Virtual Environments in Scientific Visualization

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Abstract

The use of virtual environments in scientific visualization is surveyed. Successful examples are discussed in depth. Lessons about the usefulness and applicability of virtual environments to scientific visualization are drawn. Lessons learned from these applications for the development of virtual environments are also drawn. Difficulties in the application of virtual environments to scientific visualization are discussed. Possible futures are briefly examined.

Introduction

Scientific visualization is the use of computer graphics in the investigation of scientific phenomena [1][2]. Some investigations involve large amounts of data arising from observation or from numerical simulation. Other problems, such as the structure of an exact solution in general relativity, are understood in principle but not in detail. Computer graphics assists the researcher's understanding of the qualitative structure of phenomena by drawing pictures which can be obtained in no other way. Interactive computer graphics, which allow the real-time control over how the graphics is generated, further enhances the researcher's ability to explore a phenomenon through the computer. In conventional real-time computer graphics systems, a mouse and keyboard can be used to control, for example, the position of a seedpoint of a streamline in a fluid flow. When the phenomenon under study is three-dimensional, the display is projected onto the two-dimensional display screen and the two-dimensional mouse movements are mapped into three-dimensional control. The mouse typically controls both the view point of the projection and the position of the objects in the view.

Virtual environments provide a fully three-dimensional interface for both the display and control of interactive computer graphics [3]. A wide field of view stereoscopic head-tracked display system presents a compelling illusion of a three-dimensional world generated by the computer graphics. The researcher feels immersed in this world, which is populated by computer generated objects which appear and behave as if they were real (figure 1). This three-dimensional display provides many of the depth cues that we use in the real world, such as binocular disparity and head-motion parallax, providing a display of three-dimensional structures that overcome many of the ambiguities that occur on two-dimensional screens. The display device tracks the user's head and controls the point of view of the computer generated scene. Using an instrumented glove, the researcher can reach out and directly manipulate virtual objects' position and orientation in three-dimensions. The glove also senses the user's fingers, allowing the computer to interpret hand gestures. A virtual object can be 'picked up' by simply closing the fist over the object, just as in the real world. Another object can be indicated for some action by literally pointing at it in the virtual environment. Using these techniques, virtual environments attempt to create the illusion of a computer generated reality so compelling that one naturally interacts with it as one interacts with the real world. Virtual environments do not attempt to mimic the real world, rather they provide a natural, intuitive interface to computer environments.

Virtual environments have found a fruitful application in the field of scientific visualization. When the scientific phenomena under study are three-dimensional and contain complex structures, virtual environments provide a natural way to display them. Virtual environment control via the glove and other input technologies allow the simple intuitive control of the three-dimensional position and orientation of the displays involved in the visualization of phenomena. The researcher need not remember things like "when the control key is pressed the mouse motion is mapped into roll and yaw". This control capability is particularly useful when the richness of the phenomena allows only partial display at any one time. Using virtual environment control techniques, the researcher can rapidly change what and where data is displayed, allowing the exploration of of complex data environments. We feel that it is this exploration capability which brings out the real power of virtual environments.

Virtual environment interfaces are very striking, but the advantages of this interface are apparent only for those using the virtual environment system. For this reason, virtual environment interfaces are not particularly useful for the presentation of scientific results. They are useful, however, for the exploration and hopefully discovery of phenomena which can then be presented in more conventional ways.

Research in the use of virtual environments in scientific visualization is underway at several locations. NASA Ames Research Center is pioneering these applications in several areas of scientific investigation, particularly fluid flow visualization. The Army Corps of Engineers Waterways Experimental Station has duplicated the system at NASA Ames for research in water flow visualization. The National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign is developing several virtual environment setups, including a duplicate of the system at NASA Ames. They are investigating applications in cosmology, magnetohydrodynamics, and medical imaging. The University of North Carolina at Chapel Hill is investigating several applications of virtual environments in such fields as molecular modeling and medical visualization. NASA Goddard Spaceflight Center is investigating the use of virtual environment techniques for the visualization of magnetohydronamic problems and data from the Earth Observation

Satellite. Other institutions are acquiring or thinking seriously of acquiring virtual environment systems.

