changing user requirements with a minimum of effort. Ultimately, users should be provided with toolkits that will enable them to develop and enhance their own specialized VEs.

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## Domain Analysis and Design

### State of Knowledge/Technology

User domain analysis and user domain based design are critically important for the development of useful VEs, but are currently underdeveloped. Instead, the current emphasis in most VE work is on graphical techniques and hardware integration. There is little if any literature on the spatial, environmental, and informational interaction requirements of the many user domains for which VEs are claimed to be needed. Further, the role of presence and virtual presence in these user domains is largely unexplored. While extensive literature exists regarding remote operations of robots, only recently have the elements of operator sensory immersion, presence, and virtual presence been explicitly addressed. Object-oriented analysis (OOA) and design (OOD) methods, which are still under development, are being widely discussed and refined in the computer science literature. Some VE projects are beginning to apply and extend these methods by incorporating field observation techniques derived from ethnographic field methods. The application of object-oriented techniques promises to provide analyses that can easily be incorporated into VE design, and designs which are easily understood, extended, and reused. Traditional "task analysis" is related to this activity by the common interest in humans as a component in "human-machine systems". The emphasis of task analysis, however, is very different from that of the object-oriented approach in that task analysis is procedure-oriented, concentrating on actions. By concentrating on objects, the object-oriented approach seeks to find the relatively stable structure on top of which any procedures might be layered. This lends stability and reusability to both analyses and designs that are unavailable to a procedurally oriented approach.

### Research Needs

There is a need for human performance research to analyze and model the informational and sensory components of the environments of domain experts (which are strictly relevant to their tasks) and the user-environment interactions, for applications that are to benefit from VE systems. These domain analyses must provide results in a form that can directly apply to VE system designs.

There is a need for human performance research to compare and contrast candidate VE user domains so as to extract the commonalities that might be profitably addressed by general purpose, commercial VE systems and toolkits. These cross-domain analyses must provide results in a form that can directly apply to VE system designs.

The mapping of real-world tasks to VE tasks introduces many degrees of freedom not available to the user in the non-virtual task environment. Accordingly, user domain analysis must not be limited to the real-world task as currently performed. Instead, human performance research is needed that provides a fundamental understanding of the user-environment relationships beyond the constraints of the current techniques, and these must be compared and contrasted to non-VE user-environment relationships, in order to demonstrate conclusively whether virtualization can benefit the user.

There is a need for human performance research to analyze and model the role of presence in proximal operations and the utility of a sense of telepresence in remote operations. User-environment relationships associated with presence and virtual presence in specific user domains must be analyzed, modeled, and documented in a form that contributes to VE analysis, design, and implementation.

### VE System Requirements

The results of user domain analyses must be structured so that they directly apply to VE system design. VE analyses and designs for VE systems must be reusable for a variety of applications related to the target domain.

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## Spatial Position/Orientation Trackers

### Background

Spatial trackers provide the VE system host computer and rendering software with the six degree of freedom position and orientation of various parts of the human operator's body with respect to "real" space. Trackers attached to the head permit the correct orientation and positioning of visual or audio scenes within the display hardware. Trackers on the hand allow gestural and pointing modes for manual interaction with the VE.

### State of Technology

A number of spatial sensor technologies are currently available in commercial quantities at reasonable prices. The first type of sensors are "non-contacting" devices based on measurement of either electromagnetic, ultrasound, or optical emissions, where the only encumbrance to the user is the electrical cable to transfer power signal from the component worn by the human user. The second type of sensors are "contact" devices that couple the body segment of interest to the a fixed point by a mechanical linkage that is instrumented by position transducers.

Some of the drawbacks associated with the various technologies include:

Cumbersome weight and inertia for some larger portable non-contact sensor components and all mechanical linkage devices

Limited range of travel due to transmitter strength for non-contact technologies and linkage length for contact devices.

Line-of-sight and other obstructions near or between sensor and transmitter pairs—by any object optical and ultrasound devices and metallic objects for electromagnetic ones—which can spatially distort or even completely eliminate measurements.

Unexplained systematic distortions in reported spatial measurements that require elaborate and time consuming calibration and correction procedures. [1]

Excessive time delays from on-board processing and data transfer to host computer [2, 3].

Noise (i.e., spurious time varying changes) in measurements returned by the sensors, due to presence of obstructions or other active energy sources in the "real" environment. Filtering, a common approach to noise reduction, however increases time delays [3].

### VE System Requirements

If the current dominant sensor technologies are to be used effectively and reliably for research and training purposes, the shortcomings listed above need to be addressed. At minimum detailed and accurate spatial and temporal calibrations need to be available so that tracker users can implement appropriate corrective measures, or at least be aware of limitations in data obtained with these devices.

Other sensor technologies (e.g., inertial and acceleration based schemes) that may not be as susceptible to some of the above problems need to be developed.

### References

1. Bryson, S., "Measurement and calibration of static distortion of position data from 3D trackers." in *Proceedings, SPIE Conference on Stereoscopic Displays and Applications III*, San Jose CA, 1992. SPIE paper 1669-09.
2. Adelstein, B.D., Johnston, E.R., and Ellis, S.R. (1992) A Testbed for Characterizing Dynamic Response of Virtual Environment Spatial Sensors." In *Proceedings of the Fifth Annual Symposium on User Interface Software and Technology*, (pp. 15-22). New York: ACM.
3. Liang, J., Shaw, C., and Green, M. (1991). On temporal-spatial realism in the virtual reality environment." In *Proceedings of the 4th Annual ACM Symposium on User Interface Software and Technology* (pp. 19-25). New York: ACM.

# Chapter 3: Brief Summaries of Virtual Environment Research and Applications Development at NASA

This chapter contains brief summaries of current research and development in Virtual Environment (VE) technology at NASA. The section is organized by center, and within a center by the name of the principal investigator. Descriptions include research objectives, current research status, future research plans and system configurations.

## Chapter Organization

### Ames Research Center

- Dynamic Response of Virtual Environment Spatial Sensors
- Head-Slaved Roll Compensation in Virtual/Remote Target Acquisition Tasks
- Interface Control Parameters for Effective Haptic Display
- 3D Auditory Displays in Aeronautical Applications
- The Virtual Windtunnel
- Measurement and Calibration of Static Distortion of Position Data from 3D Trackers
- Virtual Spacetime
- Human Performance in Virtual Environments
- Extravehicular Activity Self-Rescue in Virtual Environments
- Telerobotic Planning and Operational Interfaces
- Using Virtual Menus in a Virtual Environment
- Virtual Planetary Exploration Testbed
- Presence in Natural Terrain Environments
- Disparate Data Integration for Model-Based Teleoperation
- Simulating Complex Virtual Acoustic Environments
- Hearing Through Someone Else's Ears

### Goddard Space Flight Center

- Virtual Reality Applications in the Earth and Space Sciences

### Johnson Space Center

- Workload Assessment Using a Synthetic Work Environment
- Device for Orientation and Motion Environments (DOME) - Preflight Adaptation Trainer (PAT)
- Training for EVA Satellite Grapple
- Shared Virtual Environments
- Space Station Freedom Cupola Training
- Virtual Science Laboratories
- Realistic Lighting Models for Virtual Reality
- Improving Human Model Reach for Virtual Reality Applications
- Human Computer Interface Research for Graphical Information Systems

### Marshall Space Flight Center

- Macro-Ergonomics and Scaleable User Anthropometry
- Micro-Ergonomics: Virtual and Fomecor Mock-Ups
- Microgravity Mobility and Ergonomics

## Dynamic Response of Virtual Environment Spatial Sensors

Principal Investigator: Bernard D. Adelstein  
Co-investigator: Stephen R. Ellis  
NASA Ames Research Center

### Research Objective

To characterize the dynamic response of displacement transducers commonly used in VE applications.

### Status

A testbed and method for measuring the dynamic response characteristics of position and orientation sensors have been developed. The testbed consists of a motorized swing arm that imparts known displacement inputs to the VE sensor. The experimental method involves a series of tests in which the sensor is displaced back and forth at a number of controlled frequencies that span the bandwidth of volitional human movement. During the tests, actual swing arm angle, as determined by an optical encoder at the motor shaft, and reported VE sensor displacements are collected and time stamped. Because of the time stamping technique, the response time of the sensor can be measured directly, independent of latencies in data transmission from the sensor unit and any processing by the interface application running on the host computer. Analysis of these experimental results allows sensor time delay and gain characteristics to be determined as a function of input frequency. Results from tests on several different commercially available VE spatial sensors have been obtained and documented.

### Future Plans

Additional sensors will be tested. The test method and hardware will be extended to measure dynamic response of complete—i.e., end-to-end (sensor-to-display)—VE systems.

### System Architecture

Displays: na  
Input: Polhemus Isotrak, Polhemus Tracker, Polhemus Fastrak, Ascension Bird, Ascension Space Navigator (Big Bird Prototype), Ascension Flock of Birds, Logitech Red Baron. Custom built servo-motor swing-arm.  
Rendering: na  
Computation: IBM PC-AT  
Software: In-house

### References

1. Adelstein, B.D., Johnston E.R., and Ellis, S.R. (1992). A Testbed for Characterizing Dynamic Response of Virtual Environment Spatial Sensors. In *Proceedings of the Fifth Annual Symposium on User Interface Software and Technology*, (pp. 15-22). ACM, New York: ACM.
2. Adelstein, B.D., Johnston, E.R., Ellis, S.R. (1992). Spatial sensor lag in VE systems. In the *Proceeding of the SPIE Conference on Teleoperator Technology* (Vol. 1833). Bellingham, WA: SPIE.

## Head-Slaved Roll Compensation in Virtual/Remote Target Acquisition Tasks

Principal Investigators: Bernard D. Adelstein and Stephen R. Ellis  
NASA Ames Research Center

### Research Objective

To examine whether the addition of a head-slaved roll degree of freedom in a computer synthesized scene or in a camera platform assists human subjects in judgement of the planar position and planar orientation of objects in virtual or remote environments

### Status

It has been suggested that inclusion of the roll degree of freedom (dof) in either computer synthesized or remotely viewed scenes may improve situation awareness in tasks such as teleoperation. In this work, we examined whether the addition of a head-slaved roll dof in a camera platform assists human subjects in judgement of the planar position and planar orientation of objects in remote environments

Six subjects were required to match the position and orientation of a series of stationary target markers on a remote taskboard by manually placing similar response markers on an identical local taskboard. The subjects could only view the remote taskboard through a head mounted display (HMD) driven by the cameras on the platform. They could not see either the local board or their own limbs. The target locations spanned the full range of head azimuth for each subject and necessitated near maximal head elevation at maximum azimuth magnitudes.

The data show that the addition of head-slaved roll compensation to the platform had no statistically discernible effect on the ability of the subjects to match the position (*i.e.*, azimuth and elevation) of the remote targets. Nonetheless, systematic position errors were noted regardless of the roll condition. Absence of the roll dof, however, did affect the subjects' judgment of target orientation when their heads were at the peak attainable elevations for full magnitude azimuth rotations.

### Future Plans

Further target acquisition experiments requiring head azimuth-elevation-roll will be conducted in a VE. The objective of the work will be the development of minimum kinematic degrees of freedom models of head motion.

### System Architecture

Displays: VPL EyePhone HMD.  
Input: Acension Space Navigator (Big Bird prototype). Fake Space Molly three degree of freedom stereo camera platform.  
Rendering: na  
Computation: IBM PC-AT  
Software: In-house

### References

1. Adelstein, B.D., and Ellis, S.R. (1993, October). *Effect of Head-Slaved Roll Compensation on Remote Situation Awareness*. To be presented at 37th Annual Meeting of the Human Factors and Ergonomics Society, Seattle WA.



## Interface Control Parameters for Effective Haptic Display

Principal Investigators: Bernard D. Adelstein  
Co-investigators: Louis Rosenberg (Stanford University)  
NASA Ames Research Center

### Research Objective

To understand the mechanical impedance and digital (i.e., discrete time) control requirements for effective presentation of haptic information through force reflecting interfaces.

### Status

A haptic or kinesthetic virtual environment VE incorporates two principal components—the computer model (i.e., algorithms or equations) describing the physical dynamics of the objects in the VE and the interface hardware that allows the human to interact with the VE. Because a haptic interface uses the same piece of hardware serves as both control output and sensory input for the human operator, information transfer entails significant bidirectional mechanical power flow. Thus to optimize information transfer to the human, physical power flow must be modulated by selecting the appropriate impedance (i.e., mechanical characteristics) for the interface.

In this work we are conducting psychophysical experiments to see how interface computer control parameters affect haptic perception. Parameters of interest are controller sample-and-hold update rates and phase lag—features akin to screen refresh rates and persistence in CRT video displays.

### Future Plans

Examine how intrinsic mechanical properties of the interface such as friction, inertia, and compliance affect haptic perception of virtual objects.

### System Architecture

Displays:	Custom built two degree-of-freedom force reflecting joystick
Input:	Custom built two degree-of-freedom force reflecting joystick
Rendering:	na
Computation:	i486DX-50
Software:	In-house

### References

1. Adelstein, B.D., and Rosen, M.J., Design and Implementation of a force reflecting manipulandum for manual control research. In H. Kazerooni, (Ed.), *Advances in Robotics, DSC-Vol.42*(pp. 1-12). New York: American Society of Mechanical Engineers.
2. Rosenberg, L.B., and Adelstein, B.D. (1993, October). *Perceptual Decomposition of Virtual Haptic Surfaces*. Submitted to IEEE Symposium on Research Frontiers in Virtual Reality, San Jose.

## 3D Auditory Displays in Aeronautical Applications

Principal Investigator: Durand Begault  
 Co-investigator: Elizabeth Wenzel  
 NASA Ames Research Center

### Research Objective

The purpose of the research is to implement and test auditory display concepts which will allow a pilot, crew member, or ATC controller to immediately, accurately, and inexpensively monitor three-dimensional information, such as traffic location, through the use of a virtual acoustic display.

### Status

Hardware has been designed and implemented for experiments in the following areas: spoken audio warning system signals, TCAS (Traffic Collision Avoidance System) advisories, and cockpit radio communications. The TCAS traffic advisory consists of the spoken word "traffic". The actual position of the traffic is usually obtained visually, through instrument monitoring and/or out the window acquisition. In the ACFS flight simulator, the out-the-window position of the traffic is linked to the virtual auditory position of the word "traffic" heard through headphones. A pilot experiment was recently completed to determine if the time interval for traffic acquisition is reduced when binaural sound delivery is used to suggest the direction for head-up visual search of the target, compared to monotic (single ear piece), normal practice conditions. Results showed that there was a 2.2 second improvement in acquisition time. An experiment currently under development pits a normal TCAS visual display against a 3-D auditory and visual head-up display. For communications, a 3-D sound hardware system can place various radio communication streams (e.g., ATIS, ATC, VOR) in separate virtual auditory positions around the pilot. The purpose of the system is to allow greater intelligibility against noise, or in situations where more than one frequency must be monitored, such as in the vicinity of an airport. Preliminary investigations have shown a 6-7 dB intelligibility improvement over monaural systems.

Basic research in the area of human headphone localization is also underway that supports these applied research efforts. A study was completed that compared inexperienced listeners' headphone localization of speech to previous studies using noise. Another study was completed that used artificial spatial reverberation to increase the veridicality of the 3-D sound display. Another study determined that there was no perceptual degradation when using a 20:1 data reduction of the filter parameters used in the 3-D sound display hardware.

### Future Plans

Additional experiments involving target acquisition and speech intelligibility are planned.

### System Architecture

Displays: Stereo headphones.  
 Input: Polhemus, 4 analog sound sources  
 Rendering: Convolvotron, Yamaha TX-16W  
 Computation: 386 PC, Mac II cx (non-real time)  
 Software: Custom.

### References

- Begault, D. R., & Wenzel, E. M. (1992). Techniques and applications for binaural sound manipulation in human-machine interfaces. *International Journal of Aviation Psychology*, 2(1), 1-22.
- Begault, D. R. (In press). A head-up auditory display for TCAS advisories. *Human Factors*.
- Begault, D. R. (In press). Call sign intelligibility improvement using a spatial auditory display. *NASA Technical Memorandum*. Moffett Field, CA: NASA Ames Research Center.

## The Virtual Windtunnel

Principal Investigator: Steve Bryson  
Co-investigators: Creon Levit, Michael Yamasaki  
NASA Ames Research Center

### Research Objective

To make possible the visualization and exploration of three-dimensional CFD solution datasets in a natural and efficient manner. To explore the applicability of VE technology to numerical flow visualization.

### Status

A VE for the exploration of three-dimensional numerically generated flow fields has been implemented. The analogy is to a wind tunnel, with the user able to move freely about the flow, injecting "virtual smoke" into the flow to make it visible, and yet not disturbing the flow in any way. The current environment allows the exploration of large single-grid three-dimensional steady flow fields or small single-grid three-dimensional unsteady flow fields. The environment supports several numerical flow visualization techniques including streamlines, streaklines, particle-paths, and tufts. Collections of tools that generate these flow visualizations may be repositioned or reoriented in the flow in real-time. Time can be frozen for detailed exploration of complex spatial structures. A new version of the software has been written that uses a convex minisupercomputer for memory-intensive and compute-intensive tasks, but still uses the IRIS workstation for rendering and display.

### Future Plans

The system is being extended to handle a larger class of engineering flows. This involves support for multiple zone grids and large disk-resident unsteady flows on the convex. The software is also being enhanced to support multiple users exploring the same flow together in real time. A new generation of hardware, namely the Fake Space Labs BOOM IIC high-resolution two-color display and Silicon Graphics dual-pipe Skywriter are being integrated into the virtual windtunnel.