While virtual environments are rather new, there have been interesting applications developed for scientific visualization. After describing a major example, we will discuss what makes a virtual environment work and how to evaluate whether a visualization problem is suited for a virtual environment with current technology. This technology certainly has a long way to go before the full potential of virtual environments is realized, but has matured to the point where significant scientific visualization problems can be addressed.

The Virtual Windtunnel

The virtual windtunnel is an application of virtual environments to the problem of fluid flow visualization developed at the Applied Research Branch of the Numerical Aerodynamic Simulation Systems Division at NASA Ames Research Center [3]. It is designed to visualize pre-computed simulated unsteady three-dimensional fluid flows which are the product of computational fluid dynamics (CFD) calculations. These calculations are typically performed on supercomputers and provide velocity, energy, and pressure data of fluids on curvilinear multiple-zone numerical grids. Visualization of these unsteady flows are difficult due to their often extremely complex time-varying three-dimensional structures. There are many methods for visualizing these flows using computer graphics, such as isosurfaces of scalar quantities, cutting planes rendered with color maps that indicate scalar quantities, and streamlines of the flow. Due to the inherently three-dimensional structure of flow phenomena, virtual environments were expected to be useful.

The virtual windtunnel visualizes the fluid velocity vector field using streamlines, streaklines, and particle paths. *Streamlines* (figure 2) are the integral curves of the velocity vector field given an initial position or *seedpoint*, and provide insight into the field's geometrical structure. A *streakline* is a collection of particles which are repeatedly advected into the flow, and correspond to a smoke or bubble source in the flow. Streaklines (figure 3) are particularly useful in the observation of vortical structures and recirculation regions. *Particle paths* are the literal paths of the particles advected into the flow over time. In the case of steady flows these three techniques coincide. These visualizations are rendered either as lines connecting the points of the paths or as disconnected points. They are controlled by rakes, which are linear collections of seedpoints which are moved by the user's hand via an instrumented glove. A rake is simply picked up and moved to the new, desired location. Several rakes with different visualization techniques can be operated at the same time (figure 4).

By creating the illusion that the researcher is immersed in the flow under study with real rakes "out there" within reach, the researcher can concentrate on the science of the problem, and not worry about the details of the interface. By waving a rake of streamlines around, the interesting areas of the geometry of the flow can be quickly identified. By watching a streakline develop, vortical structures can be identified which can then be explored with streamlines. The passage of time can be sped up, slowed down, stopped or reversed. The scale of the display and interaction can be controlled at will, as can what parts of the object inside the flow is displayed.

The design and implementation of the virtual windtunnel involves several constraints. The most severe constraint is the requirement that as the user's head moves the scene updates sufficiently quickly that the illusion of viewing a real environment is not destroyed. Slow update causes the display to look like a series of still pictures rather than a dynamic view of a three-dimensional world. Experience has shown that to maintain the illusion an update rate of about ten frames/second is required. The control, computation, and rendering in stereo of the environment must take place in less than one tenth of a second for the illusion of reality to be compelling.

In choosing the visualizations, it was important that the computation and rendering involved could be performed fast enough for the virtual environment scene to be updated at faster than ten frames/second. This is necessary to provide the illusion of an interactive environment. Streamlines and their unsteady generalizations based on simulated particle advection were chosen as they clearly satisfy this constraint. Computation of streamlines involve only simple numerical integration of the vector field and the rendering of streamlines involve drawing simple lines in the three-dimensional environment. The accuracy of the computation was also determined by performance considerations. The second order Runga-Kutta integration technique was chosen as a good compromise between performance and accuracy.

The display device was constrained by the demand that it provide as high quality display as possible. Many wide field of view stereoscopic head-tracked displays use a pair of four-inch diagonal liquid crystal displays worn on the head, which were judged to provide too low a resolution to be acceptable. The Fake Space Labs BOOM, a device using a pair of four-inch diagonal monochromatic NTSC cathode ray tube (CRT) monitors supported on a counterweighted yoke assembly (figure 5), was chosen because of its superior display quality. This was later upgraded to the Fake Space Labs BOOM IIC, which uses 1000x1000 resolution monitors with two color channels. A standard shadow-masked three-color CRT display was rejected because the shadow mask degraded the image and because of safety uncertainties. Head tracking on the BOOM systems is performed by providing the computer system with the angles of the counterweighted yoke assembly, which are detected via optical encoders.

The Dataglove Model II developed by VPL Research, Inc. was chosen for the control device (figure 5). The dataglove uses a magnetic tracking system built by Polhemus Inc. which provides the absolute position and orientation of a sensor relative to a source. While somewhat inaccurate, this tracker is sufficient for our purposes. The glove itself uses specially treated optical fibers at ten finger joints to measure the finger bend angles of the user's hand. These angle are interpreted as gestures by the computer system, which cause different things to happen depending on where the gesture is performed. If the closed fist gesture is performed at the center of a rake, that rake is picked up and moved with the user's hand until the closed fist gesture is released. A close fist gesture in the open air allows the movement of the entire display relative to the researcher. Another gesture combined with hand motion controls the scale of the environment.

Finally, the computation and rendering platform must be sufficiently powerful to integrate the computation, control and display of all the elements of the virtual environment. For small unsteady flows, we use a Silicon Graphics Iris 380 GT/VGX system, which has eight MIPS R3000 processors for a total 37 megaflops performance and a VGX high-speed three-dimensional graphics geometry engine capable of drawing 800,000 small triangles/second. Our system contains 256 megabytes of physical memory. The Iris system reads the control devices to determine the position of the user's head and the state of the user's hand, computes the visualizations for the current display, and renders the display in stereo from the user's point of view (figure 6). This system is sufficient for unsteady data sets which involve less than a total of 250 megabytes of data and visualizations involving up to about 20,000 integrations of the vector field.

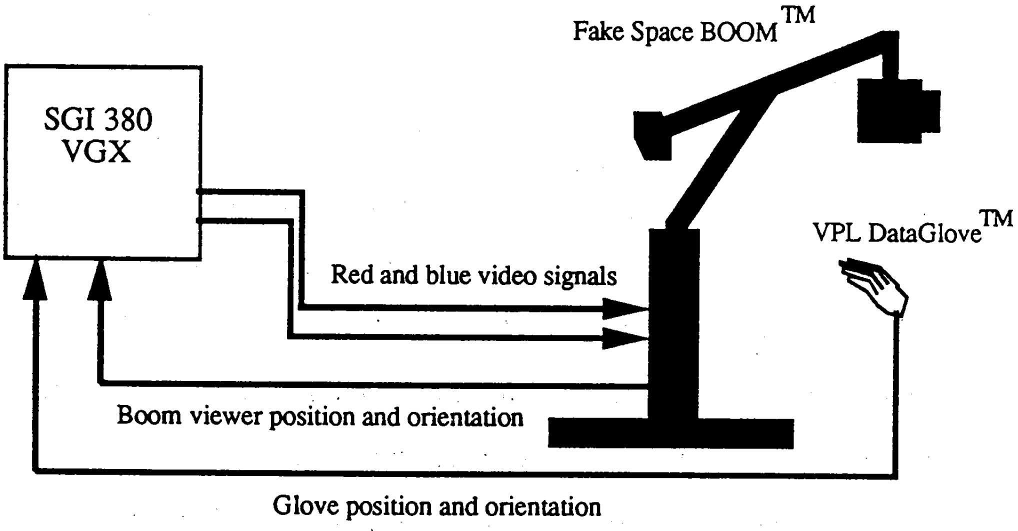

Figure 6: The system configuration of the virtual windtunnel

On the Iris, sufficient speed is attained by storing the entire data set in memory so it can be very quickly accessed. Most interesting unsteady flows involve more than 256 megabytes of data, however, and so will not fit into the Iris' memory. Storing the data on disk and reading each timestep's data when it is needed is too slow on the Iris to allow the system to run at ten frame/second. For this reason, a distributed architecture has been implemented where the flow data and computation of the visualizations all take place on a remote supercomputer [4]. We currently use a Convex 3240, which has four vector processors and a gigabyte of physical memory. This allows four times as much flow data to be visualized, but many unsteady data sets are larger still. A disk bandwidth of about 50 Megabytes/second allows the dynamic loading of data stored on disk so long as the size of one timesteps worth of data does not exceed five megabytes. One might expect that the computational performance of the Convex 3240 would also provide advantages, but particle advection is not well suited to vectorized computation, and the performance of the Convex with four processors is comparable to the Iris with 8 processors.