### System Architecture

Displays: Fake Space Labs BOOM II and BOOM IIC  
Input: VPL dataglove model 2, Polhemous, keyboard, mouse  
Rendering: Silicon Graphics 380 VGX  
Computation: Silicon Graphics 380 VGX, Convex C-240  
Software: In-house

### References

1. Bryson, S. and Levit, C. (1991). A Virtual Environment for the Exploration of Three Dimensional Steady Flows. In S. Fisher (Ed.), *Stereoscopic Displays and Applications II*. SPIE conf. proc. v. 1457. SPIE.
2. Bryson S. and Levit, C. (1991). The Virtual Windtunnel: An Environment for the Exploration of Three-Dimensional Unsteady Flows. In *Proc. IEEE Visualization '91*, San Diego, CA. IEEE Computer Society Press.
3. Bryson S. and Yamasaki M. *The distributed Virtual Windtunnel* (Technical report RNR-92-010). April 1992. Moffett Field, CA: NASA Ames research Center.

## Measurement and Calibration of Static Distortion of Position Data from 3D Trackers

Principal Investigator: Steve Bryson (Computer Science Corporation)  
NASA Ames Research Center

### Research Objective

To characterize the accuracy of the position sensitivity of trackers commonly used in VE systems. To study various methods for correcting the deficiencies in their accuracy.

### Accomplishment Description

Three-dimensional trackers are becoming increasingly important as user inputs in interactive computer systems. These trackers give the position of a sensor in three-dimensions. If the tracker were perfect, the position returned by the tracker would exactly correspond to the position of the sensor in appropriate coordinates. In reality, trackers fail to be perfect. Distortions are introduced into the tracking data so that the position returned by the tracker only loosely corresponds to the actual position of the sensor, and then only with a limited volume of space. This distortion is typically a function of the sensor's distance from some source, and is dependent on the ambient environment. If this distortion is constant in time, it can be measured and the actual position of the sensor can be inferred from the distorted data. This is called calibrating the tracker.

Detailed measurements have been made of the tracker output for a known set of tracker positions. These known tracker positions fill a volume of space with a resolution of 12 inches. Using these measurements, the distortion of the tracker data has been determined. Calibration methods that partially correct for the distortion have been implemented. These measurements have been performed on a Polhemus Isotracker, an electromagnetically based tracking system that provides three-dimensional position and orientation of a sensor. The measurements have been taken twice within the same location and at different locations to measure the dependence of the distortion on the ambient electromagnetic environment.

Study of the noise and repeatability imply limits on calibration success. When tracking greater than 50 inches from the source, the tracking signal is so noisy that no useful calibration can be expected. Inside this distance, repeatability implies a limit of about an inch in calibration accuracy. Both 4th order polynomial calibration and bump lookup calibration perform close to these limits.

### Future Plans

Further study in the calibration question can proceed in two obvious directions. The success of polynomial and lookup calibrations suggest that a three-dimensional spline calibration, a combination of global polynomials and lookup tables, should work quite well. Lookup calibration requires more study of the weighting and interpolation question. The bump lookup calibration method fails for overly distorted data sets and can be refined.

This research addresses only static position calibration. These trackers also produce orientation data, and the study of distortion in the calibration should be performed.

### References

1. Bryson S. (1992). Measurement and Calibration of Static Distortion of Position Data from 3D Trackers. In S. Fisher (Ed.), *Stereoscopic Displays and Applications 3*. San Jose, CA: SPIE.

## Virtual Spacetime

Principal Investigator: Steve Bryson (Computer Science Corporation)  
NASA Ames Research Center

### Research Objective

To make possible the visualization and exploration of the curved spacetime of general relativity. To explore the applicability of VE technology to numerical relativity

### Status

A VE for visualizing the geometry of curved spacetime by the display of interactive geodesics has been implemented. This technique displays the paths of particles under the influence of gravity as described by the general theory of relativity, and is useful in the investigation of solutions to the field equations of that theory. A boom-mounted six degree of freedom head position sensitive stereo CRT system is used for display. A hand position sensitive glove controller is used to control the initial positions and directions of geodesics in spacetime. A multiprocessor graphics workstation is used for computation and rendering. The system has been tested by visualizing the several well-known solutions to Einstein's field equations using a variety of techniques. Currently the system has been implemented only for spacetimes whose geometry data are available in closed form formulas and for spacetimes whose data are on simple static computational grids. While this work is intended for researchers, it is also useful for the teaching of general relativity.

### Future Plans

There are interesting spacetimes whose metrics are available as exact formulas. Incorporation into virtual spacetime should be straightforward. Examples include the classical Godel solution, Bianchi type IX cosmological solutions, and a metric describing collapsing dust or photons. A more difficult problem is including the results of computational spacetime simulations such as those describing colliding black holes, collapsing stars, and gravitational waves. There has been considerable interest expressed by the computational spacetime group at the National Center for Supercomputing Applications (NCSA) in Urbana, Illinois in using virtual spacetime to view the results of their computations. We are currently developing a collaboration for this purpose with Ed Seidel and Larry Smarr. Problems addressed by this collaboration include: the meaning of the coordinates used for the numerical simulation and how these coordinates should be mapped into the virtual space, developing an interpolation scheme to compute geometry data from the computational grid that is fast enough to allow real-time computation of geodesics; and managing the very large amounts of data that are the products of these unsteady spacetime computations. The data and speed problems are similar to those that arise in the virtual windtunnel. Distributing the computation to a supercomputer over a high-speed network may be necessary.

### System Architecture

Displays:	Fake Space Labs BOOM II and BOOM IIc
Input:	VPL dataglove model 2, Polhemous, keyboard, mouse
Rendering:	Silicon Graphics 380 VGX
Computation:	Silicon Graphics 380 VGX, Convex C-240
Software:	In-house

### References

1. Bryson, S. (1992). *Virtual Spacetime: An environment for the Visualization of Curved Spacetimes via Geodesic Flows* (Technical report RNR-92-009). Moffett Field, CA: NASA Ames research Center.

## Human Performance in Virtual Environments

Principal Investigator: Stephen Ellis  
Additional Investigators: M. Tyler, W. Kim, L. Stark (UC Berkeley)  
NASA Ames Research Center

### Research Objective

Using standardized human manual control tasks, develop and assess techniques to study perceptual phenomena that depend upon presentation of a convincing, visually enveloping, spatial illusion

### Status

The manual control task that has been studied in a VE is a version of a three-dimensional tracking task that has been used extensively in the study of human performance with panel mounted, three dimensional displays. In the current work this task has been used to measure human manual control plasticity as display control misalignments were introduced between the head-mounted display and the coordinates of a hand-mounted 6-degree of freedom position tracker. The subject's basic task was to move the position sensor on his/her hand to cause a virtual 3D cursor, viewed via the stereo, head-mounted displays, to track a small target that moved irregularly in three dimensions in front of the subject. In contrast to some results in the tracking literature, subjects demonstrated the capacity to learn to perform this task with display control misalignment ranging from 0 degrees to 180 degrees. With several hours practice during one day, subjects could learn to perform the task with nine different display control misalignments. [1]

The perceptual phenomenon studied was the influence of visual stimuli on the perception of gravity-referenced eye level. It has been used to measure the fidelity with which a VE system produces a simulation of three-dimensional space. Experiments have been performed in a VE and compared with results obtained in a corresponding physical environment. A virtual pitched array was produced which was geometrically identical to a corresponding physical stimuli. The virtual array had a smaller influence on perceived eye level than did the pitched physical array. Measurement of the degree to which the pitched optical array influenced the subject's sense of gravitationally referenced eye level may be taken as a measure of the completeness of the enveloping spatial illusion. Addition of several grid patterns to the virtual pitched array increased the influence of the virtual optic array and indicates the specific type of grid that may be optimal to improve the completeness of the enveloping illusion in a VEs. [2]

### Future Plans

Work will be continued utilizing higher frame rates attainable with SGI Skywriter system. Additional displays will be evaluated.

### System Architecture

Displays: Custom LCD headmount  
Input: Dataglove, Joystick  
Rendering: ISG  
Computation: HP 9000  
Software: Custom.

### References

1. Ellis, S.R., Tyler, M., Kim, W.S., and Stark, L. (1991). *Three dimensional tracking with misalignment between display and control axes* (SAE Technical paper #91-1390). SAE.
2. Nemire, K. and Ellis, S.R. (1991, November). *Influence of pitched visual frame on gravitationally reference eye level in a VE*. Paper presented at the meeting of the Psychonomic Society. San Francisco, CA.

## Extravehicular Activity Self-Rescue in Virtual Environments

Principal Investigator: Stephen Ellis  
Additional Investigators: A. R. Brody (Sterling), R. Jacoby (Sterling)  
NASA Ames Research Center

### Research Objective

The Extravehicular Activity Self-Rescue in Virtual Environments project provides a current example of a practical test of the utility of VE personal simulators.

### Status

By providing a VE simulation with the mass and moments of inertia of an EVA crew-person, and thruster characteristics for a rescue device, researchers are able to examine human performance in a rescue. Measurements such as onset time until response, time and fuel necessary to cease rotations, and time and fuel required to return to the station may be made for an assortment of failure scenarios. Thrusters may be altered in magnitude, capacity, moment arm, and number to examine the effects these parameters might have on a self-rescue capability. Different control modes such as pulse, displacement proportional, force proportional, and on/off could be compared to determine which works best in terms of fuel, time, safety, or any other desired cost function.

So far, one study was performed in the VE simulator of the Advanced Displays and Spatial Perception Laboratory. Simulations were conducted to assess the feasibility, and quantify the fuel and time requirements for a stranded crew-person to return himself to a space station after an accidental separation. A hand-held thruster, similar to the Hand-Held Maneuvering Unit (HHMU) from the Gemini Program was used for propulsion. Virtual environment simulators were determined to be useful for simulating accidental separations and provided preliminary evidence that a hand-held thruster is a viable alternative for accomplishing a self rescue. Simulation fidelity and validity remain to be established

### Future Plans

Further work will be directed towards measuring the realism of the VE simulation and relating these measures towards transfer of training to simulated real environments.

### System Architecture

Displays:	Custom LCD headmount
Input:	Dataglove, Joystick
Rendering:	ISG
Computation:	HP 9000
Software:	Custom.

### References

1. Brody, A. R., Jacoby, R. and Ellis, S. R. (1991). *Simulation of Extra-Vehicular Activity (EVA) Self Rescue* (SAE Technical Paper 91-1574). Society of Automotive Engineers.
2. Brody, A. R. and Ellis, S. R., *Motion-Based Simulation of Extra-Vehicular Rescue* (AIAA Technical Paper 92-0593). Washington, DC: American Institute of Aeronautics and Astronautics.

## Telerobotic Planning and Operational Interfaces

Principal Investigators: Stephen Ellis  
NASA Ames Research Center

### Research Objective

The paths that robotic mechanisms trace during their missions are subject to numerous quantitative and qualitative constraints. While algorithms exist to satisfy these constraints automatically, these techniques are often slow, inflexible, idealized, or incomplete. Consequently, there is a need to be able to visualize the robot's planned trajectory and to interactively edit it. The editing may be required during debugging of automatic solutions or used during actual collaborative mission planning when a human user interacts with an algorithm.

### Status

Such interaction requires a suitable communication medium. Virtual environments produced through head mounted displays coordinated with simulations of robotic manipulators are such a medium [1]. When enhanced by dynamic or kinematic simulations in the form of "geometric spreadsheets [2]", such media can extend human planning capabilities into new realms. One key benefit is that activities can be planned within the simulation and avoid the difficulties presented by long time lags associated with communication to distant robotic worksites. They additionally promise to add flexibility and speed to the planning process.

A VE created through kinematic simulation of a PUMA robot arm has been completed in the Advanced Displays Laboratory and connected through an EtherNet to a corresponding PUMA arm in a remote laboratory of the Intelligent Mechanism's Group using TCA control [3]. Bidirectional video links have also been established. Gesture planning software is currently being developed to plan sequences of robotic movements. A initial movement macro definition capability has been developed and demonstrated and icons representing potential constraints on motion, such as the forces and torques at the end effector, have been developed. Alternative menu control techniques are being developed for interacting with the macros and the VE itself and have been studied through psychophysical and biomechanical techniques.

### Future Plans

Development of VE interfaces for robot manipulators to generally advance the virtual environment technology of planning of telerobotics tasks. This will address issues functionally common to the manipulation and control of virtual objects in a large variety of application areas such as assembly training, teleoperation, or laparoscopic surgery. Software will be upgraded to run on the new SGI Skywriter dual-pipe graphics system.

### System Architecture

Displays:	BOOM 1, PUMA Arm
Input:	Dataglove, Joystick
Rendering:	ISG
Computation:	HP 9000
Software:	Custom.

### References

1. Ellis, S. R. (1991). Nature and origin of VEs: a bibliographical essay. *Computer Systems in Engineering*, 2(4), 321-347.
2. Grunwald, A. J. and Ellis, S. R. (1988). Interactive orbital proximity operations planning system (NASA TP 2839). Moffett Field CA: NASA Ames Research Center.
3. Fong, T. W., Hine, B. P., III, and Sims, M. H. (in preparation). *Intelligent Mechanism Group: Research Summary (NASA TM)*. Moffett Field CA: NASA Ames Research Center.



## Using Virtual Menus in a Virtual Environment

Principal Investigators: Richard Jacoby (Sterling Software)  
Stepehn Ellis  
NASA Ames Research Center

### Research Objective

Several aspects of VEs make menu interactions different from interactions with conventional menus. We are developing the features and interaction methodologies of different versions of virtual menus.

### Status

Teleop, the robot teleoperation application, has been the VIEW lab's primary testbed for different menu implementations. This application has been used by the first author hundreds of times and by others several dozen times over the last year and a half. Virtual menus have also been part of demonstration applications in the VIEW lab for about three years. During that time, well over two hundred people have tried these programs and experienced VE. During the development, demonstration and use of these applications, we have had the opportunity to observe the interactions between users and our menus. The results of informal observation and discussion have lead us to identify weaknesses in the initial version of the menus, and to develop a newer version that addresses those weaknesses.

Until this fall, the interactions with the VIEW menus have been performed entirely through hand gestures and pointing. This has been due, in part, to our hardware configuration: an electronic glove and tracker that the user already wears to interact with the environment in other ways. In addition, we wanted to evaluate the premise that gesturing is a natural and efficient method of interacting with the computer.

The VIEW menus are text based. They are very thin rectangular 3-dimensional objects that can be displayed at any position and orientation in the environment. Highlighting is accomplished by placing a dimly lit rectangle between the menu and the highlighted text. Menu interactions are initiated by the user making a specific hand gesture. Before the menu appears, the user sees a model of a hand and fingers at the position and orientation of his real hand and fingers. In the newer version of the menus, a pointer and cursor also become visible.

### Future Plans

Although the current menu version is substantially easier to operate than its predecessor, many improvements to menu interactions can still be made.

One possible improvement to the current interaction method would be to make the cursor "sticky". Another variation on the current paradigm is to not render the graphics model of the hand during menu interaction. Feedback for pointing would still be provided by the ray and cursor. An advantage may be a faster running simulation which would make pointing easier because of reduced transport delay.

A different interaction paradigm that has already been partially implemented entails the use of a two-button hand-grip that is held in the user's left (ungloved) hand. The buttons are used to invoke menus and cycle through menu items. It is hypothesized that this type of interaction may be quicker than pointing to a menu item. Another advantage of this paradigm is that the user's right (gloved) hand will be free for other uses. An experiment is being designed to test the hypothesis.

Further investigation is necessary to evaluate how the menu's frame of reference should be related to the user's frame of reference. Work is also needed in the area of gesture recognition. A study will be performed to determine how well the computer recognizes gestures and how well it can distinguish between the user's gestures.

### System Architecture

Displays:	Custom LCD headmounted display
Input:	Polhemous, Dataglove, hand-held button
Rendering:	ISG
Computation:	HP 9000
Software:	Custom.

### References

1. Jacoby R. and Ellis S. (1992). Using Virtual Menus in a Virtual Environment. In S. Fisher (Ed.), *Stereoscopic Displays and Applications 3*. San Jose, CA: SPIE.

## Presence in Natural Terrain Environments

Principal Investigator: Michael W. McGreevy  
NASA Ames Research Center

### Problem

Planetary geologists assert that human presence is essential to planetary field geology but the nature of that presence is not sufficiently characterized to influence exploration systems and mission operations.

### Objective

The objectives of this activity are to: (1) enhance the effectiveness of planetary surface explorers by extending the reach of human presence; (2) understand human exploration behavior, and the nature and benefits of presence within natural terrain environments; and (3) broaden the approach to VE research through complementary investigations in natural environments.

### Approach

This field component of the Virtual Planetary Exploration program approaches the question of presence, actual and virtual, through field studies in which experienced planetary scientists are observed as they explore natural environments. Methods of analysis derived from ethnographic and object-oriented analyses, which are based on traditional methods of analyzing complex systems, are being developed and applied. These analyses are being used to model human-terrain interactions characteristic of presence, and to guide user-based object-oriented design of virtual planetary exploration systems. A small element of this work involves some depth-first analysis of Apollo 17 surface operations. The Apollo missions offer a considerable amount of uniquely valuable information that make it an appropriate area for more comprehensive analysis efforts, once the necessary tools are more fully developed.