Because the virtual environment display fills the user's field of view, shutting out the real world, virtual environments are a highly personal experience. An advantage of a distributed architecture is the ability to build shared virtual environments, where two or more users using different virtual environment systems can view the same data set that is resident on a remote supercomputer. The UltraNet network system has sufficient bandwidth to transmit the visualization data. By sending the user's commands directly to the supercomputer, each of the users can interact with the same virtual environment and see the effects of the other user's actions.

Unsteady data sets can involve considerably more data. A typical example is a computation of a hovering Harrier jump jet [5] which contains hundreds of timesteps containing 360 megabytes of data each. The virtual windtunnel currently under development at NASA Ames has as its eventual goal the interactive investigation of such large data sets. The virtual windtunnel has been set up at the Army Corps of Engineers Waterways Experimental Station in Vicksburg, Miss. in collaboration with NASA Ames for the investigation of simulated water channel flows. The National Center for Supercomputing Applications at the University of Illinois Urbana-Champaign in collaboration with NASA Ames has also set up a virtual windtunnel system for the investigation of cosmic hydrodynamic jets.

Other Application Examples

The techniques developed in the virtual windtunnel have been applied to the visualization of curved spacetime in the general theory of relativity [6]. The flow data in the virtual windtunnel is replaced by geometry data in the form of the metric of spacetime. The streamlines are replaced by geodesics in the geometry data (figure 7). Geodesics in spacetime require an initial speed, direction and position as opposed to the initial position required by streamlines of a flow. The user's hand position and orientation are used to supply this initial position and orientation for a preset speed. This application is being developed jointly by the Applied Research Branch at NASA Ames and the numerical relativity group at NCSA to study the results of numerical spacetime simulations.

At NCSA, the BOOM has been used to provide a display of a static three-dimensional map of galaxy distribution due to Margaret Geller. The data in this application are the measured three-dimensional positions of galaxies on a very large scale. This application was very successful in bringing out structures in the galaxy distribution that were not previously perceived.

An application for the interactive investigation of the results of high-energy particle collisions is being explored at NASA Ames in collaboration with the Stanford Linear Detector group at the Stanford Linear Accelerator Center. The data are the measured tracks of high-energy collision events, which are displayed in three-dimensions. Each track has a set of data associated with it, and that data can be interrogated track by track via selection with the glove.

A somewhat different application that has been explored is the use of interactive virtual environments to allow the manipulation of mathematical surfaces to illustrate geometrical and topological arguements. This application involves some rather difficult questions of how the surface is to react to the user's inputs [7]. The visualiztion of arguments leading to the remarkable properties of four-dimensional spaces is one possible application [8].

Considerations in the Development of Virtual Environments

From the virtual windtunnel example, we can draw several lessons about what makes a virtual environment useful. The three-dimensional control and head-tracked display in real time are crucial to the illusion of a real virtual world. While the virtual objects must be meaningful to the researcher, it is not important that elements of the virtual world look like anything in the real world. It is the sense of presence that the virtual objects have due to the head-tracked display and the sense the user has that these objects respond to the user that compel the illusion of reality. This sense of presence allows the researcher to interact with the objects exactly as if they were objects in the real world. When the researcher says "I want to move the streamline over there", the researcher simply reaches out and grabs the seedpoint of that streamline and moves it there. Asking "I wonder where the vortices are in this time frame", the researcher grabs a rake of streamlines and waves it about in the virtual space watching the resulting streamlines to look for signs of vortical structure. This kind of exploratory interaction requires fast update rates in the virtual environment.