### Accomplishments

Two field studies have been conducted, one to the Amboy lava field in the Mojave Desert, and another to the Kaupulehu lava flow of the Hualalai Volcano in Hawaii. The Amboy lava field is a landscape which is analogous to terrain on Mars. Two planetary geologists were interviewed and observed there during the conduct of typical surface operations. Each subject then wore a head-mounted video camera/display system, which replaced his natural vision with video vision, to conduct further surface explorations. The study brought to light factors influencing field exploration behavior and continuity relationships among them, which have contributed to the elaboration of some initial elements of a theory of presence. It also helped to illuminate methodological and theoretical issues of ecological task and site validity. The second field study was conducted on the Kaupulehu lava flow of the Hualalai Volcano on the island of Hawaii. Two planetary geologists were accompanied on a multi-day geologic field trip that they had arranged for their own scientific purposes. The subjects were observed and videotaped during the course of their work, and interviewed regarding their activities. Analysis of the Hualalai field activities, related documentation, and interviews, using the ethnographic and object-oriented methods that are being developed, is contributing to the development of components of a theory of presence by revealing or confirming the nature of redundancies in the sense of presence. Further, the analysis is providing feedback useful for improving the analysis methods themselves, and is providing detailed domain structure on which to base improved designs for user-based, object-oriented virtual planetary exploration systems.

### Future Plans

Plans include: 1) completion of the Hualalai series of field studies; 2) further development of ethnographically informed object-oriented analysis capabilities; 3) investigation of related field activities and extraction of commonalities; 4) elucidation of exploration behavior and related aspects of presence.

### References

- McGreevy, M.W. and Stoker, C.R. (1990). Telepresence for planetary exploration. In *Proceedings of the SPIE 1990 Conference on Cooperative Intelligent Robotics in Space*, SPIE Vol. 1387, 110-123.
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## Disparate Data Integration for Model-Based Teleoperation

Principal Investigators: Michael W. McGreevy  
Cindy Ferguson (Sterling Software)  
NASA Ames Research Center

### Problem

Planetary geologists say that they expect VEs to be especially useful for exploration when digital models of terrain elevation and brightness are augmented with spatially correlated data from many sources, including: geologic, seismic, biologic, mineralogical, and traversibility maps; diverse static and dynamic imagery; time-varying data; volumetric data; archival data; real-time data from on-site exploration systems; and ad hoc or preliminary observations of colleagues.

### Objective

The objectives of this activity are to: 1) enhance the effectiveness of operators and analysts of planetary exploration missions by improving the integration of disparate, spatially correlated environmental data; (2) develop an object-oriented architecture for integrated exploration of disparate spatial information; and (3) support model-based exploration and teleoperation.

### Approach

The approach taken is to apply and refine object-oriented analysis, design, and implementation techniques. The project is intended to translate field, document, and other analyses to user-based, object-oriented designs. This involves analyses, coordinated with field studies, that are specifically related to the disparate nature of the spatially correlated experience and data. Also involved are analyses of the implementation environment in which the domain requirements are to be addressed. Analyses are iteratively transitioned into object-oriented designs. Currently, research is addressing a core of commonality among several related domains, including field geology at the Hualalai Volcano, Apollo surface traversals, and the scientific exploration of Monterey Canyon in Monterey Bay. The intent of this core commonality approach is to ensure that designs are robust, generalizable, and reusable. The most comprehensive design and implementation will focus on exploration of Monterey Canyon, since there is a readily accessible cadre of domain experts already cooperating with this project.

### Accomplishments

An iterative, layered, and object-oriented approach has been developed and documented. The architectural design has already gone through several iterations which have made fundamental improvements without great expense--time, effort, or funds--because the changes occurred well prior to implementation. Initial analyses of several user domains, the implementation environment, and the R&D environment are in progress, and are contributing significantly to the approach and the design. A broad domain survey, done previously, has provided outlines for the early design effort. Ethnographic and object-oriented analyses are being developed and integrated. Strategic, narrow, depth-first user domain analyses and implementation environment analyses are being done in order to further orient the early design effort. Coding has begun on basic software components that are independent of comprehensive analyses. A gesture recognition subsystem has been developed in C++. It is being made compatible with SG's high-performance simulation toolkit, Performer. Detailed domain analyses are in progress.

### Future Plans

Plans include: 1) develop a user-based, object-oriented, VE architecture for integrated exploration utilizing disparate, spatially correlated data; 2) develop the object-oriented design based on user domain analyses; 3) ensure that the design and implementation possess a core capability that supports fundamental commonalities of a wide range of related applications; 4) focus a reasonably comprehensive implementation on a user domain in which diverse data and users are readily available

### References

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- McGreevy, M.W. and Ferguson, C. (1993). *Presence and virtual presence for planetary exploration: Program definition, current elements, and plan for desired improvements*. Unpublished document.

## Virtual Planetary Exploration Testbed

Principal Investigators: Michael W. McGreevy  
 Lewis Hitchner (Western Aerospace)  
 Co-Investigator: William Briggs (San Jose State University Foundation)  
 NASA Ames Research Center

### Problem

NASA's operational experience in planetary exploration indicates that spatial visualization of human scale planetary surfaces is critically important to the success of manned and unmanned missions. Systems available for this purpose have very limited capability and users want improvements.

### Objective

The objectives of this activity are to: (1) contribute to the success of planetary exploration missions by improving the operational effectiveness of human and machine explorers; (2) extend the reach of human presence and democratize space exploration; and (3) develop concepts and systems for generating and testing user-based virtual planetary environments.

### Approach

Consideration of the needs of the ultimate users is paramount. Fundamental to the VPE approach is the use of actual planetary terrain data from NASA exploration missions. Further, use of data from engineering tests of future rover imaging systems has been central to development of the VPE Testbed. This provides a necessary reality check for concepts and methods. The sheer magnitude of the terrain data sets is itself a significant factor in the interaction between the user and the VE. So, rather than develop VEs based on toy worlds (a common practice), the VPE Testbed activity directly addresses the essential conflict between data complexity and user-environment interactivity.

### Accomplishments

The VPE Testbed can be used to virtually explore digital terrain models (DTMs) of Mars using Viking orbiter data, panoramic surface images from Viking orbiter and lander data, and high resolution DTMs from sites on Earth. Several techniques have been developed, including a digital version of the Surveyor Mosaic Spheres and virtual interactive flight over digital terrain models of variable resolution. Algorithms to interactively and non-uniformly vary terrain model complexity, based on user interest, have been developed and implemented. Several hand gesture recognition algorithms, and a recognition subsystem, have been developed. The recognition subsystem, written in C++ on an SGI Indigo, is being ported to the SkyWriter and made compatible with SGI's high-performance simulation toolkit, Performer.

### Future Plans

Plans include: 1) enhancement of user interactions with human scale terrain data; 2) further development of complexity management algorithms and software that will provide additional user-based criteria for adaptively modifying model complexity to that which is essential to the user and task at any given moment.

### References

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- Musgrave, F. K. (1992). A panoramic virtual screen for ray tracing. In D. Kirk (Ed.), *Graphics Gems III*. Boston, MA: Academic Press.

## Simulating Complex Virtual Acoustic Environments

Principal Investigator: Elizabeth Wenzel  
 Co-Investigator: Durand Begault  
 NASA Ames Research Center

### Research Objective

Investigate the underlying perceptual principles of auditory displays and develop an advanced signal processor (the "Convolvotron") based on these principles.

### Status

Spatial auditory displays require the ability to generate localized sound cues in a flexible and dynamic manner. Rather than use an array of speakers, the Convolvotron maximizes portability by synthetically generating three-dimensional sound cues in realtime for delivery through earphones. Unlike conventional stereo, sources are perceived outside the head at discrete distances and directions from the listener. This is made possible by numerically modeling the effects of the outer ears (the pinnae) on the sounds perceived at various spatial locations. These 'Head-Related Transfer Functions' (HRTFs) can then be applied to arbitrary sounds (voices, for example) in order to cause them to seem spatially located. The Convolvotron, a set of two printed circuit (PC) boards hosted by a personal computer, is capable of synthesizing up to four simultaneous, localized sources, and implementing smooth motion trajectories in a head-stable environment. It is currently being used in a variety of government, academic, and industrial laboratories in addition to the Ames Spatial Auditory Displays Lab.

### Future Plans

While the initial implementation simulates only the direct paths of up to four virtual sources to the listener, it possesses a high degree of interactivity. In a simple anechoic space, it is possible to freely manipulate source position, listener position, and listener orientation in a dynamic, real time display. It is desirable to be able to achieve the same level of interactivity in more complex acoustic environments.

Psychoacoustical research suggests that synthesis of purely anechoic signals can result in perceptual errors, in particular an increase in front-back reversals and a failure of externalization. There is reason to believe that such errors can be alleviated by providing more complex cues resulting from reverberant environments.

Of particular interest here is the work on image models for simulating room characteristics with synthetic early reflections using a kind of ray-tracing approach. For example, the walls, floor, and ceiling in an environment are simulated by using HRTF-based filters to place the "mirror image" of a sound source behind each surface to account for the specular reflection of the source signal. The filtering effect of surfaces such as wood or drapery can also be modeled with a separate filter whose output is delayed by the time required for the sound to propagate from each reflection being represented.

In future work, we plan to extend this simulation to more realistic models of acoustic environments. Some of the issues that need to be addressed are diffuse reflections, scattering reflectors, diffraction and partial obscuration by walls or other objects, near-field effects (e.g., head-shadowing), and perceptually-viable methods of simplifying the synthesis technique.

### System Architecture

Displays:	Stereo headphones.
Input:	Polhemus, 4 analog sound sources
Rendering:	Convolvotron
Computation:	386 PC
Software:	Custom.

### References

- Begault, D. R. (1991). Perceptual effects of synthetic reverberation on 3-D audio systems. *Journal of the Acoustic Engineering Society*, 40, 895-904.
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## Hearing Through Someone Else's Ears

Principal Investigator: Elizabeth Wenzel  
 Co-Investigator: Durand Begault  
 NASA Ames Research Center

### Research Objective

Synthesis of virtual sources involves the digital filtering of sounds using filters based on acoustic Head-Related Transfer Functions (HRTFs) measured in human ear-canals. In practice, measurement of the HRTFs of each potential user of may not be feasible. Thus, a critical research question is whether inexperienced listeners can obtain useful directional information in a virtual acoustic display without requiring that the cues be individualized for each potential user.

### Status

Early experience has suggested that using non-individualized HRTFs is possible, so long as the filters that are used were originally measured for someone with accurate localization in both real world and synthesized conditions. This study represents a more formal test of this hypothesis. Sixteen blindfolded listeners judged the apparent spatial location (azimuth [left-right] and elevation [up-down] ) of stationary sounds presented either over loudspeakers in the free-field (a non-reverberent environment) or over headphones. The headphone sounds were synthesized using HRTFs from a "good localizer" in a previous study.

In general, the data suggest that most listeners can obtain useful directional information from a spatial auditory display without requiring the use of individually-tailored HRTFs, particularly for the dimension of azimuth. However, the high rates of reversals for some people remain problematic. Comparison to a study using subjects' own HRTFs suggests that "listening through someone else's ears" primarily results in an increase in front-to-back reversals. Note, though, that the existence of free-field confusions shows that these reversals occur in the real world and so are not strictly the result of the simulation.

### Future Plans

Several stimulus characteristics may help to minimize these errors and are being examined in current and future studies. For example, the addition of dynamic cues correlated with head-motion, well-controlled environmental cues generated from models of room acoustics, and correlated visual cues should improve the ability to resolve these ambiguities and substantially enhance the efficacy of any virtual acoustic display.

### System Architecture

Displays: Stereo headphones.  
 Input: Polhemus, 4 analog sound sources  
 Rendering: Convolvotron  
 Computation: 386 PC  
 Software: Custom.

### References

- Begault, D. R. (1991). Challenges to the successful implementation of 3-D sound. *Journal of the Audio Engineering Society*, 39(11), 864-870.
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## Virtual Reality Applications in the Earth and Space Sciences

Principal Investigators: Horace G. Mitchell and Daniel S. Spicer  
NASA Goddard Space Flight Center

### Research Objective

To provide Earth and space science researchers with a VE based on a familiar user interface so as to introduce and evaluate VEs as a research tool.

### Status

Research scientists working in the Earth and space sciences require VE tools that they can immediately utilize as an extension of their existing tools and methods. In this way they can minimize both learning and development time and evaluate VEs directly as a research tool. The Flow Analysis Software Toolkit (FAST) is a popular, NASA-developed visualization tool, specifically designed to visualize the physics of three dimensional flows and optimized for high-end graphics hardware. By utilizing a subset of FAST modules for data input, analysis, and visualization control, a VE version of FAST is being developed (VR-FAST) which will allow research scientists to work with a VE package that they are already familiar with.

Initial development of the VR-FAST is currently in progress. The development hardware system has been purchased and delivered to Sterling Software, the developers of FAST. Helmet tracking modifications have been integrated and 75% of the glove software is done (innate gestures and learn gestures done, with applications integration in progress).

### Future Plans

The initial, deliverable VR-FAST system will be completed this year (FY93). Immediate subsequent development will focus first on a multiple user version, for collaborative research efforts, and then on versions that are distributed over multiple machines and graphics hardware and are parallelized for high performance.

### System Architecture

Display:	Dual display color helmet
Input:	VPL DataGlove, keyboard, mouse
Rendering:	Silicon Graphics Dual Reality Engine Skywriter
Computation:	Silicon Graphics Dual Reality Engine Skywriter
Software:	FAST

## Workload Assessment Using a Synthetic Work Environment

Principal Investigator: Susan Adam  
Co-investigators: Manny Diaz  
NASA-Johnson Space Center

### Research Objective

To quantify the additional mental workload imposed by microgravity. To develop tools for assessing the mental workload imposed by proposed spacecraft systems.

### Status

A series of mental workload studies using a synthetic work environment has been completed. These studies sought to demonstrate the utility of Response Surface Methodology (RSM) central-composite designs for predicting mental workload. The intent was to conduct the first in a series of studies that would ultimately establish systems operating conditions for proposed spacecraft systems that do not overload the capabilities of the operator. Eight subjects participated in a testing situation comprised a synthetic work environment consisting of four tasks: visual monitoring, Sternberg memory, arithmetic computations and auditory monitoring.

Preliminary results suggest that RSM provides an effective tool for evaluating operating conditions in synthetic work environments in terms of the imposed mental workload. Plans call for augmentation of the first-order model to a second-order central composite design to more accurately characterize the response surface. Then, the predictively validity of the response surfaces will be established, further demonstrating the utility of RSM for evaluating the operating conditions in proposed spacecraft systems.

### Future Plans

The results of these studies will advance current understanding of the relation between the simultaneous affects of various systems operating conditions and how they impact the mental workload imposed by spacecraft systems proposed for extended duration spaceflight. However, the synthetic work environment does not provide the fidelity necessary for comprehensive human workload analysis. Virtual reality technology can be expected to provide a new level of fidelity and an enhanced capability for in-depth evaluation of the workload imposed by microgravity and by proposed spacecraft systems.

### System Architecture

Displays:	Compaq PC
Input:	Mouse
Rendering:	M68000
Computation	M68020
Software	SYNWORK1



## Device for Orientation and Motion Environments (DOME) -- Preflight Adaptation Trainer (PAT)

Principal Investigator: Deborah L. Harm

Co-investigators: Donald E. Parker, Miami University--OH, and Millard F. Reschke  
NASA Johnson Space Center

### Research Objective

To develop training devices and procedures to preadapt astronauts to the sensory stimulus rearrangements of microgravity. The trainers are intended to demonstrate sensory phenomena likely to be experienced inflight and immediately postflight, allow astronauts to train preflight in an altered sensory environment, alter sensorimotor reflexes (appropriate for microgravity), and eliminate or reduce space motion sickness and orientation and motion disturbances.

### Status

The DOME-PAT system is currently being used to train astronauts in the recognition of, and quantitative description of perceptual experiences associated with head and body movements made on-orbit, during entry and immediately postflight. Postflight, astronauts report which set(s) of conditions in the DOME are similar to their flight related perceptual experiences and help evaluate potentially useful training tasks. The system is a 3.7 m diameter spherical dome with a 1.8 m diameter hole in the bottom. The inner surface of the dome serves as a projection surface for two Triuniplex video projectors with custom wide angle optics providing a 100° X 170° field of view. An adjustable trainee restraint assembly, along with the projectors, is mounted on a 1.8 m diameter rotating base which fills the hole in the bottom of the dome. The trainee restraint adjusts for positioning the trainee to: (1) sit upright, (2) lie on either the left or right side, or (3) lie supine. A 6 DOF isometric joystick or forceplate is used by the trainee and/or the instructor for virtual motion within the visual environment. The joystick can be used to control real whole body rotation when the rotating base is enabled. Position signals derived from torque sensors in a trainee head restraint assembly can also be used to drive the visual scene in a manner appropriate for either real or intended head movement. Real head movements are permitted only in a plane orthogonal to gravity to eliminate a gravity stimulus to the gravity receptors in the inner ear.

### Future Plans

In the near-term future: (1) new training tasks/protocols will be developed and evaluated by astronauts as part of an ongoing detailed supplementary objective (DSO) activity, (2) criteria for evaluating the efficacy of different training protocols will be determined, and (3) a visual data base for simulating EVA will be developed. Ultimately, we expect the full complement of training procedures to be implemented as part of the astronaut's operational training. For long-duration missions (STS and Space Station) and Mars missions we expect to develop a compact inflight VR system and protocols for maintaining adaptation to 0g, 1/3g and 1g.