The control and display devices are also critical. The control device must track the user's body in such a way that the user can forget that the device is there. We wish to make the interface to the virtual environment as invisible as possible. The magnetic trackers and gloves used in current virtual environments have serious accuracy problems and are functional within only a limited range. The display devices suffer from a severe resolution restriction, due to the fact that a four-inch display is blown up to a typically 100 degree image to cover the user's field of view. Pixels become large with this kind of magnification, and even in the highest resolution systems with 1000 pixels on a side the pixels are plainly visible. In this case the pixels are as large as one tenth of a degree across, which is one fifth of the full moon. Stereoscopic display and color rendering help considerably. The CRT systems used in the boom have enough resolution to be useful, but higher resolution is highly desirable.

Other control and display devices would also be useful. The virtual windtunnel system contains only the minimum control and display capability for a viable virtual environment. An obvious addition would be a voice recognition system. This would allow the researcher to talk to the system directing various aspects of the environment. While the glove is appropriate for 'manual' tasks such as the movement of a rake, it is less suited for the control of more abstract quantities such as the type and number of seedpoints on a rake. A voice recognition system will be integrated into the virtual windtunnel this year for additional control. Other possible controls include the six-degree-of-freedom spaceball, which senses the force and torque applied by the user about a point. The force and torque can be interpreted as six numbers that are used to control various aspects of the environment. One use of the spaceball is to control the user's position and orientation within the virtual environment.

The computational platform for the virtual environment must be capable of performing the computations involved in the desired visualizations. Isosurfaces, for example, are computationally intensive and require more computational speed for real-time interaction than is available in most graphics workstations. The computer platform must, on the other hand, read the interface devices and render the graphics associated with virtual environments. Workstations are typically well suited for this task. The further development of high-power graphics workstations will enable a wider variety of applications of virtual environments to scientific applications. Distributed architectures when available are often desirable, where the workstation reads the interface devices and renders the graphics, while a remote supercomputer performs the computations.

The most severe problem is that of large amounts of data. The nature of interactive exploration requires that the data be accessed at high speed in unpredictable ways. This problem was already discussed in the context of large unsteady flows in the virtual windtunnel. Interesting data sets besides fluid flow have this problem in very severe ways. Numerical spacetime data are on grids of size comparable to those in fluid flow, but each grid point has much more data. Data returned by the Earth Observation Satellite (EOS) will have massive amounts of data. The ability to quickly get at large amounts of stored data is one of the primary bottlenecks in the use of virtual environments for the visualization of large data sets.

Future Directions

The advantages of virtual environments in the unambiguous display of three-dimensional structures and the intuitive three-dimensional control of objects in the virtual environment have been covered in the examples above. The ability to explore complex data by selectively displaying aspects of that data is the most dramatic aspect of these advantages.

The real power of virtual environments comes when abstract concepts which have no tangible real world counterpart such as streamlines in an unsteady flow are used to create virtual objects. By making these abstract concepts tangible their investigation is greatly facilitated. One is tempted to call this process "scientific reification". The examples above take physical quantities such as airflow and render derived structures such as vortices as real things with real properties. The same principles can be applied to more abstract quantities, such as statistical data or mathematical models. This would aid the pedagogical presentation of abstract concepts as well as the investigation of abstract phenomena.

What kinds of applications will find virtual environments useful? At this stage of development, virtual environment technology is "clumsy", full of difficulties and limitations which must be worked around to provide a viable application. There are undoubtedly several interesting applications that can be developed now with the current technology. As the technology advances, qualitatively different applications may appear that are as far beyond the current systems as the current systems are beyond early computer plotter drawings.

Given the current state of the art, any visualization that involves complex three-dimensional data which is moderately computationally intensive will probably benefit from a virtual environment interface. While the current cost in both hardware and labor of virtual environment development is high, research in the effective use of virtual environments in scientific visualization is needed. The few successful examples that exist only hint at the usefulness and limits of virtual environments.