### System Architecture

Displays:	Space Lab, Middeck/Flight deck, and polarized checkerboard room
Input:	6 DOF isometric force joystick, torque sensors in trainee head restraint system
Rendering:	Silicon Graphics 4D-440 VGX, two Triuniplex projectors with custom optics
Computation:	Silicon Graphics 4D-440, Vision Works (Paradigm)
Software:	In-house

### References

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## Training for Eva Satellite Grapple

Principal Investigator: R. Bowen Loftin (NASA JSC and University of Houston)

Additional Investigators: Lui Wang (NASA/JSC); Mark Voss and Jeff Hoblitt (LinCom); Lac Nguyen (CSC)  
NASA-Johnson Space Center

### Research Objective

To develop a proof of concept training environment that provides astronauts with a simulation of satellite dynamics that match those observed during STS-49.

### Status

A proof of concept VE for EVA satellite grapple is under development. Elements include models of the orbiter, the RMS, and Intelsat. The Intelsat model is dynamic and will respond to impulses imparted by a human hand or a hardware fixture. A Polhemus device is used to track hand or fixture motion. The model detects collisions and infers the impulse imparted to the payload from a simple mass model of the hand or fixture and its velocity on collision with the payload.

### Future Plans

If the proof of concept system is judged to be valuable for training by training personnel and experienced astronauts, a more complete model will be developed and delivered as a training system for future payload retrieval missions.

### System Architecture

Displays: VPL EyePhone, LX and HRX  
Input: VPL DataGlove, Model 2; Polhemus  
Rendering: SGI 320VGX  
Computation: SGI 320 VGX  
Software: TDM, OOM (in-house)

## Shared Virtual Environments

Principal Investigators: R. Bowen Loftin (NASA JSC and University of Houston) and Joe Hale (MSFC)  
Additional Investigators: Lui Wang (NASA/JSC); Lac Nguyen (CSC); Mark Voss (LinCom)  
NASA-Johnson Space Center

### Research Objective

To develop the capability for sharing VEs via long-distance networks.

### Status

The capability of sharing the same VE between JSC and MSFC has been demonstrated. Such a shared environment permits personnel at both centers to simultaneously observe and interact with the same virtual objects. The use of existing networks imposes unpredictable latencies due to other network traffic.

### Future Plans

The installation of a dedicated communication link between JSC and MSFC is planned. The nature of the shared environments will be increased in complexity and more interactive tasks will be performed.

### System Architecture

Displays: VPL EyePhone, LX and HRX  
Input: VPL DataGlove, Model 2; Polhemus  
Rendering: SGI 320 VGX  
Computation: SGI 320 VGX  
Software: TDM, OOM (in-house)

## Space Station Cupola Training

Principal Investigators: R. Bowen Loftin (NASA JSC and University of Houston) and Beth Holewinski (NASA/JSC)

Additional Investigators: Lui Wang (NASA/JSC); Lac Nguyen (CSC); Mark Voss (LinCom)  
NASA-Johnson Space Center

### Research Objective

To develop a training environment that supports astronaut training for Space Station cupola operations.

### Status

A VE for Space Station cupola operations training is under development. Elements include models of the exterior of Space Station and the interior of the cupola. Scenarios to be supported include remote operation of the Space Station RMS with payload grapple and interaction of EVA personnel with Space Station RMS.

### Future Plans

Transition of models from VPL software to in-house software; testing the efficacy of this approach to cupola training compared to dome and/or pancake window simulation.

### System Architecture

Displays: VPL EyePhone, LX and HRX  
Input: VPL DataGlove, Model 2; Polhemus  
Rendering: SGI 320 VGX  
Computation: SGI 320 VGX  
Software: VPL Swivel 3-D, Body Electric, Isaac; TDM, OOM (in-house)

## Virtual Science Laboratories

Principal Investigator: R. Bowen Loftin  
NASA-Johnson Space Center and University of Houston

### Research Objective

To develop virtual laboratories that provide students access to experiments that cannot be performed in "real" laboratories, thereby enhancing student mastery of difficult concepts and increasing student motivation for science.

### Status

A prototypical Virtual Physics Laboratory has been constructed. This laboratory provides for user control of gravity (both magnitude and direction), friction, atmospheric drag, and the coefficient of restitution for elastic bodies. Measurements of both time and length can be performed. Trajectories of objects can be traced for future measurement. Time in this "world" can be stopped and started at will to support both observation and measurement. Objects such as a plane pendulum (with variable length), balls, and plane surfaces are available for experimentation.

### Future Plans

During the fall, 1992, formative testing of the Virtual Physics Laboratory will be conducted with both high school and college students. Based on this evaluation, a second version of the laboratory will be developed using in-house software. Additional plans call for the development of virtual laboratories to support chemistry, biology, and earth science.

### System Architecture

Displays: VPL EyePhone, LX and HRX  
Input: VPL DataGlove, Model 2; Polhemus  
Rendering: SGI 320VGX  
Computation: SGI 320 VGX  
Software: VPL Swivel 3-D, Body Electric, Isaac

### References

1. Loftin, R. B., Engleberg, M., and Benadetti, R. (1992, October). *A Virtual Physics Laboratory*. Paper presented at CAI, Washington, DC.

## Realistic Lighting Models for Virtual Reality

Principal Investigator: James Maida (NASA JSC)  
 Additional Investigators: Ann Aldridge, Abhilash Pandya ( Lockheed ESC)  
 NASA Johnson Space Center

### Research Objective

To develop a comprehensive lighting model to simulate realistic lighting conditions for potential use in virtual reality environments. The research will include study of camera and lens behavior, material properties, and light parameters.

### Status

Computer simulation of lighting scenarios is important. Typical viewing simulations are often simple color shaded images showing what is in the field of view. However, previous use of these images in mission planning and operations has shown the need to accurately simulate the effects of lighting. This has been done using common lighting simulation algorithms such as ray tracing and radiosity. However, it is important that lighting simulations be accurate, and that the parameters describing the material and lighting properties are valid. These are the areas of research currently underway.

1. Resources of NASA's lighting laboratory are being used for the collection of lighting and material reflectivity properties. This data will be used to correlate input parameters of the light models to the physical properties of the materials and lights.
2. Model extensions are underway which more accurately represent the relationships of light attenuation with distance and the scattering effects of materials.
3. Human eye and cameras are sensitive to variations in light intensity. They modify the amount of light entering the visual system by automatically adjusting the aperture of the lens with an iris. This behavior significantly changes what is visible and must be modeled. We are studying the image processing (intensity mapping, gamma correction) done by camera systems such as the human eye and shuttle cameras.

### Future Plans

To develop and optimize a lighting system which incorporates realistic material and light parameters which might be used in a VE.

### System Architecture

Displays: Silicon Graphics 360, VGX  
 Input: Polhemus magnetic tracker  
 Rendering: Silicon Graphics (R3000- RISC)  
 Computation: Silicon Graphics (R3000- RISC)  
 Software: In-house

### References

1. Xiao, D. He, Torrance, K., Sillion, F., & Greenberg, D. (1991). A Comprehensive Physical Model for Light Reflection, *Computer Graphics*, 25(4), 175-186 (Proceedings SIGGRAPH '91).
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## Improving Human Model Reach for Virtual Reality Applications

Principal Investigator: James Maida (NASA JSC)  
Additional Investigators: Ann Aldridge, Abhilash Pandya (Lockheed ESC)  
NASA Johnson Space Center

### Research Objective

To develop an accurate human computer reach model able to simulate complex three dimensional tasks with potential application in virtual reality applications.

### Status

The most kinematically complex interaction to model in the human arm is the shoulder girdle. The motion of the shoulder complex involves several joints moving simultaneously with a complicated and dependent interaction. This shoulder motion was measured using a magnetic tracking device in all rotational planes. These measurements were used to validate and refine a clavicle /shoulder kinematic model. With this shoulder model, accurate reach positions can be predicted in all planes of motions to within, on average, 1 cm of the measured data.

### Future Plans

To extend the human reach model to include realistic and detailed motions of the hand and the spinal cord.

### System Architecture

Displays: Silicon Graphics 360, VGX  
Input: Polhemus magnetic tracker  
Rendering: Silicon Graphics (R3000- RISC)  
Computation: Silicon Graphics (R3000- RISC)  
Software: In-house

### References

1. Otani, E. (1989). *Software Tools for Dynamic and Kinematic Modeling of Human Motion*. Unpublished Master Thesis, University of Pennsylvania.
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## Human Computer Interface Research for Graphical Information Systems

Principal Investigator: Kevin O'Brien PHD. (Lockheed)  
Additional Investigators: Benjamin Beberness (Lockheed), Steve Chrisman (Lockheed)  
NASA-Johnson Space Center

### Research Objective

The Human-Computer Interaction Laboratory (HCIL) has conducted an assessment of the information technology projected for lunar and Mars missions and the applicability of projected technology for supporting space exploration tasks (Advanced Information Technology Data-base). The task of selecting the geographic location of planetary activities was identified as benefiting from technological advances. Site selection is important to a variety of larger tasks including conducting remote surveys, vehicle landing, and surface activities such as scientific exploration. Of specific interest to those involved in site selection is the rapidly developing Geographic Information Systems (GIS) technology. While the benefit of GIS's to site selection in earth-based activities has been demonstrated in a variety of fields (urban planning, petroleum exploration and drilling, land management), many challenges to the development of the technology exist, and the development of the technology for the purpose of supporting planetary exploration is as yet unexplored. The HCIL has completed a background report on issues involved in the application of GIS technology to space exploration, including reviews of four existing personal-computer based GIS's.

### Status

Our current focus is defining, evaluating, and illustrating user interface issues relevant to a GIS supporting space exploration decision making. Currently we are collaborating with Space Shuttle Earth Observation Project (SSEOP) people in developing a GIS to aid the Flight Crew Office in performing site selection task. This collaboration allows us to: 1) obtain a good understanding how a GIS can be built from the ground up in a space based environment, and 2) research issues are expected to evolve that we will test at a later date.

### Future Plans

Long term goals are: 1) demonstration package on GIS user interface issues, 2) Completion of "Issues in the Design of Geographic Information Systems", 3) empirically examine GIS human-computer interface factors affecting user performance in site selection tasks, 4) identify factors affecting user performance in a planetary GIS work task, and 5) develop parameter models of site selection for earth based tasks, previous planetary site selection, and projected planetary site selection.



## Macro-Ergonomics and Scaleable User Anthropometry

Principal Investigator: Joseph P. Hale  
Additional Investigators: Michael Flora, Peter Wang (NTI)  
NASA Marshall Space Flight Center

### Objective

To develop, assess, and validate VR as a macro-ergonomics analysis tool for considering operational, viewing, and reach envelope requirements in the topological design of work areas. To develop, assess, and validate scaleable user anthropometry attributes. A study will compare Virtual Payload Operations Control Centers (VPOCC) with the existing Payload Operations Control Center (POCC).

### Status

Two VPOCCs have been developed that contain the basic objects of the POCC (e.g., tables, monitors, printers, communication panels, etc.) and their spatial layout. One "operational" VPOCC permits the relocation of objects that are generally moveable and moved in an operational environment (e.g., keyboards). Another "non-operational" VPOCC permits the relocation of all objects that can be moved in the "real world" (e.g., tables).

Test scenarios will be performed in both the POCC and operational VPOCC and their results compared to ascertain what, if any, distortions arise in a Virtual World (VW). The test scenarios will focus on what one can see from a variety of eye reference points using a range of real and virtual anthropometric sizes. These scenarios will also include operationally-driven components such as translation paths among the various console-, printer-, fax-, file-locations.

An algorithm has been developed to rescale user anthropometric attributes to any desired virtual anthropology. Thus, a 95th %-ile male could view and reach as a virtual 5th %-ile female and vice-versa.

The non-operational VPOCC will be used to explore alternative POCC configurations, i.e., different topological arrangements of consoles, printers, faxes, files, etc. The various configurations will be compared using much the same methodology developed for the operational VPOCC.

### Future Plans

As confidence is gained in VR as a macro-ergonomic analytical tool, it will be applied in upcoming topological design efforts such as the Space Station Payload Operations Integration Center (POIC). Specific options to be addressed in the design of the POIC, in addition to "standard" topological design issues, include slanted walls (to cover utility runs) and tiering of the control room and viewing area floors. The validated scaleable user anthropometry capability will be applied in future macro- and micro-ergonomic analyses.

### System Architecture

Displays: VPL Eyephones  
Input: VPL Dataglove model 2, Polhemous, keyboard, mouse.  
Rendering: Silicon Graphics 310 VGX, Silicon Graphics 320 VGXB  
Computation: Macintosh II fx  
Software: Swivel 3D, Body Electric, ISAAC

## Micro-Ergonomics: Virtual and Fomecor Mock-Ups

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 NASA Marshall Space Flight Center

### Objective

To develop, assess, and validate VR as a micro-ergonomics analysis tool for considering operational, viewing, and reach envelope requirements in the spatial layout of workstations and worksites. To develop, assess, and validate scaleable user anthropometry attributes. A study will compare a Virtual Crew Interface Coordinator (VCIC) console with a proposed redesigned Crew Interface Coordinator (CIC) console.

### Status

The CIC console is part of the Payload Operations Control Center (POCC). The CIC position is analogous to the Mission Control Center's "Capcom" position, communicating directly with the Spacelab payload crew about payload operations issues. Two types of virtual mock-ups will be developed. One "operational" VCIC console will permit the relocation of objects that are generally moveable and moved in an operational environment (e.g., keyboards). Another "non-operational" VCIC console will permit the relocation of all objects that can be moved in the "real world" (e.g., monitors, worksurfaces).

Test scenarios will be performed on both a "Fomecor" mock-up and the VCIC console and their results compared to ascertain what, if any, distortions arise in a Virtual World (VW). The test scenarios will focus on what one can see from a variety of eye reference points and on what one can touch from a variety of shoulder reference points using a range of real and virtual anthropometric sizes. An algorithm has been developed to rescale user anthropometric attributes to any desired virtual anthropometry. Thus, a 95th %ile male could view and reach as a virtual 5th %ile female and vice-versa. Results of these analyses will also be compared to determine the relative merits of VR vis-a-vis an existing, "standard" Human Factor's tool (i.e., "Fomecor" mock-up).

The non-operational VCIC console will be used to make real-time design changes with immediate Human Factors analyses of the consequences. This capability is one of the benefits of VR analyses. Because the VWs are nothing more than computer files, design changes can be done more quickly and more candidate configurations can be subsequently analyzed than is currently possible with existing, "standard" Human Factor tools. The Fomecor mock-up will then be updated, based on the design of the "refined" virtual mock-up, and a second validation study with the CIC console will be conducted.

### Future Plans

As confidence is gained in VR as a micro-ergonomic analytical tool, it will be applied in future workstation and worksite design efforts as might be found in the Space Station Payload Operations Integration Center (POIC). The validated scaleable user anthropometry capability will be applied in future macro- and micro-ergonomic analyses.

### System Architecture

Displays: VPL Eyephones  
 Input: VPL DatagGlove model 2, Polhemous, keyboard, mouse.  
 Rendering: Silicon Graphics 310 VGX, Silicon Graphics 320 VGXB  
 Computation: Macintosh II fx  
 Software: Swivel 3D, Body Electric, ISAAC

## Microgravity Mobility and Ergonomics

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NASA Marshall Space Flight Center

### Objective

To develop, assess, and validate VR as a Human Factors design analysis tool for considering operational, viewing and reach envelope requirements in a microgravity environment. To develop, assess, and validate techniques and methods that provide some of the various advantages and disadvantages of reaching and maneuvering in microgravity. To compare the results from a "virtual analysis" with a previously conducted analysis relating to the operation of the Electromagnetic Processing Facility (TEMPUS), an experiment to fly on the Second International Microgravity Laboratory (IML-2) Spacelab mission.

### Status

TEMPUS is a levitation melting facility for processing of metallic samples in an ultra-clean environment. Sample positioning and heating can be controlled separately by two independent RF oscillating circuits. The issue driving the previously conducted analysis was whether a crewmember could adequately control the position of a sample in the facility with controls located in the right half of Rack 10 while monitoring the results on a CRT in the right half of Rack 8. The CRT was co-planar with the rack face and 42 inches away from the controls. A full-scale part-task Fomecor mock-up of both racks was fabricated to determine the crewmembers ability to view the CRT while touching the controls.

A virtual mock-up of racks 8 and 10 has been developed and placed inside of a virtual Spacelab module. A method to enable the various advantages and disadvantages of reaching and maneuvering in a microgravity environment has been developed, within existing VR technology capabilities and limitations. In particular, the user can manipulate the attitude of the Spacelab, as a whole, while "grabbing" a handrail, giving the egocentric perception of microgravity mobility. Viewing and reach envelope analyses will be conducted and the results compared with the previously conducted "Fomecor study". This study will also include scaleable user anthropometry, currently being developed and assessed in another study. This will help to further refine this capability.

### Future Plans

In addition to applying the VR analytical tools as they "come on-line", the VR toolkit will be further refined and augmented. One particularly valuable enhancement to be addressed in this area is the incorporation of an anthropometric model. This would enable dynamic work envelope analyses. The anthropometric model should include link lengths to reflect a broad anthropometric design range (e.g., 5th %-ile female through the 95th %-tile male) and realistic joint range-of-motion capabilities and constraints. A candidate subject to be used to evaluate and refine this feature is an unplanned In-Flight Maintenance (IFM) that occurred on Spacelab 3 (Drop Dynamics Module (DDM)). The goal would be to actually recreate the IFM environment and operation, then compare this virtual IFM experience with the actual flight experience. This would include reference to video and audio recordings of the on-board operation, written logs, and participation of the actual Spacelab crew involved in the IFM operation.

### System Architecture

Displays: VPL Eyephones  
Input: VPL DatagGlove model 2, Polhemous, keyboard, mouse.  
Rendering: Silicon Graphics 310 VGX, Silicon Graphics 320 VGXB  
Computation: Macintosh II fx  
Software: Swivel 3D, Body Electric, ISAAC

# Chapter 4: Near Term Mission Support

This chapter contains examples of possible applications of VE technology to near term NASA Space missions. The chapter is organized by missions or sets of missions. The list is by no means exhaustive.

## Chapter Organization

### **Aeronautics**

- Head-Mounted Displays for Aircraft Assembly
- Safer Communications in Air Traffic Control
- Aeronautical Virtual Acoustic Displays

### **Space Transportation System, Space Station, Exploration**

- Automated Training Evaluation and Improvement
- Designing Tools for Humans in Space

### **Exploration (Lunar/Mars) and Planetary Science**

- In Situ* Training

### **Exploration (Lunar/Mars)**

- Crew Health and Performance
- Dynamic Virtual Environment Database
- Task Analysis

- Crew Health -- Medical

- Crew Health -- Entertainment

- Crew Health -- Virtual Confidant

- In Situ* Training

- Planetary Science

- Shared Experience: Science, Operations, and Education

- Proficiency Training

### **Space Transportation System**

- After-the-Fact Analysis, Accident or Event Reconstruction

- Hubble Space Telescope Maintenance/Repair

- EVA/RMS Training and Procedures Development for HST Repair

- Crew Training for Satellite Retrieval and/or Repair

- EVA Operations Development

- RMS Training

- Near-Term VR Applications in Spacelab

### **Space Transport System and Space Station**

- Crew Health and Performance

- SAFER Engineering Test and Development

### **Space Station**

- Manipulator Systems Training

- Space Station Construction

- In Situ* Training

- Crew Medical Restraint System

- Space Station Operations (IVA and EVA)

- Near-Term VR Applications in Space Station

### **The Great Observatory Series**

- Near-Term VR Applications in the Design of the Advanced X-ray

- Astrophysics Facility

## Head-Mounted Displays for Aircraft Assembly

**Mission:** Improve productivity in aircraft manufacturing  
**Center:** Ames Research Center

**Problem:** Assembly of commercial aircraft requires the transfer of spatial information concerning wiring, rivets, and hydraulic lines from CAD/CAM databases onto the skin of aircraft subsections under construction. Some of this information is used automatically during assembly but much is currently used semiautomatically by skilled technicians who need to visualize the spatial layout of the design elements on or in their work surface. Current manufacturing techniques require them to move back and forth between displays or blueprints to as they transfer templates of layouts to complete fabrication of aircraft subsections in what is currently a labor-intensive, inefficient method of aircraft manufacturing.

**VR Application/Approach:** A head-mounted, see-through stereoscopic display presented as a spatially conformal projection of the layout information visually superimposed on the work surface will provide a convenient and more efficient means for the aircraft worker to transfer the necessary information. The visual and oculomotor characteristics of such displays, however, must be carefully designed so that the stereoscopic virtual images that they present are seen in the correction direction and at the appropriate apparent distance.

Perceptual errors in distance with such displays are especially troublesome if the viewer attempts to manipulatively interact with the virtual images treated as virtual objects. Recent observations of the apparent egocentric distances of stereoscopic virtual images have indicated that the perceived distance of virtual stereo images can be very labile, depending upon individual differences and the physical background against which they are seen (Ellis & Bucher, 1992). The interaction can be especially striking when an extended physical object is introduced as the apparent distance of the virtual object. Though in this condition vergence and accommodation conflict may be expected to be small, the apparent distance to the virtual image is for most observers shifted towards the viewer even when the distance based on disparity is within the approximately 1 meter setting of resting accommodation and vergence. The presumptive cause of this reduction is that the optical overlay of the virtual image, makes it appear to occlude the background, and thus appear closer. Planned research will test this hypothesis by studying the effects of varying the capacity of the virtual image to occlude the background and assist development of compensatory techniques to correctly display the apparent distance to spatial conformal, virtual images, close to the human operator.

**Benefits:** Successful design of head-mounted see-through stereo displays for fabrication will markedly increase assembly worker productivity and will provide information for improved design of nonsee-through head-mounted stereo viewing systems which may be used for visualizing and programming industrial robots as well as telerobots and for human operators procedure training.

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## Safer Communications in Air Traffic Control

**Mission:** Terminal Area Productivity Program, AS/A  
**Center:** Ames Research Center

**Problem:** In order to facilitate the increased traffic in the terminal area mandated by TAP, there must be a plan to facilitate an increased number of radio communications between tower and incoming and outgoing aircraft. Currently, single earpiece systems are used for one incoming channel, with additional communications relegated to a loudspeaker or telephone handset. There will also be a need for an increase in the number of warnings and alerts, within a high-stress environment that already places maximal demands on the visual system.

**VR Application/Approach:** The approach involves implementing a virtual auditory display for each controller's workstation, with air traffic controllers using 2-ear headsets. The cognitive workload involved in separating various communication streams can be reduced by using 3-D sound techniques within the auditory display to assign communications to specific locations. The placement of these communications can correspond to proximity, flight phase, or actual location out the window (with the addition of head-tracker technology). In addition to radio communications, psychoacoustically optimized aural alerts are desirable for integrating within the auditory display because of the increased load on the visual system for monitoring situational awareness. These aural alerts can be used either in addition to or as a substitute for visual alerts; their placement in virtual auditory space can be separated from radio communications, and spatialized according to operational criteria. Active noise reduction techniques allow the use of lightweight headsets and a reduction in background noise.

**Benefits:** Initial investigations have shown about a 6-7 dB improvement in intelligibility using a 4-channel system. A lessening of the demands on the visual modality will be beneficial. Because an auditory display controls all of the sound input to a controller's auditory system, distracting noise sources can be significantly attenuated, and a single control device can display all voice and alert communications in a coherent manner, either manually, or automatically. The load on the visual modality can be decreased.

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## Aeronautical Virtual Acoustic Displays

**Mission:** Terminal Area Productivity Program, AS/A  
**Center:** Ames Research Center

**Problem:** Current "glass cockpit" human factors design has relegated considerable attention to improving visual displays. Contrasting this, the display of acoustic information does not reflect an integrated design philosophy. The result is that desired signals- radio communications, inter-aircraft communications, auditory warning signals & alerts, feedback from aircraft engine system, control panel switch activation, etc.- are heard from indiscriminate sources (headset, various speakers) against a high level of background noise (76 dB at the left ear of the pilot in a Boeing 737). The priority of acoustic information under the best circumstances is a function of loudness (e.g., a loud fire alarm bell), an undesirable state of affairs in a high-stress human interface.

**VR Application/Approach:** The approach involves implementing a virtual auditory display, with pilots using 2-ear headsets. The placement and intensity of all of the auditory input to the pilot is strategically placed in a concordant manner that allows maximal intelligibility, prioritization, and positive redundancy. The cognitive workload and overall fatigue levels involved in separating various communication streams over one ear can be reduced by using 3-D sound techniques to separate auditory input to different locations. Previous studies at NASA Ames have shown a 6-7 dB improvement in intelligibility with 3-D auditory displays, which would help minimize hearback-readback problems between pilot and ATC; especially for airlines with hub operations, where call signs across one frequency are very similar. In addition to radio communications, psychoacoustically optimized aural alerts are desirable for integrating within the auditory display because of the increased load on the visual system for monitoring situational awareness. These aural alerts can be used either in addition to or as a substitute for visual alerts; their placement in virtual auditory space can be separated from radio communications, and spatialized according to operational criteria. The 3-D sound TCAS studies conducted at Ames have shown about a .5 second improvement in target acquisition time when using only 3-D sound alerts for aurally guided search, compared head down, standard TCAS displays; and a 2.5 second improvement when comparing one ear to two ear 3-D audio alerts. The placement of aircraft system alerts should correspond to meaningful, positive-redundant locations: e.g., the "left engine fire" verbal announcement comes from the left side. Aural feedback from non-visible sources (e.g., landing gear, control panel switches above the head) or visible "virtual" sources (e.g., the touch screen switches on the CDU panel) can be readily synthesized to give aural feedback about positive engagement, allowing the eyes to remain out-the-window. Active noise reduction techniques allow the use of lightweight headsets and a reduction in background noise, minimizing fatigue and the need to turn the head to direct the voice, e.g., pilot to flight engineer communications in a Boeing 727. Active noise reduction also allows reducing the level of one's own voice against noisy backgrounds (the *Lombard* effect), also contributing to less fatigue.

**Benefits:** Allowing pilots to have a quieter, organized presentation of desirable auditory information will allow safer operation of aircraft. This is certain to occur due to the known benefits from reduction of noise levels; the increase in intelligibility; positive redundancy between visual and auditory modalities; aural feedback from non-visible sources; and the advantages of aurally guided visual search as demonstrated in the NASA Ames 3-D audio TCAS studies.

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## Automated Training Evaluation and Improvement

**Mission:** Space Transportation System, Space Station, Exploration (Lunar/Mars)  
**Center:** Johnson Space Center

**Problem:** Systematic and objective collection of crew performance data during training for evaluation and for direct input into improvement measures is very difficult under present conditions. Data is now based on subjective crew comments and the opinion of trainers who must concentrate on conducting training, not evaluating it.

**VR Application/Approach:** When developing a virtual reality (VR), one needs to incorporate a large number of scenarios, each built up of a combination of specific events. If one has a list of these events and their parameters ahead of time, one can record how often an astronaut in the VR chooses to make them occur. In essence, you record a person's behavior, or at least the consequences of their behavior. The VR computer can also record instances where an astronaut wishes to do something in the VR but cannot. These occurrences can be used to augment the VR capability and repertoire, or they can be recorded as errors and trained away with feedback. Other astronauts could then actively or passively experience such errors to recognize and avoid them. Data could even be collected and applied in-flight during missions to the moon and Mars on the same tasks completed on the ground—something which is not possible now because of obvious constraints.

**Benefits:** Automated astronaut performance data collection during training would ensure objective data and continuous improvement. It would save time on the ground and in-flight, and would allow less expensive program upgrades. Operational experience would also be preserved from one crew (and astronaut) to another.

**Coordination:** SP/Man-Systems Division, CB/Astronaut Office, DG/Training Division, DT/Space Station Training Division

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## Designing Tools for Humans in Space

**Mission:** Space Transportation System, Space Station, Exploration (Lunar/Mars)  
**Center:** Johnson Space Center

**Problem:** Tools used in the exploration of space are often specially designed and manufactured in small numbers. The cost of designing and testing these tools is high because it cannot be offset with the reduced cost per unit gained from mass production. How can the cost of designing and testing these tools be reduced without compromising quality?

**VR Application/Approach:** If the design phase of a tool can incorporate a simulated utility phase, the iterative process of design and redesign will converge to a solution faster. Using VR as a means to simulate tool utilization will permit the designer to manipulate a tool with virtual hands and feet to test its performance in an infinite variety of scenarios while designing the tool. Issues such as clearance, leverage, ease of use and constraints can be analyzed in the design cycle. While not a substitute for the actual testing a manufactured tool, resolution of many of these issues will increase the probability of a successful design.

**Benefits:** The closer a tool design is to a quality product prior to manufacture the better and less costly the final product will be. Use of VR to enhance tool design will 1) permit redesign prior to manufacture to reduce cost and 2) increase the level of testing at the redesign stage to improve quality.

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## *In Situ Training*

**Mission:** Exploration (Lunar/Mars) and Planetary Science  
**Center:** Johnson Space Center

**Problem:** Long-duration missions, such as those envisioned in the SET, will require refresher crew training for infrequently performed tasks. Simulators containing hardware elements cannot be flown to support such training.

**Description:** Virtual environment technology would provide access to a complete simulation for crew training while in transit. Such simulation could encompass both EVA and IVA tasks and would be especially effective for infrequently performed tasks. This training could be extended to include planetary surface excursions and activities.

**Benefits:** Provide training capabilities not available through other mechanisms; enhance training and probability of mission success.

**Coordination:**

CB/Astronaut Office  
DG/Training Division  
DT/Space Station Training Division  
ER/Automation & Robotics Division  
PT4/Software Technology Branch  
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## Crew Health and Performance

**Missions:** Exploration (Lunar/Mars)  
**Center:** Johnson Space Center

**Problem:** Lunar and Mars missions will require astronauts to develop and maintain appropriate neurosensory and sensory-motor responses to three different gravito-inertial environments (1g, 0g, and 1/6 or 1/3 g). The adaptive responses developed for one environment will not be appropriate for the other two gravito-inertial environments. Generally speaking, the longer the exposure duration to a given gravity environment the more complete the adaptation to that environment which will likely result in a longer period of re-adaptation to either of the other gravity environments. Transition periods between different gravito-inertial environments can result in postural, gait, and visual instabilities, disturbances in eye-hand coordination, and motion sickness symptoms; all of these may impact crew health and performance.

**VR Application/Approach:** A head-mounted system, configured with head position or rate sensors, could be used to present and desired visual environment; a dataglove and or joystick could be used for performance of predetermined tasks. The head and limbs of the user could be loaded to simulate the appropriate gravitational force. In addition, a VR system integrated with an on-board centrifuge may be used to generate different gravitational force environments. The centrifuge could take the form of a bicycle mounted on a circular track inside the payload bay; the force field would be crew member generated, thus eliminating the need for Shuttle power to operate a traditional centrifuge. A set of tasks requiring eye-head and eye-hand coordination, and possibly locomotion could be designed with visual and tactile or force feedback correct for specific gravito-inertial environments. Crew members would practice various task scenarios throughout their mission. Such a system may include hardware for recording eye and limb movements.

**Benefit:** Inflight VR systems could help crew members maintain appropriate neurosensory and sensory-motor responses for multiple gravito-inertial environments.

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## Dynamic Virtual Environment Database

**Mission:** Exploration (Lunar/Mars)  
**Center:** Johnson Space Center

**Problem:** The Lunar/Mars environment is not well known by the crew. Simulators, mockups, photos will not give the crew enough information to plan and train for exploration on the lunar surfaces.

**VR Application/Approach:** A VE database would be a database of virtual experiences experienced from previous mission explorations and/or recordings of explorations done from non-manned vehicular exploration. These experiences could be used by flight planners to determine access to available sites. This type of planning would be done prior to training of the Crew. Crew members then would be able to retrace the previously explored terrain and plan paths for exploration based on the current sites explored. An example might be on the first mission the crew searched for Mare sites. The next crew mission is looking for areas that have mature regolith. If the crew could experience the previous EVA they may find the site they are looking for, or delete areas as possible exploration site. Note: The database is considered to be dynamic because it would have to be updated after every mission and in between missions from non-manned exploration data.

**Benefits:** Crew members could experience EVA environment before performing an EVA. The VE database would help crew train for different seasons, terrain, and tasks. It could reduce the cost and time of training the crew, performing the site selection task, and aid in mapping of lunar surfaces.

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## Task Analysis

**Mission:** Exploration (Lunar/Mars)

**Center:** Johnson Space Center

**Problem:** Analysis of problems that arise real-time is often times accomplished by the ground crew. It is sometimes necessary to use existing mockups to simulate the problem to be analyzed. These mockups do not always have the fidelity needed to accurately simulate the problem. The mockup may need to be reconfigured.

**VR Application/Approach:** Simulate the hardware of the space vehicle in a VR environment. The ground crew could reconfigure it to duplicate the problem. The VE could then be used to analyze the best approach to accomplish the appropriate task. The VE could then be stored for future use. The VR solution could be sent to the VR system on-board for training of the crew members.

**Benefits:** The VR environment of the space vehicle could be done before the hardware is flown. It could be used during the design phase to get the best human factor design. Used during all design and construction phases, the VE would be constantly kept updated. It is much less expensive and time consuming to redesign a virtual piece of hardware. It would give the crew members a better way of understanding the solution to the problem and also give them a chance to try the solution on the virtual hardware.

**Benefits:** A VR environment would allow faster and less expensive simulation and reconfiguration of the appropriate hardware for real-time task analysis.

**Coordination:** SP/Man-Systems Division

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## Crew Health -- Medical

**Mission:** Exploration (Lunar/Mars)

**Center:** Johnson Space Center

**Problem.** Crew members on long duration exploration missions will need medical treatment during the mission. A medical doctor may not be available onboard or may not be current in the treatment procedure for the crew member's illness/injury.

**VR Application/Approach:** A treatment procedure such as surgery could be sent electronically to the onboard medical attendant and that person could then use a VR system to experience the treatment, thereby gaining sufficient knowledge to carry it out onboard.

**Benefits:** The onboard medical attendant could be more effective in the treatment of crew member illness/injury by receiving such training.

### **Savings**

- Less People/Time: possibly enables a smaller crew.
- Less Money
- More Effectiveness

**Safety:** increases chances of crew member recovery.

**Increased Effectiveness:** enhance effectiveness of medical attendant

### **Coordination:**

IA/Advanced Initiatives Office

AP/Office of Public Affairs

CD/Astronaut Office

D/EVA and Crew Systems

DC/Training

PT4/Software Technology Branch

SP/Man-Systems

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## Crew Health -- Entertainment

**Mission:** Exploration (Lunar/Mars)  
**Center:** Johnson Space Center

**Problem:** Entertainment during long duration missions will be an important factor. Considerations for entertainment include: space & weight requirements, power requirements, cost, challenge for the mind, and flexibility.

**VR Application/Approach:** Virtual reality is making headway in the entertainment field at the present time. A VR system could be designed with a great many levels of flexibility and challenge. Different VR entertainment systems could be designed to suit different crew member's interests. The cost, space & weight requirements, and power requirements should be minimal with a VR system.

**Benefits:** A VR entertainment system would relieve the boredom that free time may bring during long duration missions. Crew members will be happier if they have a challenging and changing form of entertainment.

**Benefits:** A VR entertainment system could use a computer that is also utilized for other purposes.

**Coordination:** SP/Man-Systems Division

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## Crew Health -- Virtual Confidant

**Mission:** Exploration (Lunar/Mars)  
**Center:** Johnson Space Center

**Problem:** During long duration missions a problem or circumstance may be encountered that makes a crew member want to discuss their feelings with a confidant.

**VR Application/Approach:** With a confidant in a VR world, the crew member would be free to discuss their feelings about the problem without involving other crew members or the ground crew. This virtual confidant would have characteristics of some that the crew member trusts.

**Benefits:** Strife or preoccupation with personal matters can cause problems, not only with the individual crew member, but also with the team. Some crew members would be happier during long duration missions if they had this avenue available to them. Also, it would be less likely that they would involve others if there were another avenue to go through.

**Savings:** Happier crew members are more effective and efficient.

**Coordination:** SP/Man-Systems Division

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## *In Situ Training*

**Mission:** Exploration (Lunar/Mars)  
**Center:** Johnson Space Center

**Problem:** Crew members on extended missions will have to maintain their vehicle systems during the mission. They cannot train for all possible maintenance actions prior to the mission.

**VR Application/Approach:** An onboard VR system could be used for crew training and familiarization with maintenance actions they must accomplish.

**Benefits:** This could result in reduced preflight training requirements and increased inflight maintenance effectiveness.

**Savings:**

- Less People/Time: possibly reduces crew training time.
- Less Money
- More Effectiveness

**Safety:** reduces safety risk of inflight failures.

**Increased Effectiveness:** enhances mission success.

**Coordination:**

- IA/Advanced Initiatives Office
- AP/Office of Public Affairs
- CD/Astronaut Office
- D/EVA and Crew Systems
- DC/Training
- PT4/Software Technology Branch
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## Planetary Science

**Mission:** Exploration (Lunar/Mars)  
**Center:** Johnson Space Center

**Problem:** Crew members on planetary missions will explore the planet surface as much as possible. Scientists on Earth will also participate in this exploration.

**VR Application/Approach:** A VR system on Earth could allow scientists to more fully participate in planetary exploration.

**Benefits:** This could result in increased effectiveness in on-site crew members' exploration of the planet surface by utilizing inputs from Earth-based scientists who are also experiencing the exploration environment.

**Savings:**

- Less People/Time: possibly reduces crew size needed.
- Less Money
- More Effectiveness

**Increased Effectiveness:** enhances mission science return.

**Makes Impossible Possible:** enables Earth-based personnel to experience the planet surface.

**Coordination:**

- IA/Advanced Initiatives Office
- AP/Office of Public Affairs
- CD/Astronaut Office
- D/EVA and Crew Systems
- DC/Training
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## Shared Experience: Science, Operations, and Education

**Mission:** Exploration (Lunar/Mars)  
**Center:** Johnson Space Center

**Problem:** The experience of extended habitation in a sub-g environment will be difficult to communicate. Yet that communication will be important to at least four classes of people: mission planners responsible for subsequent missions; mission specialists who will train for subsequent missions; "earth-bound" scientists and other professionals who need to understand the human experience of exploring and working in an extraterrestrial environment; and the general public from whom NASA's support ultimately comes.

**VR Application/Approach:** A virtual model of the habitat and a portion of the surrounding environment can not only provide a faithful model of the spatial layout and the gravitational effects but can also be easily changed and can be ported to other computational platforms or shared through networking.

**Benefits:** Virtual simulation can disseminate information more widely than could be done in any other affordable way. Changes can be incorporated relatively easily, as modifications occur through time and as new features are discovered through exploration. The portability of software will allow planning and familiarization to take place in locations unrestricted by location and schedule of a physical simulator. Essentially the same models used for planning and training can be made available to scientists for their work and to the general public for their education.

**Coordination:**

- IA/Advanced Initiatives Office
- AP/Office of Public Affairs
- CD/Astronaut Office
- D/EVA and Crew Systems
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## Proficiency Training

**Mission:** Exploration (Lunar/Mars)  
**Center:** Johnson Space Center

**Problem:** As space flight becomes increasingly complex and of longer duration, higher levels of crew performance in an unfamiliar and stressful environment will be required. Stressors will include isolation from familiar work and living environments, potentially high workloads, weightlessness, and danger. In addition, due to the anticipated length of these missions, countermeasures for maintaining performance at acceptable levels will need to be developed. The current proposal seeks to explore the utility of VR technology as a proficiency training tool.

**VR Application/Approach:** Phase I -- Conduct an analysis of those activities to be performed on extended-duration missions and determine those which are likely to degrade due to lack of practice. Conduct a media analysis to assess those training objectives best taught through VR technology. Implement those objectives through a VR simulation. Phase II -- Conduct attribute and performance evaluations to assess the effectiveness of VR technology as a proficiency training tool. Phase III -- Demonstrate the use of VR technology as a proficiency training tool by developing an abbreviated training module.

**Benefits:** Use of this type of embedded training technology can be expected to provide a vehicle for maintaining the proficiency of those tasks to be performed on extended missions through intermittent virtual training enroute.

**Benefits:** Given the space limitations of current spacecraft, VR will provide a less expensive and more comprehensive means for ensuring acceptable levels of both individual and crew-coordinated task performance.

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## **After-the-Fact Analysis, Accident or Event Reconstruction**

**Mission:** Space Transportation System (STS)  
**Center:** Johnson Space Center

**Problem:** After problems arise aboard the Space Shuttle, methods used to assess the situation are often expensive, time-consuming, and inadequate for grasping the intricacies and complexity of the situation.

**VR Application/Approach:** Use the extensive available data to construct a VR and allow investigators and problem-solvers to more than review the data, but to actually immerse themselves in the scene and evaluate the situation as an observer or even participant.

**Benefits:** The added insight available to the investigators would allow a faster interpretation of the situation and result in faster corrective recommendations. This approach, rather than setting up full-size mockups for evaluation, could result in much less time and expense necessary for real-time problem-solving during a mission and could lead to better, more successful methods of dealing with the problem.

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## Hubble Space Telescope Maintenance/Repair

**Mission:** Space Transportation System (STS)  
**Center:** Johnson Space Center

**Problem:** Ground-based training for Hubble Space Telescope maintenance and repair is currently insufficient. No high fidelity mock up of the telescope exists on the earth, making it difficult to train for maintenance and repair work.

**Description:** NASA Hubble photo databases are currently available and can be used to create a visualization of the Hubble Space Telescope. Additionally, a Shuttle Extra Vehicular Activity can be simulated to effect Hubble repair actions. This virtual trainer would allow the astronaut to practice the sequence of actions required to successfully perform a Hubble repair mission.

**Benefits:** Provide currently unavailable training; reduce the time and cost required to train for HST maintenance and repair; enhance safety.

**Coordination:**

CB/Astronaut Office  
DG/Training Division  
DT/Space Station Training Division  
ER/Automation & Robotics Division  
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## **EVA/RMS Training and Procedures Development for HST Repair**

**Mission:** Space Transportation System (STS)  
**Center:** Johnson Space Center

**Problem:** Scenarios, such as the Hubble Space Telescope (HST) Repair Mission, require a great deal of coordinated interaction between the EVA crewmen and the Remote Manipulator System (RMS) operator. Development of detailed timelines and procedures to adequately train for such a mission is compromised by the fact that for ground based training there is no facility that can fully integrate EVA and RMS operations. Neutral Buoyancy facilities are available to simulate EVA activities, but no facility is large enough to employ a fully functional RMS; while computer graphics generated or hydraulically operated simulations of the RMS are used to train RMS operators, but provide no direct interaction with the EVA crew.

**Description:** A Virtual Reality system provides a relatively inexpensive and readily adaptable method for choreographing and integrating EVA tasks with RMS tasks to arrive at more realistic timelines and procedures. Each EVA crewman would be provided with a VR "helmet and gloves" to allow him to visually assess and interact with the movements of the other EVA crewman, the RMS, the HST and the orbiter payload bay configuration. The system could also be used to evaluate acceptable rates at which to maneuver the RMS while an EVA crewman is positioned on the Manipulator Foot Restraint (MFR). This system will not replace any of the current simulation facilities, but will effectively integrate multiple part task trainers. The same scenario is applicable to any mission involving coordinated EVA and manipulator operations whether they be orbiter based or station based.

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## Crew Training for Satellite Retrieval and/or Repair

**Mission:** Space Transportation System (STS)  
**Center:** Johnson Space Center

**Problem:** Ground-based systems for astronaut training cannot provide complete fidelity in the area of dynamic response to impulses imparted by crew and/or the Remote Manipulator System (RMS). Ground-based training systems are also expensive to build, maintain, and operate. Such systems may require large number of support personnel and may have limited access due to scheduling constraints.

**Description:** Simulation-based models of satellites are commonly-available for both engineering and operations development. These models may be modified to include sufficient dynamic behavior to support crew training for proximity operations, grapple, retrieval, repair, and redeployment. A VE utilizing such models would provide relatively low-cost, unlimited training experiences to astronauts as EVA procedures are developed and pre-flight training is conducted. Coupling the VE to an Intelligent-Computer Aided Training (ICAT) system would further reduce manpower and cost requirements, allowing astronauts to train independent of training personnel and facility availability.

**Benefits:** This approach would provide training unavailable in existing simulators, reduce training costs, and reduce training time.

**Coordination:**

CB/Astronaut Office  
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DG/Training Division  
DT/Space Station Training Division  
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## EVA Operations Development

**Mission:** Space Transportation System (STS)  
**Center:** Johnson Space Center

**Problem:** EVA operations development are currently performed with "pencil and paper" or with the use of expensive and scarce simulator resources.

**Description:** Virtual environment technology would provide those developing EVA operational procedures with a relatively inexpensive and accessible tools for primary operations development, verification, and the exploration of options. The speed with which applications can be developed and modified would also permit this approach to support real-time operations development during missions.

**Benefits:** Reduce the time and cost required to develop EVA operations; enhance safety; support real-time operations development in response to mission problems/challenges.

**Coordination:**

CB/Astronaut Office  
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## RMS Training

**Mission:** Space Transportation System (STS)  
**Center:** Johnson Space Center

**Problem:** The Shuttle Mission Simulator (SMS) at JSC is used for crew on-orbit training. The SMS currently does not provide complete fidelity in the area of dynamic response to impulses imparted by the Remote Manipulator System (RMS).

**Description:** The SMS provides a high fidelity crew station and state-of-the-art out-the-window and CCTV visual simulation using Evans & Sutherland ESIG-3000 image generators. Enhancement of simulator math models to include accurate dynamic behavior of free-flying payloads interacting with the RMS would maximize the effectiveness of the SMS for crew training. These math models could be adapted directly from application software developed for VE part-task trainers at little additional cost.

**Coordination:**

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## Near-Term VR Applications in Spacelab

**Mission :** Spacelab on Space Transportation System (STS)  
**Center:** Marshall Space Flight Center

Spacelab is a modular laboratory facility that is carried to and from orbit by the Space Shuttle. It includes a pressurized module (short and long configurations) and pallets that can be used in various combinations. It provides a shirt-sleeve, well-equipped laboratory environment where scientists can conduct investigations in a variety of disciplines, including material sciences, life sciences, astronomy, physics, etc.

**Objective:** The planning and preparation for a Spacelab flight begins years before the actual mission flies. Payload experiments must be defined and the equipment designed and fabricated. Operational concepts must be developed and procedures defined. The individual payloads must be analytically, as well as physically, integrated into the Spacelab system. Individual and integrated payload training, for both the crew and the Payload Operations Control Center (POCC) cadre, must take place. During the flight, significant ground support resources are expended on payload operations support, science monitoring, replanning, and Fault Detection, Isolation, and Recovery (FDIR).

Each of the planning, preparation, and execution activities present opportunities for application of VR technologies and techniques. Examples of applications that can utilize existing VR technology and capabilities can be found in the chapter on current VR activities. In large part, the current activities are focused on validating VR as a design and operations analysis tool. This section will propose specific applications of VR technologies and techniques that initially focus on the continued validation of classes of applications, but eventually evolve into strict application of VR as a design and operations analysis and support tool. The first two applications can be accomplished with the existing VR technology capabilities, though each is limited, for the most part, to visualization with minimal engagement of the object behavior and dynamics attributes. The other proposed applications require enhancements over existing VR technology and capabilities, particularly in the area of object behavior and dynamics attributes. As these enhancements come on line, future Spacelab flights (i.e., those occurring within the next 3-4 years) will benefit.

**VR Application/Approach:** The first proposed application is related to initial crew and POCC cadre training. As a new crew or cadre member is assigned to a Spacelab mission there is a familiarization phase for both mission independent Spacelab systems and capabilities and mission dependent payload systems and capabilities.

Early in the mission planning and development process, this training is accomplished in the classroom and through Spacelab systems and mission documentation. The full-scale Payload Crew Training Complex (PCTC) training mock-up and simulators are not yet available. For personnel assigned later, the PCTC training mock-up may be in place, but access may be limited due to simulator development and training activities.

In either case there is a period during which the newcomer must quickly assimilate a large amount of information into his or her concurrently evolving schema or mental model of Spacelab. A tour through a virtual Spacelab may initialize the newcomer *and* provide insights into system functionality and capabilities. If successful, this could provide a basis for a more accelerated training program and a better integrated understanding of Spacelab systems and payloads.

The essential feature of this application is one or more Virtual Spacelab Modules (VSLMs). Depending on the focus of the "lesson", there may be several VSLMs, each configured to support that lesson objective. For example, Spacelab Program Overview may use standard Spacelab systems in both the long and short modules and perhaps even the pallets only configuration. Mission specific training could use a Spacelab systems only VSLM and/or an integrated systems/payload VSLM. In addition, each system and payload could be "exploded" to permit visualization of its constituent components and their interrelationships.

The exact details for a particular VSLM would depend on specific training objectives and existing VR technology capabilities and limitations. Validation of this application will be based primarily upon subjective data gathered through questionnaires and structured. As the VR technology capabilities are enhanced, this application can be expanded to include additional, more complex training objectives.

A related "real world" application, utilizing existing VR technology capabilities, involves using VSLMs during the last nine-to-six months before launch. There are always late changes to on-board stowage. As changes are made, the PCTC Training mock-up is updated. It is desirable to allow the crew the opportunity to tour the mock-up to "see" the latest stowage configuration. This helps to "internalize" the location of items within the Spacelab module. Unfortunately, as the launch date approaches, access to the crew becomes more and more limited, particularly during the last three months.

A VSLM with the updated stowage configuration would enable a more convenient, even remote, method to "visualize" changes in stowage locations. Updated VSLM files could even be electronically transmitted to the Johnson Space Center (JSC) for the crew to "tour" on the JSC VR system. Validation of this application, like the previous real-world application, will be based primarily upon subjective data gathered through questionnaires and structured.

This ability to electronically transfer Virtual Worlds (VWs) further enhances the familiarization/initialization training application discussed above. In fact, another existing VR technology capability can enhance both of the "real world" Spacelab applications. Using both the MSFC and JSC VR systems simultaneously, the users could enter and interact within the same VSLM at the same time, even though they are physically located in different states! This would permit, for example, a "tour guide" for the Spacelab Program Overview or a Mission Specialist accompanied by the stowage manager or a Payload Specialist for the stowage "walk-thru".

Two major enhancements are required in object behavior and dynamics attributes for more advanced applications of VR technology. These are incorporation of an anthropometric model and a physics properties simulator reflecting physical laws concerning motion and collisions.

The anthropometric model should include link lengths to reflect a broad anthropometric design range (e.g., 5th percentile female through the 95th percentile male) and realistic joint range-of-motion capabilities and constraints. The physics properties simulator should include realistic linear and angular acceleration/velocity and kinetic energy transfer.

As these enhancements come on line, the training application discussed above, for example, can be expanded to cover more demanding training objectives. However, instead of discussing an expanded training application, another application will be proposed, although the discussion applies to the training application as well.

A demanding and comprehensive application for VR is support of unplanned Inflight Maintenance (IFM). That is, subsets of the features and VR capabilities required to support this application are used in a variety of other applications. Support to unplanned IFM requires Human Factors analyses (e.g., viewing, reach, and dynamic work envelope analyses), operations development, training, mission support, and even simultaneous participation by physically separated users in the same VE.

An example of an unplanned IFM occurred on Spacelab 3. This actual Spacelab mission experience will also be used for comparison in the validation of this application. The goal would be to actually recreate the IFM environment and operation, then compare this virtual IFM experience with the actual flight experience. This would include reference to video and audio recordings of the on-board operation, written logs, and participation of the actual Spacelab crew involved in the IFM operation.

During Spacelab 3, the Drop Dynamics Module (DDM) developed a problem with a power supply module. No procedures or plans had been developed pre-mission for this particularly contingency. No spare power supplies were stowed. It was decided to remove an in-service power supply, from another on-board system, and use it in the DDM. Procedures had to be developed and validated on the ground and approved by both MSFC and JSC before uplink to the crew. The procedure required removal of the rack front panel before the Payload Specialist (PS) entered head first. Only his legs remained visible outside of the rack. Inside the cramped rack interior, the PS successfully exchanged the power supply modules and continuation of the science objectives resumed.

It is anticipated that enhanced VR will be capable of supporting many of the activities and analyses that occurred on the ground in support of this unplanned IFM. Viewing analyses, reach envelope analyses, and, with an incorporated anthropometric model, dynamic work envelope analyses can be achieved

concurrently with procedure development. Although much of this can be done in an engineering mock-up, VR offers several unique capabilities.

First, VR could provide a timely and safe method to enable the various advantages and disadvantages of reaching and maneuvering in a microgravity environment. This includes body attitudes and positions difficult to recreate in a one-G environment. This would be superior to existing methods for simulating micro-gravity because existing methods can not be used in a timely manner and are of limited durations (KC-135) or require ancillary equipment (Neutral Buoyancy Simulator) that can interfere with operations in restricted volumes.

Second, VR would permit anthropometric sizing to reflect the dimensions of the on-board crew. This is particularly useful for operations being planned in relatively tight spaces.

Once the DDM IFM procedures had been developed and validated, MSFC and JSC had to approve the operation before it could be implemented. VR would offer the mission and payload managers the ability to visualize the procedure and environment to gain a faster and more in-depth understanding of the operation. This could be accomplished while the managers are sitting at their consoles in the control center. Further, managers, at both centers, could enter the VW, simultaneously, to review and discuss the operation. This capability for direct mission support would be unprecedented, though the possibilities are not limited unplanned IFM.

Pre-mission operations development and validation could also be carried out in the same manner, even though the rapid turn-around capability of VR is not necessarily a requirement. Pre-mission crew training could use the same VWs developed to support procedure development. This would prove particularly beneficial for operations where the various advantages and disadvantages of reaching and maneuvering in a microgravity environment make a difference.

The second United States Microgravity Laboratory (USML-2), scheduled for launch on May 6, 1995, is proposed as the first "full-up" VR applications Spacelab. VR will have been applied, for selected analyses, on earlier Spacelab missions, but USML-2 will be the first mission to which all of the techniques and validated tools, resulting from the previous phases, will be applied.

USML-2 is the second in a series of Spacelab flights that focus on microgravity materials processing technology, science, and research. These USML missions emphasize technology development within the United States to develop Space Station applications.

USML-2 was selected primarily because it is the first full module mission to which the validated VR tools will be "on-line" during the appropriate phase of the program. That is, for example, validated Human Factors analytical tools during the design phase, Spacelab module familiarization trainer early in the training phase, stowage trainer in the last months before launch, and an enhanced set of tools for real-time mission support.

A secondary reason USML-2 was chosen is because USML-1 flies June 3, 1992. It is anticipated that a portion of USML-2 will be of USML-1 experiments. Thus, USML-1 provides actual flight experiences upon which to base USML-specific validation studies. Further, it might provide insights into potential mission peculiar IFMs. This could help refine the USML-2 VW requirements.

**Benefits:** The potential benefits from the application of VR technologies and techniques to Spacelab planning, preparation, and execution are significant. More efficient utilization of constrained resources can be realized.

Viewing analyses, reach envelope analyses, and, with an incorporated anthropometric model, dynamic work envelope analyses can be achieved concurrently with procedure development. VR can provide a timely and safe method to enable the various advantages and disadvantages of reaching and maneuvering in a microgravity environment. This would be superior to existing methods for simulating micro-gravity because existing methods can not be used in a timely manner and are of limited durations. Even where the KC-135 and/or the NBS are appropriate, prior utilization of virtual mockups can result in more efficient use of these micro-gravity simulators. Hardware and operations design can be more mature, resulting in fewer and/or more productive simulator sessions.

Pre-mission operations development and validation can utilize VR. Pre-mission crew training could use the same VVs developed to support procedure development. This would prove particularly beneficial for operations where the various advantages and disadvantages of reaching and maneuvering in a microgravity environment make a difference.

A VSLM with the updated stowage configuration can enable a more convenient, even remote, method to "visualize" changes in stowage locations. Using both the MSFC and JSC VR systems simultaneously, the users could enter and interact within the same VSLM at the same time. This can permit, for example, a "tour guide" for the Spacelab Program Overview or a Mission Specialist accompanied by the stowage manager or a Payload Specialist for the stowage "walk-thru".

Once unplanned IFM procedures have been developed and validated, MSFC and JSC must approve the operation before it can be implemented. VR would offer the mission and payload managers the ability to visualize the procedure and environment, while sitting at their consoles in their respective control centers. Further, managers, at both centers, could enter the VW, simultaneously, to review and discuss the operation. This capability for direct mission support would be unprecedented, though the possibilities are not limited unplanned IFMs.

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## Crew Health and Performance

**Mission:** Space Transport System (STS) and Space Station  
**Center:** Johnson Space Center

**Problem:** Resolution of space motion sickness, and improvements in spatial orientation, posture and motion control, and compensatory eye movements occur as a function of neurosensory and sensory-motor adaptation to microgravity. These adaptive responses, however, are inappropriate for return to Earth and can result in postural, gait, and visual instabilities as well as disturbances in eye-hand coordination. As mission duration increases, these neurosensory and sensory-motor disturbances are expected to be magnified and may impact crew safety during the entry/landing and egress phases of the mission.

**VR Application/Approach:** A head-mounted system, configured with head position or rate sensors, could be used to present and desired visual environment; a dataglove and or joystick could be used for performance of predetermined tasks. The head and limbs of the user could be loaded to simulate a 1g gravitational force. A set of tasks requiring eye-head and eye-hand coordination, and possibly locomotion could be designed with visual and tactile or force feedback correct for a 1g environment. Crew members would practice various task scenarios prior to their return to Earth. Such a system may include instrumentation for recording eye and limb movements.

**Benefits:** A VR system and training scenarios are being developed for preadapting astronauts to microgravity and to maintain adaptation to Earth (i.e., to produce dual-adapted states). This system is called the device for orientation and motion environments (DOME) - preflight adaptation trainer (PAT). For long-duration STS and Space Station missions, an inflight VR system could help crew members maintain appropriate neurosensory and sensory-motor responses for the 1g Earth environment.

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## SAFER Engineering Test and Development

**Mission:** Space Transportation System (STS) / Space Station  
**Center:** Johnson Space Center

**Problem:** The Simplified Aid For EVA Rescue (SAFER) project is developing a "mini-backpack" for use by EVA crew members at Space Station as a means of self-rescue in the event that they inadvertently become untethered from the structure. Control algorithm development and testing for the SAFER are performed on ground based simulators and have to take into account all the various control modes and operational scenarios to validate the functional design. Stereo visual cues, with a wide field-of-view, are a major contributor to the operation and thus the design of the control system. Motion base simulations for this type of development are cost prohibitive.

**Description:** A VR system provides the display technology required for crew evaluation of the SAFER system's ability to perform its desired function, as well as a means of investigating additional operating scenarios or control system strategies. The VR system also provides a realistic training environment for future users of the SAFER.

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## Manipulator Systems Training

**Mission:** Space Station  
**Center:** Johnson Space Center

**Problem:** The Space Station Training Facility (SSTF) at JSC will include a cupola trainer for crew out-the-window training tasks. The SSTF is not planned to provide complete fidelity in the area of dynamic response to impulses imparted by the manipulator systems controlled from the Space Station cupola.

**Description:** The SSTF will provide a high fidelity crew station and state-of-the-art out-the-window and CCTV visual simulation using Evans & Sutherland ESIG-3000 image generators. Enhancement of simulator math models to include accurate dynamic behavior of free-flyers interacting with the station manipulators would maximize the effectiveness of the SSTF for crew training. These math models could be adapted directly from application software developed for VE part-task trainers at little additional cost.

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## Space Station Construction

**Mission:** Space Station  
**Center:** Johnson Space Center

**Problem:** The Space Systems Automated Integration and Assembly Facility (SSAIAF) at JSC will be used for on-orbit assembly procedures development and training. The SSAIAF is intended to provide good fidelity in the area of dynamic response between free-flying structures, the shuttle orbiter, and manipulator systems using a high-fidelity real-time simulation driving mechanical systems. Currently, there are no plans for a system to validate results from SSAIAF simulations.

**Description:** A VE component dedicated to the SSAIAF facility could reduce risk by providing a check against hardware system results and a visual view of scenes not possible to represent accurately with the test-oriented hardware.

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## *In Situ Training*

**Mission:** Space Station

**Center:** Johnson Space Center

**Problem:** Long-duration missions, such as the Space Station, will require refresher crew training for infrequently performed tasks. Simulators containing hardware elements cannot be flown to support such training.

**Description:** Virtual environment technology would provide access to a complete simulation for crew training while onboard the Space Station. Such simulation could encompass both EVA and IVA tasks and would be especially effective for infrequently performed tasks.

**Benefits:** Provide training capabilities not available through other mechanisms; enhance training and probability of mission success.

**Coordination:**

CB/Astronaut Office

DG/Training Division

DT/Space Station Training Division

ER/Automation & Robotics Division

PT4/Software Technology Branch

SP/Man-Systems Division

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## Crew Medical Restraint System

**Mission:** Space Station  
**Center:** Johnson Space Center

**Problem:** Simulating transport of an injured crew member on the Crew Medical Restraint System (CMRS) from Space Station to the orbiter mid-deck through the transfer tunnel in 1 g. The difficulty arises in performing the simulation when passing the restrained injured crew member through the 90 degree turn in the tunnel prior to entry into the orbiter airlock.

**VR Application/Approach:** VR could be used to verify whether transport of the restrained crew member with attending Crew Medical Officer(s) (CMO) and medical equipment is actually possible. Furthermore, VR could be used to determine the optimal configuration for passing the patient and CMO(s) through the tunnel and into the orbiter.

**Benefits:** This application of VR would simplify a logistically difficult Health Maintenance Facility (HMF) simulation scenario. Other possible options for performing this simulation have various limitations associated with them. For example if CHeCS were to perform this simulation in the WETF they would have to deal with the divers oxygen tanks which would probably add a level of difficulty to passing through the tunnel and thus would not provide an accurate simulation of the transport scenario or the volume envelope of the crew members. When CHeCS performs this simulation on the KC-135 the period of weightlessness is not long enough to definitively determine if there should be two patient attendees as opposed to one. In addition the KC-135 is not large enough to create an actual mockup of the tunnel with the 90 degree turn which is one of the main problems in the simulation. The only other possible alternative to assess a complete solution is to simulate this patient transport scenario on the shuttle which would be costly and probably could not be manifested during the development period of the CMRS. Consequently the use of Virtual Reality in this simulation would probably have safety and reliability benefits as well as an increased effectiveness in the design of the CMRS and the actual development of the operational scenario.

**Coordination:**

IA/Advanced Initiatives Office  
AP/Office of Public Affairs  
CD/Astronaut Office  
D/EVA and Crew Systems  
DC/Training  
PT4/Software Technology Branch  
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## Space Station Operations (IVA and EVA)

**Mission:** Space Station  
**Center:** Johnson Space Center

**Problem:** EVA and IVA operations development are currently performed with "pencil and paper" or with the use of expensive and scarce simulator and/or mockup resources.

**Description:** Virtual environment technology would provide those developing Space Station operational procedures with a relatively inexpensive and accessible tools for primary operations development, verification, and the exploration of options. The speed with which applications can be developed and modified would also permit this approach to support real-time operations development during missions.

**Benefits:** Reduce the time and cost required to develop Space Station EVA and IVA operations; enhance safety; support real-time operations development in response to mission problems/challenges.

**Coordination:**  
CB/Astronaut Office  
DG/Training Division  
DT/Space Station Training Division  
ER/Automation & Robotics Division  
PT4/Software Technology Branch  
SP/Man-Systems Division

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## Near-Term VR Applications in Space Station

**Mission :** Space Station  
**Center:** Marshall Space Flight Center

Space Station will be a permanently manned orbiting facility that will serve as a permanent observatory and provide research capabilities in such disciplines as fluid physics, materials sciences, combustion, biotechnology, life sciences and technology. The Space Station Program is currently entering the critical design phase where major decisions regarding design and operations are being made. As the operations and utilization phase approaches, planning for payload operations is beginning. This includes payload experiment development, payload analytical integration, training and operations support.

**Objective:** During the critical design phase, intra- and inter-system design is progressing to an ever finer level of detail. Throughout this phase, analytical studies compare alternate candidate design solutions and evaluate the consequences of design decisions. Operations concepts, for both system operation and maintenance, are also maturing during this phase. Operations development is accomplished hand-in-hand with hardware development, both in turn being refined during each iteration to approach an "optimal" man-machine system. This hardware and operations development can benefit through the application of VR technologies and techniques.

The planning and preparation for an Space Station increment begins years before the actual mission flies. Payload experiments must be defined and the equipment designed and fabricated. Operational concepts must be developed and procedures defined. The individual payloads must be analytically, as well as physically, integrated into the Space Station system. Individual and integrated payload training, for both the crew and the Payload Operations Integration Center (POIC) cadre, must take place. During the increment, significant ground support resources are expended on payload operations support, science monitoring, replanning, and Fault Detection, Isolation, and Recovery (FDIR). Each of the planning, preparation, and execution activities present opportunities for application of VR technologies and techniques.

Examples of applications that can utilize existing VR technology and capabilities can be found in the chapter on current VR activities. In large part, the current activities are focused on validating VR as a design and operations analysis tool. This section will describe potential applications of VR technologies and techniques as a design and operations analysis and support tool. Many applications can be accomplished with the existing VR technology capabilities, though each is limited, for the most part, to visualization with minimal engagement of the object behavior and dynamics attributes. Other applications require enhancements over existing VR technology and capabilities, particularly in the area of object behavior and dynamics attributes. As these enhancements come on line, future Space Station development, and operations will benefit.

**VR Application/Approach:** Human Factors issues and considerations in hardware and operations development present a large class of potential VR applications. VR technologies and techniques currently provide some limited macro- and micro-ergonomic analytical tools for consideration of operational, viewing and reach envelope requirements, in both one-gravity and microgravity environments.

An algorithm has been developed to rescale user anthropometric attributes to any desired virtual anthropometry. Thus, a 95th percentile male could view and reach as a virtual 5th percentile female and vice-versa. Further, a technique has been developed where the user inside a virtual module can manipulate the attitude of that module, as a whole, while "grabbing" a handrail, giving the egocentric perception of microgravity mobility. This can provide some of the various advantages and disadvantages of reaching and maneuvering in microgravity.

Combined with scaleable user anthropometry attributes, macro-ergonomics analyses for the topological design of work areas can consider what one is able to see from a variety of eye reference points using a range of virtual anthropometric sizes. These analyses can include operationally-driven components such as translation paths among the various worksites. Micro-ergonomics analyses for the spatial layout of workstations can consider what one is able to see from a variety of eye reference points and on what one is able to touch from a variety of shoulder and seat reference points and/or foot restraint locations.

VR technologies and techniques can be applied in the Space Station Program, starting during the critical design phase. Many analyses that use Fomecor mockups, the KC-135, or the Neutral Buoyancy Simulator are candidates for VR. It is not that VR would completely replace these other technologies and techniques, but that it adds another tool to the analytical toolkit.

In some instances, VR might be considered for use in an analysis that would have otherwise not be undertaken. Resources (time, people, materials, etc.) required for a "standard" simulation or mock-up analysis may be greater than the expected return. In this case VR, due to its relatively low utilization costs, would surpass the cost/benefit ratio threshold and enable an analysis that would have otherwise been forgone.

Similarly, VR can enhance and enable more effective utilization of standard simulations and mock-up analyses. By preceding these analyses with preliminary VR analyses, both the hardware and operations can be refined so that the return from the standard analyses is increased. This is accomplished by either reducing the magnitude or number of standard analyses and/or improving the fidelity of those analyses with a more mature design.

Because the Virtual Worlds (VWs) are nothing more than computer files, design changes can be done more quickly and more candidate configurations can be subsequently analyzed than is currently possible with existing, "standard" Human Factor tools (e.g., Fomecor mockups).

The list of potential VR critical design phase assessments/analyses is extensive. Only a few examples are given here, these include maintenance access (e.g., within a rack, behind a standoff, etc.), restraint and mobility aid location, rack pivot/removal, module topology and color selections, and logistics module access and resupply operations (e.g., translation routes, mobility aids, etc.). Design of ground support and processing facilities and operations can also benefit through VR utilization. Using VR to visualize and interact with various Payload Operations Integration Center (POIC) configuration options, for example, provides a design analytical capability that is not otherwise possible.

Many of the design analytical applications for the SSFP critical design phase can be applied equally effectively to the design and integration of payloads. A more general operations and utilization application is related to initial crew and POIC cadre training. As a new crew or cadre member is assigned to a Space Station increment there is a familiarization phase for both increment independent Space Station systems and capabilities and increment dependent payload systems and capabilities.

Early in the increment planning and development process, this training will be accomplished in the classroom and through Space Station systems and increment documentation. The full-scale Payload Training Complex (PTC) training mock-up and simulators will not yet be available. For personnel assigned later, the PTC training mock-up may be in place, but access may be limited due to simulator development and training activities.

In either case there is a period during which the newcomer must quickly assimilate a large amount of information into his or her concurrently evolving schema or mental model of Space Station. A tour through a virtual Space Station may initialize the newcomer and provide insights into system functionality and capabilities. If successful, this could provide a basis for a more accelerated training program and a better integrated understanding of Space Station systems and payloads.

A related application, utilizing existing VR technology capabilities, involves using a virtual Space Station during the last nine-to-six months before an increment. As with Spacelab, it is anticipated there will be late changes to on-board stowage. As changes are made, the PTC Training mock-up will be updated. It is desirable to allow the crew the opportunity to tour the mock-up to "see" the latest stowage configuration. This helps to "internalize" the location of items within the Space Station module. Unfortunately, as the launch date approaches, access to the crew becomes more and more limited, particularly during the last three months.

A virtual Space Station with the updated stowage configuration would enable a more convenient, even remote, method to "visualize" changes in stowage locations. Updated VW files could even be electronically transmitted to the Johnson Space Center (JSC) for the crew to "tour" on the JSC VR system.

This ability to electronically transfer Virtual Worlds (VWs) further enhances the familiarization/initialization training application discussed above. In fact, another existing VR technology capability can enhance many Space Station applications. Using both the MSFC and JSC VR systems simultaneously, the users could enter and interact within the same virtual Space Station at the same time, even though they are physically located in different states! This would permit, for example, a "tour guide" for the Space Station Program Overview or a Mission Specialist accompanied by the stowage manager or a Payload Specialist for the stowage "walk-thru".

Two major enhancements are required in object behavior and dynamics attributes for more advanced applications of VR technology. These include the incorporation of an anthropometric model and a physics properties simulator reflecting physical laws concerning motion and collisions. The former should include link lengths to reflect a broad anthropometric design range (e.g., 5th percentile female through the 95th percentile male) and realistic joint range-of-motion capabilities and constraints. This enhancement would enable dynamic work envelope analyses. The physics properties simulator should include realistic linear and angular acceleration/velocity and kinetic energy transfer.

As these enhancements come on line, the training application discussed above, for example, can be expanded to cover more demanding training objectives. However, instead of discussing an expanded training application, another application will be proposed, although the discussion applies to the training application as well.

A demanding and comprehensive application for VR is support of unplanned Inflight Maintenance (IFM). That is, subsets of the features and VR capabilities required to support this application are used in a variety of other applications. Support to unplanned IFM requires Human Factors analyses (e.g., viewing, reach, and dynamic work envelope analyses), operations development, training, mission support, and even simultaneous participation by physically separated users in the same VE.

It is anticipated that enhanced VR will be capable of supporting many of the activities and analyses that occur on the ground in support of an unplanned IFM. Viewing analyses, reach envelope analyses, and with an incorporated anthropometric model, dynamic work envelope analyses can be achieved concurrently with procedure development. Although much of this can be done in an engineering mock-up, VR offers several unique capabilities.

First, VR could provide a timely and safe method to enable the various advantages and disadvantages of reaching and maneuvering in a microgravity environment. This includes body attitudes and positions difficult to recreate in a one-G environment. This would be superior to existing methods for simulating micro-gravity because existing methods can not be used in a timely manner and are of limited durations (KC-135) or require ancillary equipment (Neutral Buoyancy Simulator) that can interfere with operations in restricted volumes. Second, VR would permit anthropometric sizing to reflect the dimensions of the on-board crew. This is particularly useful for operations being planned in relatively tight spaces.

VR would offer the mission and payload managers the ability to visualize the procedure and environment to gain a faster and more in-depth understanding of the operation. This could be accomplished while the managers are sitting at their consoles in the control center. Further, managers, at both centers, could enter the VW, simultaneously, to review and discuss the operation. This capability for direct mission support would be unprecedented, though the possibilities are not limited unplanned IFM.

Pre-mission operations development and validation could also be carried out in the same manner, even though the rapid turn-around capability of VR is not necessarily a requirement. Pre-mission crew training could use the same VWs developed to support procedure development. This would prove particularly beneficial for operations where the various advantages and disadvantages of reaching and maneuvering in a microgravity environment make a difference.

**Benefits:** The potential benefits from the application of VR technologies and techniques to the Space Station design phase and operations and utilization phase are significant. More efficient utilization of constrained resources can be realized.

Viewing analyses, reach envelope analyses, and, with an incorporated anthropometric model, dynamic work envelope analyses can be achieved concurrently with procedure development. VR can provide a timely and safe method to enable the various advantages and disadvantages of reaching and



maneuvering in a microgravity environment. This would be superior to existing methods for simulating micro-gravity because existing methods can not be used in a timely manner and are of limited durations. Even where the KC-135 and/or the NBS are appropriate, prior utilization of virtual mockups can result in more efficient use of these micro-gravity simulators. Hardware and operations design can be more mature, resulting in fewer and/or more productive simulator sessions.

Pre-increment operations development and validation can utilize VR. Pre-increment crew and cadre training could use the same VWs developed to support procedure development. This would prove particularly beneficial for operations where the various advantages and disadvantages of reaching and maneuvering in a microgravity environment make a difference.

A virtual Space Station with the updated stowage configuration can enable a more convenient, even remote, method to "visualize" changes in stowage locations. Using both the MSFC and JSC VR systems simultaneously, the users could enter and interact within the same VW at the same time. This can permit, for example, a "tour guide" for the Space Station Program Overview or a Mission Specialist accompanied by the stowage manager or a Payload Specialist for the stowage "walk-thru".

VR can support operations development and validation during an increment. VR would offer the mission and payload managers the ability to visualize the procedure and environment. Both could enter the VW, simultaneously, to review, discuss, and approve the operation. This capability for direct mission support would be unprecedented.

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## Near-Term VR Applications in the Design of the Advanced X-ray Astrophysics Facility

**Mission :** The Great Observatory series  
**Center:** Marshall Space Flight Center

The Advanced X-ray Astrophysics Facility (AXAF) will serve as a permanent X-ray observatory for studying such phenomena as stellar evolution and the structure of active galaxies. The AXAF Program is currently being redefined. Two spacecrafts will be developed and launched separately. AXAF-I (Imaging) will be launched aboard the Space Shuttle and placed in a "parking orbit" to be later boosted, with a "kick-motor", to probably a 10K by 100K km orbit. The other spacecraft, AXAF-S (Spectrometry) will be launched aboard a Delta rocket, possibly to a 10K by 100K km polar orbit. AXAF-I is currently approaching the Systems Requirements Review. AXAF-S is still in the definition phase.

**Objective:** Neither AXAF spacecraft are being designed for on-orbit maintenance, as the Hubble Space Telescope was. Thus, the scope of potential VR applications is somewhat reduced. That is, operations concepts for maintenance and associated hardware features (e.g., restraints and mobility aids) are not being considered. These areas provide a fertile environment for VR applications. However, since the AXAF-I is shuttle-deployed, there will be, at some point, planning for mission-success contingency Extravehicular Activities (EVAs). VR can contribute to this process. Throughout this process, analytical studies compare alternate candidate design solutions and evaluate the consequences of design decisions. Operations development can be accomplished hand-in-hand with hardware development, both in turn being refined during each iteration to approach an "optimal" man-machine system. This hardware and operations development can benefit through the application of VR technologies and techniques.

Examples of applications that can utilize existing VR technology and capabilities can be found in the chapter on current VR activities. In large part, the current activities are focused on validating VR as a design and operations analysis tool. This section will describe potential applications of VR technologies and techniques as a design and operations analysis and support tool. Many applications can be accomplished with the existing VR technology capabilities, though each is limited, for the most part, to visualization with minimal engagement of the object behavior and dynamics attributes. Other applications require enhancements over existing VR technology and capabilities, particularly in the area of object behavior and dynamics attributes. As these enhancements come on line, future AXAF development, and operations will benefit.

**VR Application/Approach:** Human Factors issues and considerations in hardware and operations development present a large class of potential VR applications. VR technologies and techniques currently provide some limited macro- and micro-ergonomic analytical tools for consideration of operational, viewing and reach envelope requirements, in both one-gravity and microgravity environments.

An algorithm has been developed to rescale user anthropometric attributes to any desired virtual anthropometry. Thus, a 95th percentile male could view and reach as a virtual 5th percentile female and vice-versa. Further, a technique has been developed where the user can manipulate the attitude of virtual spacecraft, as a whole, while "grabbing" a handrail, giving the egocentric perception of microgravity mobility. This can provide some of the various advantages and disadvantages of reaching and maneuvering in microgravity.

Combined with scaleable user anthropometry attributes, macro-ergonomics analyses for the topological design of work areas can consider what one is able to see from a variety of eye reference points using a range of virtual anthropometric sizes. These analyses can include operationally-driven components such as translation paths among the various worksites. Micro-ergonomics analyses for the spatial layout of worksites can consider what one is able to see from a variety of eye reference points and on what one is able to touch from a variety of shoulder and seat reference points and/or foot restraint locations.

VR technologies and techniques can be applied in the AXAF Program. Many analyses that use Fomecor mockups, the KC-135, or the Neutral Buoyancy Simulator are candidates for VR. It is not that VR would completely replace these other technologies and techniques, but that it adds another tool to the analytical toolkit.

In some instances, VR might be considered for use in an analysis that would have otherwise not be undertaken. Resources (time, people, materials, etc.) required for a "standard" simulation or mock-up analysis may be greater than the expected return. In this case VR, due to its relatively low utilization costs, would surpass the cost/benefit ratio threshold and enable an analysis that would have otherwise been forgone.

Similarly, VR can enhance and enable more effective utilization of standard simulations and mock-up analyses. By preceding these analyses with preliminary VR analyses, both the hardware and operations can be refined so that the return from the standard analyses is increased. This is accomplished by either reducing the magnitude or number of standard analyses and/or improving the fidelity of those analyses with a more mature design.

Because the Virtual Worlds (VWs) are nothing more than computer files, design changes can be done more quickly and more candidate configurations can be subsequently analyzed than is currently possible with existing, "standard" Human Factor tools (e.g., Fomecor mockups).

In addition to the planning and development of contingency EVAs, design of ground support and processing facilities and operations can also benefit through VR utilization. Using VR to visualize and interact with various AXAF control center configuration options, for example, provides a design analytical capability that is not otherwise possible. A more general operations and utilization application is related to initial AXAF ground support personnel training. As a member is assigned to the AXAF cadre there is a familiarization phase for AXAF systems and capabilities.

There is a period during which the newcomer must quickly assimilate a large amount of information into his or her concurrently evolving schema or mental model of AXAF. A tour through a virtual AXAF may initialize the newcomer and provide insights into system functionality and capabilities. If successful, this could provide a basis for a more accelerated training program and a better integrated understanding of AXAF systems.

A virtual AXAF would enable a more convenient, even remote, method to "visualize" AXAF systems. Updated VW files could even be electronically transmitted to other VR sites for visualizing. This ability to electronically transfer Virtual Worlds (VWs) further enhances the familiarization/initialization training application discussed above. In fact, another existing VR technology capability can enhance many AXAF applications. Using both the MSFC and JSC VR systems simultaneously, the users could enter and review contingency EVA procedures and hardware implications.

Two major enhancements are required in object behavior and dynamics attributes for more advanced applications of VR technology. These include the incorporation of an anthropometric model and a physics properties simulator reflecting physical laws concerning motion and collisions. The former should include link lengths to reflect a broad anthropometric design range (e.g., 5th percentile female through the 95th percentile male) and realistic joint range-of-motion capabilities and constraints. This enhancement would enable dynamic work envelope analyses. The physics properties simulator should include realistic linear and angular acceleration/velocity and kinetic energy transfer.

As these enhancements come on line, the training application discussed above, for example, can be expanded to cover more demanding training objectives. However, instead of discussing an expanded training application, another application will be proposed, although the discussion applies to the training application as well.

A demanding and comprehensive application for VR is support of unplanned contingency EVAs. That is, subsets of the features and VR capabilities required to support this application are used in a variety of other applications. Support to unplanned EVAs requires Human Factors analyses (e.g., viewing, reach, and dynamic work envelope analyses), operations development, training, mission support, and even simultaneous participation by physically separated users in the same VE.

It is anticipated that enhanced VR will be capable of supporting many of the activities and analyses that occur on the ground in support of an unplanned EVA. Viewing analyses, reach envelope analyses, and, with an incorporated anthropometric model, dynamic work envelope analyses can be achieved

concurrently with procedure development. Although much of this can be done in an engineering mock-up, VR offers several unique capabilities.

First, VR could provide a timely and safe method to enable the various advantages and disadvantages of reaching and maneuvering in a microgravity environment. This includes body attitudes and positions difficult to recreate in a one-G environment. This would be superior to existing methods for simulating micro-gravity because existing methods can not be used in a timely manner and are of limited durations (KC-135) or require ancillary equipment (Neutral Buoyancy Simulator) that can interfere with operations in restricted volumes. Second, VR would permit anthropometric sizing to reflect the dimensions of the on-board crew. This is particularly useful for operations being planned in relatively tight spaces.

VR would offer the mission and payload managers the ability to visualize the procedure and environment to gain a faster and more indepth understanding of the operation. This could be accomplished while the managers are sitting at their consoles in the control center. Further, managers, at both centers, could enter the VW, simultaneously, to review and discuss the operation. This capability for direct mission support would be unprecedented, though the possibilities are not limited unplanned EVA.

**Benefits:** The potential benefits from the application of VR technologies and techniques to AXAF are significant. More efficient utilization of constrained resources can be realized.

Viewing analyses, reach envelope analyses, and, with an incorporated anthropometric model, dynamic work envelope analyses can be achieved concurrently with procedure development. VR can provide a timely and safe method to enable the various advantages and disadvantages of reaching and maneuvering in a microgravity environment. This would be superior to existing methods for simulating micro-gravity because existing methods can not be used in a timely manner and are of limited durations. Even where the KC-135 and/or the NBS are appropriate, prior utilization of virtual mockups can result in more efficient use of these micro-gravity simulators. Hardware and operations design can be more mature, resulting in fewer and/or more productive simulator sessions.

Pre-mission operations development and validation can utilize VR. Pre-mission crew and cadre training could use the same VWs developed to support procedure development. This would prove particularly beneficial for operations where the various advantages and disadvantages of reaching and maneuvering in a microgravity environment make a difference.

A virtual AXAF would enable a more convenient, even remote, method to "visualize" AXAF systems. Updated VW files could even be electronically transmitted to other VR sites for visualizing.

VR can support operations development and validation during the deployment mission. VR would offer the mission and payload managers the ability to visualize the procedure and environment. Both could enter the VW, simultaneously, to review, discuss, and approve the operation. This capability for direct mission support would be unprecedented.

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# Chapter 5: Conclusions

## General Issues

- Visualization and spatial interpretation of massive databases, such a lunar /planetary surface, the human body, ocean-land interfaces, and so forth.
- Interactive presence to manipulate, recombine, or restructure complex, environmental data sets.
- General of visual, aural, or haptic representations via Information processing subsystems.
- Degree of sensory distortion, imaging limitations and information representations congruent to normative human behavior.
- Advanced visual, aural, and haptic rendering and feedback capabilities for analysis of real of hypothetical databases.
- Advance computer science for data access, data processing, and multi-sensory fusion algorithms.
- Advance US competitiveness and productivity in civilian and military applications, such as:
  - Mission/event simulation for rehearsal and training
  - Architectural layout for design and marketing
  - Telepresence and teleoperations
  - Public awareness
  - Design and engineering development
  - Medical, scientific and arts education
  - Recreational and motivational enhancement

## NASA Issues

A second set of issues will drive NASA's Virtual Environment technology are collectively called "Programmatic Issues". Some are internal to NASA and reflect the expected direction of the Agency, future budget, and continued major programs and responsibilities of the agency--Space Transport System, Space Station, and Aeronautical programs that may benefit from VE technology.

Other issues are external to NASA, but will impact the extent to which NASA takes a leadership role. These include:

- National policy on VE as set by the President's Science Advisor, OSTP, and FCCSET.
- Development of supporting technology in VE by other government agencies and private industry.
- Marketplace forces for low-cost technology for mass market applications.

## Center Activities in VE

### Ames Research Center

- Responsible for human performance research relevant to developing VE for NASA applications.
- Responsible for the development of human centered technology for aeronautics.

### Goddard Space Flight Center

- Responsible for unmanned scientific studies and applications for unmanned space flight, in the areas of:
  - Space physics
  - Astrophysics
  - Earth sciences
  - Flight project support

### Jet Propulsion Laboratory

- Responsible for research, development and applications for unmanned spacecraft, satellites and ground data systems.

### Johnson Space Flight Center

- Responsible for manned space flight research, development, and applications.
- Responsible for astronaut training.

### Marshall Space Flight Center

- Responsible for spacecraft design, structure, development and operations.

## Conclusions

Since beginning research and technology development in 1985, NASA Centers have learned important lessons about the technology itself and the value it can provide in accomplishing the gamut of NASA's missions in aeronautics, science, and space.

1. Cost savings could be dramatic since Virtual Environment can potentially allow change to be made in a small way which can have a large effect; can potentially analyze situations with Virtual Environment with capabilities not heretofore available; can potentially analyze situations quicker and cheaper than with conventional methods; analyses can potentially be done which allow unique insights for investigators/scientists.
2. Networking is critically important to users of Virtual Environment because of the need to share data among many investigators.
3. Since model and database development are critical and time consuming for virtual world development, techniques for streaming this modeling are essential. Standardization, and maintenance are also critical and need to be address.

- 4. NASA recognizes the need for human performance validation and that human performance requirements drive the technology.**
- 5. The productivity benefits of Virtual Environment will critically depend upon validated modeling of the specific task domain.**
- 6. Challenging mission applications within NASA call for a responsive Virtual Environment technology. Typically, this is a high technology need. NASA has a leadership role in the technology development without depending upon the value of low-tech commercial development.**
- 7. Virtual Environment is pervasive and the implications are extensive within NASA's many missions and research programs. NASA should be prepared to respond to such demands by supporting the technology.**
- 8. Uses of Virtual Environment technology for human performance applied studies and critical descriptive research matches both applied mission needs as well as fundamental research needs.**
- 9. Uses of Virtual Environment technology provide a flexible, relatively low-cost method for operational analysis, scientific studies, and critical discipline research.**
- 10. Although Virtual Environment technology is evolutionary, building upon technologies such as simulation, computer graphics and so forth; implications for its use are revolutionary.**
- 11. A well-documented, international interest and economic position of Virtual Environment technology exists. NASA has a well understood role in technology development and transfer. This transfer must be fostered if the US is to maintain its leadership position.**
- 12. Current Virtual Environment systems generally do not have sufficient sensory-motor fidelity and human-machine interface design to deliver the performance necessary to achieve many of the above potential applications but foreseeable technical advances may change this situation within 1-3 years.**

## APPENDIX A

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