Conclusions

Virtual environments, at least at the current level of technology, is not intended to be a panacea for every computer graphics interface problem. Virtual environment interfaces are a tool and like all tools have their place. Ultimately, it may be that virtual environments will include all other interface paradigms as subsets, but that day is far in the future. In the meantime, however, there seems to be a class of problems, particularly in the scientific visualization of complex three-dimensional phenomena, where virtual environments provide significant advantages.

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Figure captions

Figure 1: The Virtual Windtunnel in use, with the flow around the space shuttle.

Figure 2: Streamlines of the flow around the tapered cylinder at two successive moments of time.

Figure 3: Streaklines of the flow around the tapered cylinder rendered as smoke

Figure 4: The user environment in the virtual windtunnel, showing a rake of streaklines rendered as bubbles used in combination with a rake of streamlines

Figure 5: Boom and glove hardware interface to the Virtual Windtunnel

Figure 6: An illustration of virtual spacetime in use. The user is manipulating a spray of geodesics in a curved spacetime with an instrumented glove while observing the results in a head-tracked, wide field of view stereo display.

Figure 1:

Figure 2:

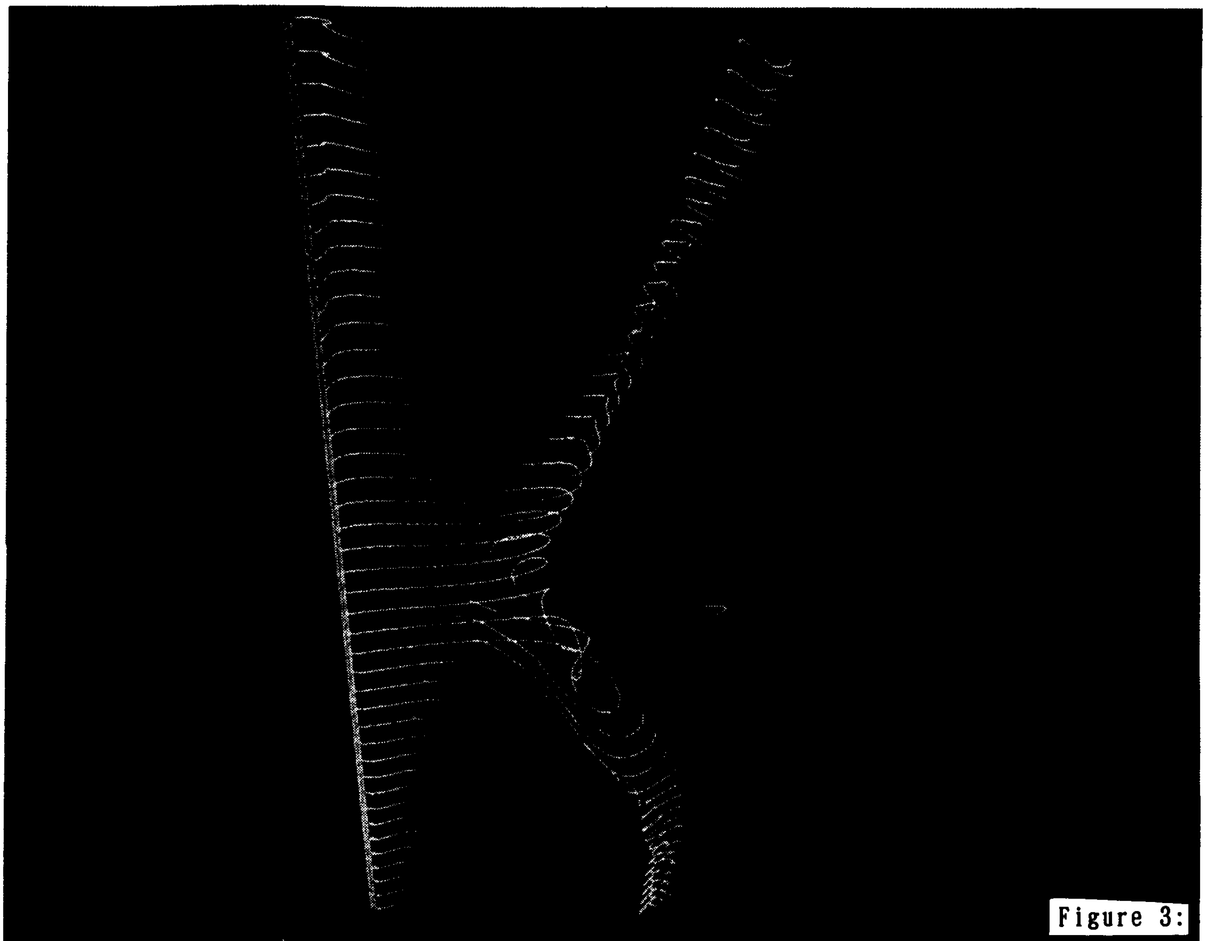

Figure 3:

Figure 4:

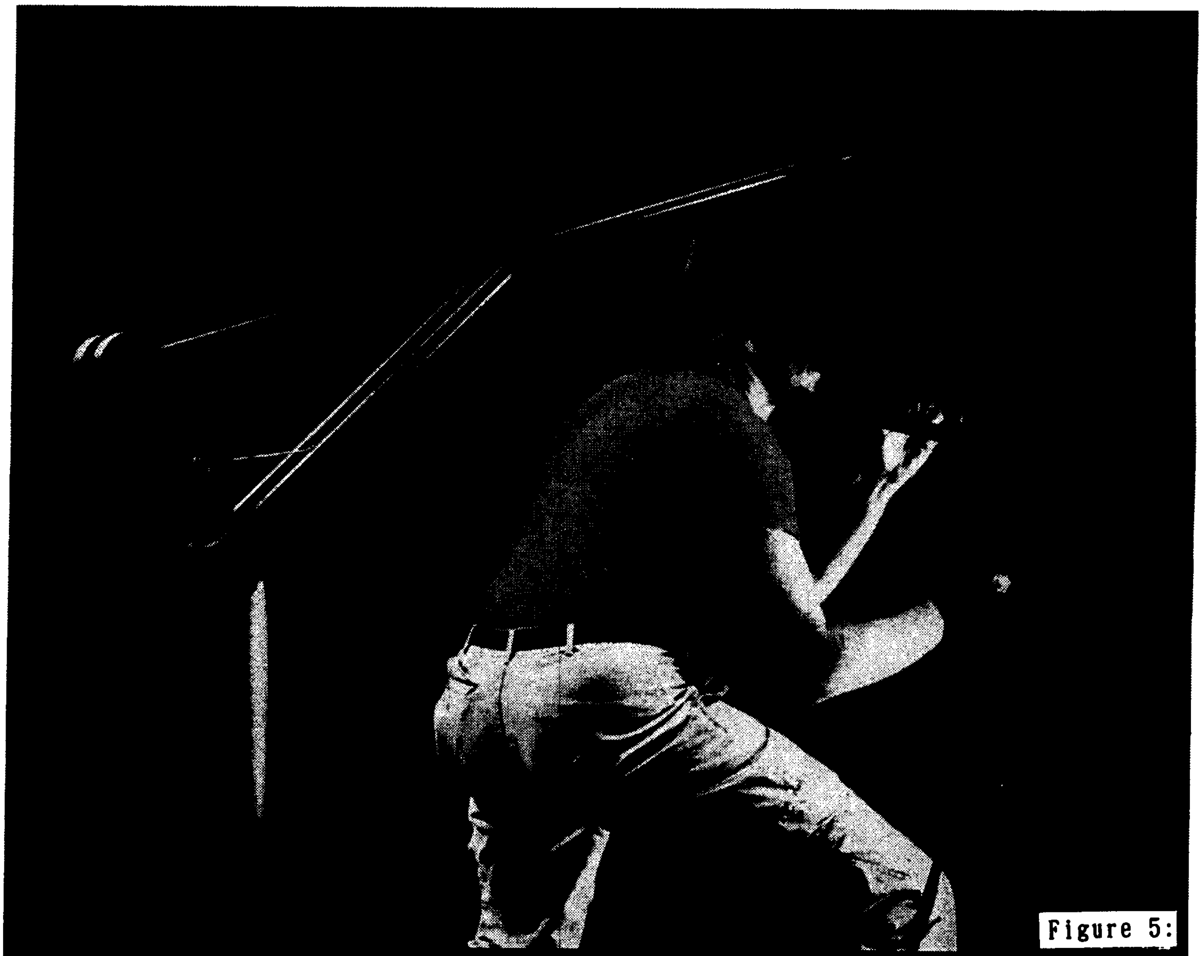

Figure 5:

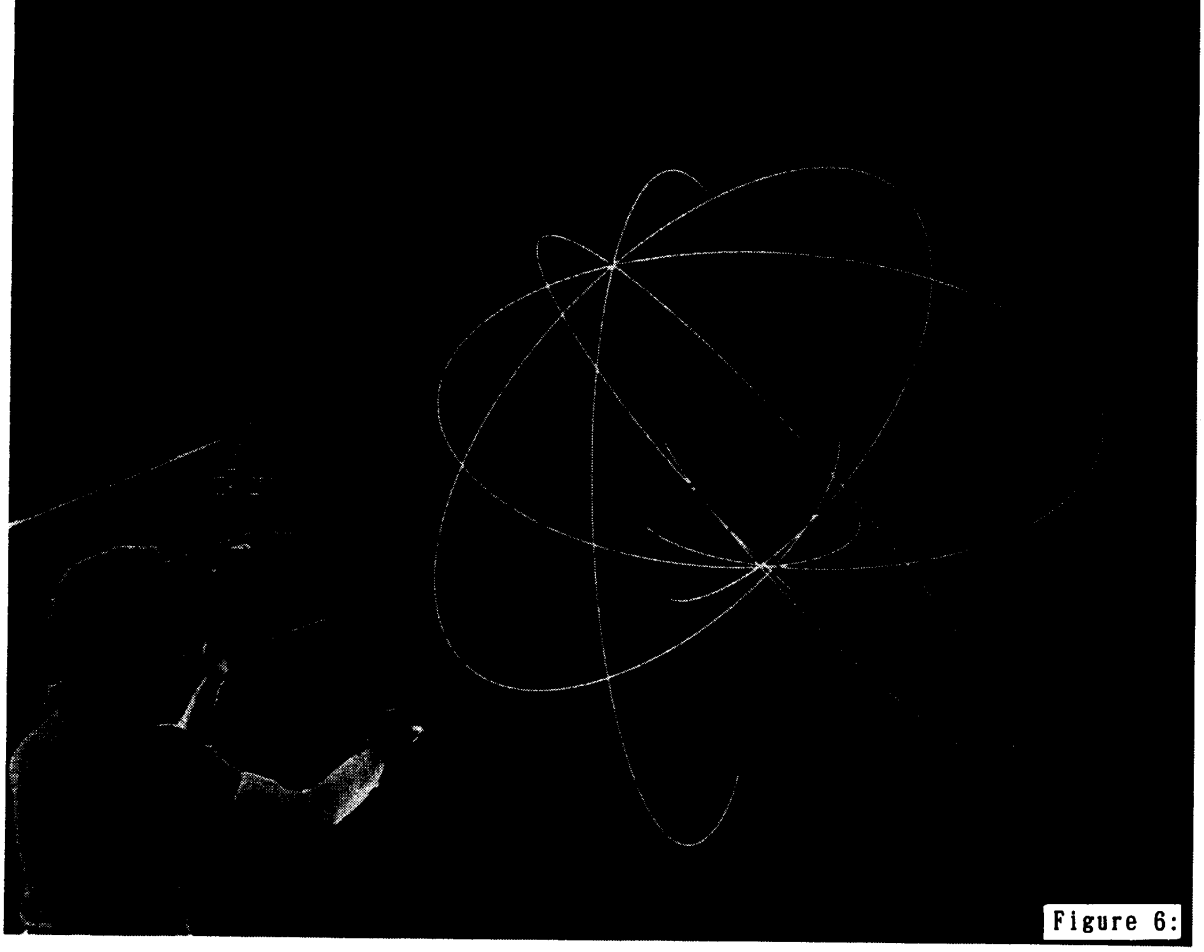

Figure 6: