"Studierstube"

An Environment for Collaboration in Augmented Reality

Zsolt Szalavári, Dieter Schmalstieg, Anton Fuhrmann, Michael Gervautz

Institute of Computer Graphics
Vienna University of Technology
Karlsplatz 13/186/2, A-1040 Vienna, Austria
szalavari|schmalstieg|fuhrmann|gervautz@cg.tuwien.ac.at

Abstract: We propose an architecture for multi-user augmented reality with applications in visualization, presentation and education, which we call "Studierstube". Our system presents three-dimensional stereoscopic graphics simultaneously to group of users wearing light weight see-through head mounted displays. The displays do not affect natural communication and interaction, making working together very effective. Users see the same spatially aligned model, but can independently control their viewpoint and different layers of the data to be displayed. The setup serves computer supported cooperative work and enhances cooperation of visualization experts. This paper presents the client-server software architecture underlying this system and details that must be addressed to create a high-quality augmented reality setup.

Keywords: augmented reality, multi-user applications, collaboration, distributed graphics

1. Introduction

Daß ich erkenne, was die Welt
Im Innersten zusammenhält,
Schau alle Wirkenskraft und Samen,
Und tu nicht mehr in Worten kramen.

To realize what holds the world
Together in its core,
I see all seeds and force of act
And search for words no more.

Johann Wolfgang von Goethe, Faust

We selected the project name "Studierstube", after the play *Faust* by Johann Wolfgang von Goethe, in which the leading character uses a study room for performing research and philosophy: the *Studierstube*.

This paper deals with an attempt to combine two very important evolving fields:

- The method for visual improvement or enrichment of the surrounding environment by overlaying spatially aligned computer-generated information onto a human's view, called *Augmented Reality* (AR), has potential for a broad range of applications, including mobile context-sensitive information systems, scientific visualization, in-place display of measurement data, medicine and surgical planning, education, training and entertainment.

- The primary goal to provide insight into a complicated problem by the enrichment of simulation data, that is mapped and rendered to a displayable image (Figure 1) has become important to numerous fields of science outside of computer graphics and augmented reality. *Scientific visualization* realizes projects of higher and higher complexity.
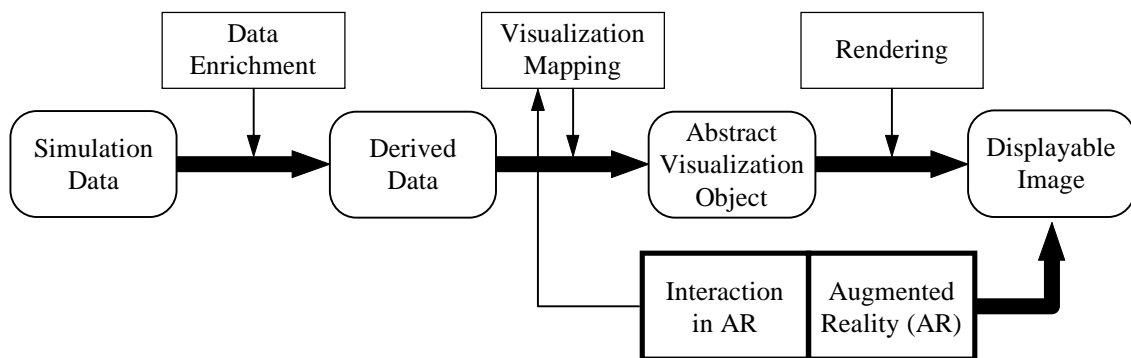

Figure 1: Visualization pipeline (Nielsen, 1990)

As a highly interdisciplinary field, scientific visualization frequently requires experts with different background to cooperate. Collaborators may have different preferences concerning the chosen visual representation of the data, or they may be interested in different aspects. An efficient collaboration requires that each of the researchers has a customized view of the data set. At the same time, presence in the same room is preferred because of the natural interaction during a discussion. These requirements can uniquely be fulfilled in an augmented reality system which combines real world experience of the collaborators and physical equipment with the visualization of the synthetic data.

Compared to visualization in immersive virtual reality, augmented reality allows the use of detailed physical models, the properties of which cannot be met by their virtual counterparts: arbitrarily detailed visual representation, no visual or temporal artifacts and force-feedback for free. Only those aspects of the model that cannot be seen in reality have to be added by the computer system: For example, one could take the physical model of an airplane or airplane wing to investigate the flow around this object, which is simulated by computer and added to the display. Manipulation of the real world model (e. g. its orientation) is more intuitive and simpler to support than a purely virtual environment. A related example would be the use of a humanoid torso or puppet that is overlaid with medical information from inside the human body in the style of (Bajura, 1992).

This combination of conventional experimental work with scientific visualization and augmented reality technology leads to the concept of an augmented laboratory, which

would provide a superior research environment in which to conduct experiments that are executed solely inside the computer, while maintaining a conventional and familiar work setup.

The "Studierstube" approach concentrates on the seamless combination of a physical world workspace and an augmented environment for multiple users in three dimensions, with unaffected social communication channels and an augmented user interface that supports natural handling of complex data at interactive rates. In this type of distributed multi-user systems adequate communication strategies for continuous synchronization and real-time performance are required that also allow the interaction with a shared geometric database.

2. Related Work

The evolution of augmented reality started in the early days of computer graphics, when Sutherland pioneered research on head mounted displays (Sutherland, 1968). His work still inspires the virtual reality research community of today. Although only capable of simple vector drawings, his prototype head mounted display was the first binocular see-through system, effectively the first augmented reality system. Feiner et al. (Feiner, 1992) (Feiner, 1993) described a knowledge based augmented reality system. As a demonstration, they chose to configure the system to support people with the maintenance of laser printers. However, a lot of effort is required to generate accurate models, and extremely precise registration is required. Bajura et.al. (Bajura, 1992) described a medical visualization system based on augmented reality techniques. A see-through head mounted display (HMD), also developed at UNC (Holmgren, 1992), allows geometrically correct superposition of ultrasound data of the unborn onto the belly of the mother-to-be, so the gynecologist can examine the position of the unborn within the mother. Another medical application of AR has been presented by State et. al. (State, 1996) for ultrasound guided needle biopsy of the breast. Sharma and Molineros (Sharma, 1996) present a system for mechanical assembly guidance using annotations attached to real world scenery.

Scientific visualization in virtual reality becomes increasingly a field of interest for many researchers. In the early 90ies at UNC within the GROPE project a group around Fred Brooks produced a haptic arm-like device and a large stereo display for the visualization and manipulation of chemical data (Brooks, 1990). Their nanomanipulator (Taylor, 1993) allows precise manipulation of a scanning tunneling microscope and works also with force feedback. Another important milestone for the combination of VR and Scientific Visualization was the development of the virtual wind tunnel at NASA-AMES by Steve Bryson. Using a BOOM device and a data glove as interaction tool (Bryson, 1991), scientists were able to see and interact with true stereoscopic images of a flow field visualization. A follow-up project, the distributed wind tunnel (Bryson, 1993) was developed, which divided computation in a distributed system for better efficiency, and allowed multiple users to experience the simulation at the same time. Collaboration in a distributed virtual environment, not necessarily limited to scientific visualization has been proposed by Fahlén et. al. (Fahlén, 1993).

Most existing augmented applications are single user setups, or do not exploit the multi-user character of their systems. Exceptions are the CAVE-System (Cruz-Neira, 1993 a) (Cruz-Neira, 1993 b), the responsive workbench (Krüger, 1995) and the Shared Space (Billinghurst, 1996) which are examples of multi-user augmented reality systems. In the

CAVE users see stereoscopic 3-D scenes with LCD-shutter glasses on large projection walls surrounding them. One user is head-tracked, so that the images on all walls correspond to this viewer's position. The viewers have the impression to be surrounded by 3-D virtual scene. A disadvantage of this system is that the presented images fit to the head position only for one viewer; noticeable visual artifacts exist for all other viewers. The responsive workbench uses one display area, which is built into a table top. Like in the CAVE, viewers wear LCD shutter glasses and only one user can see the objects in correct stereoscopy. Furthermore, a relatively steep viewing angle is necessary to achieve a good 3D impression, i.e. the viewers have to stay close to the table. Closest to our work is the prototype implementation of Shared Space. Users wearing head-mounted see-through displays can discuss shared information in three dimensions floating around them in space and interact using gestures and speech commands. As the focus of this work is on ubiquitous computing and not in situ cooperative work, distribution of data, information sharing and interaction techniques face different problems as presented in our work.

3. The "Studierstube" approach

We propose a system capable of visualization of three-dimensional scientific data for multiple simultaneous viewers within one room. The choice of this setting limits the complexity of the problem, as the "real world" is limited to a room, which is complemented by the "virtual world". Each viewer wears magnetically tracked see-through HMDs providing a stereoscopic real-time display, and can freely walk around in order to observe the augmented environment from different viewpoints.

Figure 2. Three people wearing see-trough glasses at a meeting, viewing a virtual globe. Note that the table is an object in the real world, the globe just an image projected into the space by the head-set.

The mixture between real and virtual visual experience, created in our system by see-trough HMDs, is a key feature of our system. Thus, it is possible to move around freely without fear to bump into obstacles, as opposed to fully immersive displays, where only virtual objects can be perceived. This enables a work group to discuss the viewed object,

because the participants are seeing one another and can therefore communicate in the usual way.

Interaction with the augmented part of the scenery is maintained using high-level interaction metaphors and tools like the *Personal Interaction Panel* (PIP) (Szalavári, 1997). We incorporate this new two-handed input device that supports a multitude of interaction styles and is particularly well suited for augmented reality applications. It unifies general control functions of Studierstube, usual 3D manipulation tasks, as well as application specific interaction methods. The PIP is composed of position and orientation tracked lightweight, notebook sized hand-held panel and a pen and carries instant augmented elements for interaction.

3.1 Properties of our system

The following key properties summarize the attributes of our system:

Virtuality

Viewing and examining of objects that are not accessible directly or that do not exist in the real world can be carried out in this environment. Investigation of data-sets using information visualization becomes a task of handling almost "real" objects. Size, complexity, physical properties are just parameters in a simulation, no longer are they constraints for the analysis.

Augmentation

Real-world objects can be augmented with spatially aligned information. This allows smooth extension of real objects with virtual properties in design processes, like variations of new parts for an existing system. Superimposed information can also incorporate enhancing elements for real objects, like descriptions or guidance in training or education situations, which we call annotations.

Multi-user support

A situation where multiple users congregate to discuss, design, or perform other types of joint work is generally categorized as CSCW (computer supported cooperate work). Much research has been devoted to the question how conventional software and desktop computers can be enhanced with measures to support effective group interaction. Fortunately, a benefit of augmented reality is that sophisticated groupware mechanisms are not really needed to perform real work. Normal human interactions (verbal, gestures, etc.) are easily possible in an augmented reality setup, and they are probably richer than any computer-governed interaction can ever be.

Independence

Unlike the CAVE and the Workbench, control is not limited to a guiding person, while other users act as passive observers. Each user has the option to move freely and independently of the other users. In particular, each user may freely choose a viewpoint with stereoscopy for correct depth perception. But not only is observation independent, interaction can also be performed on a personal base. The semi-immersive character of our augmentation helps to keep human communication channels open, thus improving the quality of collaboration.

Sharing vs. Individuality

Investigated objects are in general shared among users, in the sense of visibility, this means that all participants can see the same coherent model, consistent in its state over time. By presenting the visual sensation directly to each user with the lightweight see-trough HMDs, the displayed data set can also be different for each viewer, as required by the application's needs and the individual's choice. Personal preferences on different layers of information can be switched on and off, as described in the next sub-section.

Interaction and Interactivity

With the support of augmented tools like the proposed PIP, visualized data can be explored interactively. Changes inherent in the scientific simulation can be viewed immediately. The visual components of the panel in one users hand can be kept private, invisible for other users, or public, sharing even 3D information by direct visibility or projection to projection walls, as described in the next section.

3.2 Augmented features

We incorporated layers and annotations as augmented features to our system. Furthermore we show uses of mobile tracked objects in an augmented environment.

Layers

We incorporate layers similar in concept to the ones found in technical illustration programs or CAD packages and the work of Fritzmaurice (Fritzmaurice, 1993). Data is separated into disjoint sets according to semantic considerations (e.g. floor plan with walls only - furniture - measurements). Display can be turned on and off for every layer individually. This concept is fundamental for allowing individuals to customize the display to their needs. Users may see the same model and at the same time *not* see the same model, as everyone sees a different set of aspects of the same thing. Aside from personal taste and interest, this is useful if professional people (e.g. an architect) talk to inexperienced people (e.g. customer), or if people with different interest (e.g. designer and engineer) collaborate.

Annotations

Augmentation is not necessarily limited to 3D graphics added to the physical world. General multi-media data can be useful (e.g. sound cues), but what we consider absolutely essential to support are textual annotations. While it is often true that illustrations and graphics make difficult concepts clearer than textual explanations can, for complicated models a legend that explains important parts and gives names is just as important. The system provides a possibility to link text to specific 3D points of a model. The text is then displayed "in place", but in 2D overlaid onto the 3D image similar to (Rekimoto, 1995). As the user moves his viewpoint, the text stays screen-aligned so that it is always clearly readable. The system takes care that multiple text elements do neither overlap nor occlude each other. By means of the layer mechanism, individual annotation sets can be switched on and off. The annotation concept will be especially useful if physical props (e.g. demonstration objects or mock-ups for education) are used, but it will also improve the quality of purely virtual presentations. Annotations can be created, edited and directly placed or moved in the augmentation with the Personal Interaction Panel. A three dimensional drag and drop mechanism gives a natural interactive feeling of handling spatially aligned multi-media data.

Tracked mobile objects

Static objects become part of the augmentation in a simple setup phase. Geometric properties such as size and position have to be registered for inclusion in an environment. To include a real world object completely in the system and an ongoing simulation, the system needs to have information about changes in position, orientation and state in addition to the static properties, so that they can interact with other parts of the augmentation.

For this reason we introduce tracked mobile objects as functional part of our system, which can be moved, held in hand by users, passed on from user to user and so forth. Typically, the number of such objects will be small, but their role in the application will be significant. Main usage of mobile objects are manipulation tools such as the PIP, and physical models (mock-ups) that are augmented with supplementary information not physically available (e.g. isolines of stress). Technically, the position of these objects is determined by a dedicated tracking sensor, and a representation of the physical model is rendered in background color to resolve the occlusion problem among physical and virtual objects.

4. System Overview

We consider our system to work in a stationary environment, e.g. a room, so we can assume sufficient network bandwidth for communication between parts of our client-server approach, both for geometric and application data, as well as supporting information like tracker data. The representation of this data and communication concerning the changes, as well as interaction between users and system are crucial factors calling for detailed presentation.

4.1 Data representation and modeling

We use three different kinds of 3D models, each for a different purpose:

Static data

Static data describes the geometry of the presentation room (walls, windows, doors etc.). Because this kind of data is completely static (does not change at all), it can be prepared for taking occlusion with real objects into account.

Data representing mobile objects

Within our environment the system also supports mobile objects, which can have virtual data representing or supporting them. This type of data differs from static registration data, as it has to be updated in real-time during operation.

Display data

Data presented or added to the environment is generally handled as display data. This data is shared between the Studierstube and the underlying simulation. Simulation engines have to provide visual output in the same format, so that inclusion in the geometric database of the Studierstube is rather simple, but major changes to this database can still be controlled directly by the application.

4.2 Client-Server Approach

We propose a software architecture for our augmented reality system, which is based on a client-server structure. A server holds a database of all data types, including registration, mobile object and display or application data. Users connect to this *Environment Server* via a network using client software. The client obtains a replica of the database from the server, which is used by the client locally to render the image presented to the user.

Except for special customizations, the view that concurrent users have of the scene (position, color of objects etc.) must be consistent. As there are multiple local copies of an object, if any change is made to the presented scene (e.g. color of an object changed), changes must be propagated to other replicas. This is done by sending a message to the server, which in turn distributes them to the other participants. As such update events only happen occasional (note that tracker data is handled separately!), the improved consistency outweighs the longer communication involving a server.

Tracker data is managed by a special tracker demon running on the *Tracker Server*. The quality of tracking is crucial to the quality of the experience, so a separate machine is dedicated to the tracking. The tracker demon is continuously running, and clients can connect at will to obtain a stream of tracker data. Our system involves multiple tracked points (head tracking for multiple users, hand/pointer tracking, tracking of mobile objects). All the data from these tracked points influences the state of the scene and is therefore propagated to the connected clients as a bundle, which improves throughput and consistency of the data.

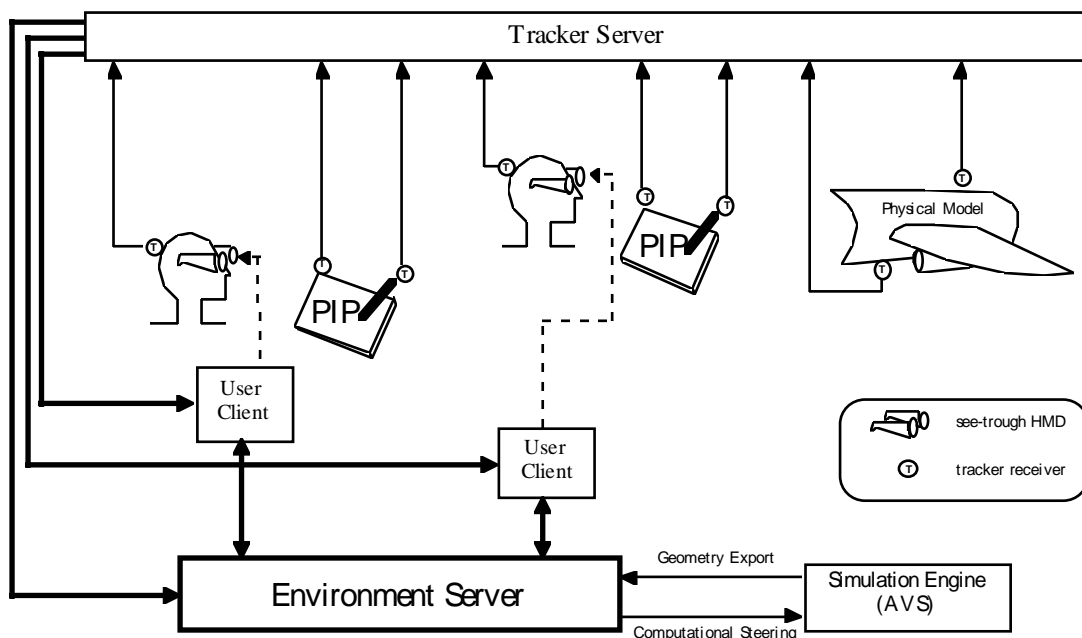The proposed overall system architecture can be seen in Figure 3.

Figure 3. System architecture: The augmented reality environment is maintained by a server that takes care of the synchronization needs of the clients and interoperates with the simulation backend. The clients are responsible for displaying the environment. A tracker server manages input devices.

4.3 Visualization loop

A *Simulation Engine* is required to provide the data for the scientific visualization task in our implementation. This data can be precomputed and loaded into the system at runtime. Simple visualizations such as analytical dynamical systems can be hand-coded. However, a capable simulation system is better suited to address the diverse needs of multiple visualization tasks, and also eases development. In previous projects, we have used AVS (AVS, 1992) to create scientific visualization data. Its data flow concept allows export of the data in almost any desired format and lends itself naturally to an integration into our system architecture.

A loose coupling is defined between AVS as the computational back end and the visualization server that coordinates interaction with the model in the Studierstube. Visualization data is exported from AVS to the visualization server that takes care of distribution of the data among the Studierstube's clients. Computational steering is achieved by using special input modules for AVS that accept new values for simulation parameters from the Studierstube. If re-generation of the model or its parts with modified parameters is reasonably fast, real-time or near real-time steering can be achieved.
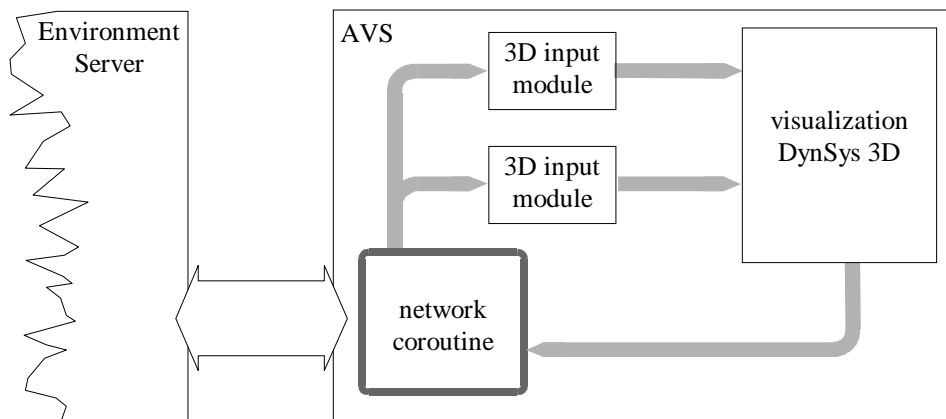

Figure 4. Integration of AVS-DynSys3D as a Simulation Engine in Studierstube

Modifications of the visualization data that do not involve the simulation (such as rotating the simulated model) can be carried out in a close loop by the Studierstube system alone and do not pass data between Studierstube and AVS. Such simple interactions are not affected by the performance penalty created by invoking a complex software system such as AVS and can therefore always be carried out with real-time response and high fidelity.

The distribution and consistency of the shared geometric database plays a significant role in the quality of our system. To handle coherence and merge the interaction of multiple users and communication between server and simulation engine, we base the intercourse between all parts of our client-server environment on sophisticated protocols and message passing algorithms. We are currently developing an in-house communication standard for connection of three dimensional user interfaces to visualization.

4.4 Interaction tools

Interaction with the augmented part of the scene is performed with the Personal Interaction Panel is a unique tool that combines physical and virtual attributes: The physical nature of the pen and panel makes it a very simple, yet effective and precise device for interaction, that supports tactile feedback and has good ergonomics. However, the surface of the panel is a virtually unlimited information display of computer generated (augmented) information.

There are many different possibilities to use the PIP as interaction tool in the augmented environment, we will show features for general tasks and in the application section those supporting our implementation of a scientific visualization environment.

The pen alone can be used for any 3D pointing operation and direct manipulation, where a 3D mouse (6 degrees of freedom) is normally used. This feature is integrated with the extended PIP functionality, so that the PIP supports a superset of "standard" 3D operations in virtual and augmented reality.

A conventional 2D computer display can be projected onto the board, supporting a 2D desktop metaphor better than "flying menus" so traditional 2D user interaction and parameter manipulation is possible. In addition to "flat" 2D user interface elements, three-dimensional widgets that "float" above the panel's surface are supported (e.g., selection of a point on a sphere), clipboard functionality and drag-and-drop in 3D can also be implemented.

Using the pen and panel, a snapshot camera metaphor has been implemented. The direction of the pen orients a virtual camera, the resulting snapshot is shown on the PIP for immediate feedback.

Multiple navigation metaphors are supported by two handed interaction as featured by the PIP: Among them are use of hand-held miniatures (compare (Pausch, 1995)) specifying direction of movement with the pen or "spaceship" control gadgets (2-D buttons or 3-D widgets) on the panel's surface.

The general controls for Studierstube can easily be made available by the PIP, so reconfiguration of the application can largely be achieved without leaving the augmented environment. For example, loading a new model can be done with a graphical file selector presented on the PIP.

4.5 Implementation details

Our current implementation of the described system above consists of an environment for two users. The hardware configuration includes i-Glasses head mounted see-trough displays and a Polhemus Fastrak tracking device connected to a tracker server PC. Tracker data is transmitted over Ethernet using TCP/IP protocols and multicast technology. Rendering is done on Silicon Graphics workstations (Maximum Impact graphics) using Open Inventor libraries. The hardware of the Personal Interaction Panel consists of a lightweight wooden panel and a plastic pointer, both tracked in position and orientation with Fastrak receivers. From our current implementation we can conclude, that for high-fidelity augmented reality, precise registration of the real world with the augmented display is crucial, and our current static registration is barely sufficient. Nevertheless, our experiences show that users feel comfortable and working in the environment is pleasant. Concerning the tracking problem enhancement of

registration by hybrid tracking technology is currently under developed in cooperation with the Vision Group of the Graz University of Technology as part of a parallel project.

5. Applications in Scientific Visualization

As described above, we set the focus of our applications to scientific visualization. Augmented reality for scientific visualization can provide an intuitive, even transparent, interface for computational steering. Consequently, a test case was needed in the beginning that is simple enough for interactive steering even on conventional workstations, yet complex enough to be interesting to researchers working in the field.

The Wonderland Model

Following a previous cooperation with researchers from econometrics, we first concentrated on population models like the "Wonderland Model", where for example the interaction between population growth, economic activity and environmental impact is modeled (Gröller, 1996). Changing certain parameters of such systems only slightly may have significant impact on the long term behavior, making interactive computation steering essential for the understanding of such systems. The simulation of such systems required the numerical approximation of differential equations fast enough for interactive computational steering.
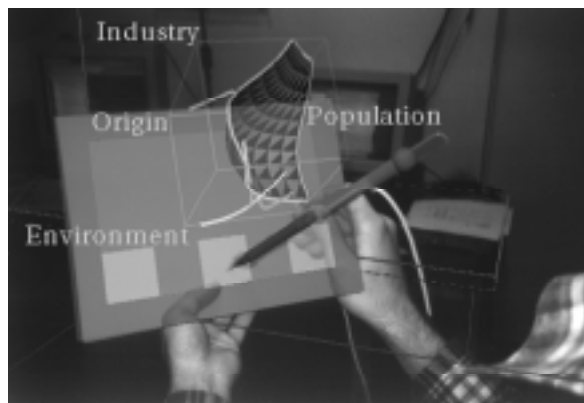

Figure 5. The Wonderland Model (Gröller, 1996) on the Personal Interaction Panel in Studierstube

Dynamical systems

Based on our first experiments with the integration we generalized our concept of connecting a Simulation Server to Studierstube and connected the multi-purpose workbench for the rapid development of advanced visualization techniques in the field of three-dimensional dynamical systems *DynSys3D* into Studierstube (Löffelmann, 1997)(Fuhrmann, 1997). Standard visualization techniques including stream lines, stream surfaces, and particles support the illustration of the investigated systems.

One design guideline of this system, namely that all of its modules have to produce standard AVS geometry, was very important for the integration. A simple conversion utility that converts AVS geometry into the display data-format of Studierstube (Open Inventor) was sufficient to exchange geometric information. Interaction messages from the Environment Server are sent to the visualization systems input modules as AVS

geometry items. To proof our concept and test the stability of the system following DynSys3D applications were selected as representative examples.

Mixed-mode Oscillations

A model we investigated together with colleagues from our econometrics department is the 3D autocatalator (Milik 1996), a simple 3D dynamical system which exhibits mixed-mode oscillations. These oscillating phenomena often encountered in real world systems, e.g., chemical systems. Depending on the parameters of this system either periodic or quasiperiodic (chaotic) solutions can be found. The investigation of the 3D phase space as a direct three dimensional augmentation provides better understanding of the structure of this system and the direct control on placing streamlines or streamsurfaces makes the analysis of a given parameter set much more intuitive.

RTorus

RTorus is a 'synthetic' dynamical system which is very useful for demonstrating certain properties that are common to lots of others. Abraham and Shaw use this model as an example to explain several fundamental flow properties (Abraham, 1992). This dynamical system models a coupled oscillation within three-space. Depending on the parameters of the model either an attracting cycle within the x-y-plane or an attracting torus around the z-axis appears. By placing streamlines and stream surfaces interactively, lots of interesting settings of RTorus can be found as, e.g., the Möbius band. Due to the interactive response times the RTorus-system can be especially well investigated within Studierstube, details can be obtained that would require long-term adjustments using the standard AVS interface.
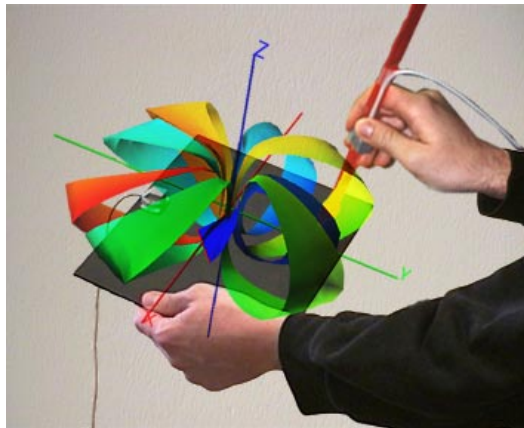

Figure 6: Investigating the RTorus on the Personal Interaction Panel

Rössler

As a rather well-known dynamical system we also investigated the Rössler attractor in Studierstube. Rössler is also a three-dimensional dynamical system that exhibits a chaotic attractor if parameters are set properly. Taking this familiar dynamical system for analysis in Studierstube allowed us to easily compare visualization in AR to established techniques.

magnetic tracker

view HMD#1

view HMD#2

3D-mouse

virtual object

Figure 7: Two users investigating the Rössler-attractor in the Studierstube setup. Due to the direct correspondence of positions in real world and the augmentation, simple interactions, e.g. pointing are possible and enrich communication.

Interaction with visualization data

We enhance the expressive power of the display by interface techniques exploiting the augmented reality setup. Using the PIP metaphor (see above) custom tailored for interaction with the dynamical system, as a probing tool to define 2-D cross sections and to specify the origin of particles introduced into the flow gives a natural feeling of handling visualization data. The augmented reality setup also allows the use of an additional high-resolution CRT monitor for the display of high quality 2-D images (e.g., the mentioned cross sections) without leaving the augmented environment.

6. Conclusions and Future Work

We presented a collaborative augmented environment setup supporting interactive scientific visualization for multiple users. Our system provides 3D display of synthetic data and augmentation of physical objects with geometrically aligned information. Co-workers wear position and orientation tracked see-trough head mounted displays, allowing independent choice of viewpoint. Interaction is performed using the Personal Interaction Panel, a two-handed interface for augmented reality.

The system provides a natural working atmosphere, by enriching reality with spatially aligned information while leaving natural communication channels unaffected. Annotations enhance understandability of the discussed topic while customization of different data layers support cooperation of experts from different fields. Direct exploration and modification in visualization provides improved insight in complex problems.

We have verified that true three-dimensional viewing and manipulation is indeed superior to screen-and-mouse based interaction of complex 3D models. The tedious work of positioning, orienting, and zooming, typical for conventional systems, can be reduced significantly. Alternatives in the operation (e.g. moving ones head vs. rotating

the object) make exploration less computer-centric and are easy to learn for inexperienced users, however surprising in the beginning.

Although experiments with unskilled users show promising results regarding acceptance, enhanced registration and correct matching of real environment and overlaid graphics is required. Our restricted implementation supporting two users should be extended to a number of participants, allowing more complex collaborative situations. Connection to external modules with standardized protocols for image and interaction data will provide a wide variety of different applications. To improve the visualization setup, we will also use the PIP's pen as a probing tool to display local properties of the visualization data with real-time update on the panel.

7. Acknowledgments

8. References

Abraham, R.H., Shaw, C.D. (1992). *Dynamics: The Geometry of Behavior.* (Redwood City/California: Addison-Wesley).

AVS (1992). *AVS Developers Guide - Release 4*. Advanced Visualization Systems Inc.

Bajura, M., Fuchs, H. and Ohbuchi, R. (1992). *Merging Virtual Objects with the Real World: Seeing Ultrasound Imaginary within the Patient*. In proceedings of SIGGRAPH'92: 203-210.

Billinghurst, M., Weghorst, S., Furness, T. III (1996). *Shared Space: An Augmented Reality Interface for Computer Supported Collaborative Work*. In proceedings of Collaborative Virtual Environments'96.

Brooks, F. Jr. et. al. (1990). *Project GROPE - Haptic Displays for Scientific Visualization*. In proceedings of SIGGRAPH'90: 177-185.

Bryson, S. (1991). *The Virtual Wind Tunnel*. In proceedings of IEEE Visualization'91: 17-25.

Bryson, S. (1993). *The Distributed Virtual Wind Tunnel*. In proceedings of Supercomputing '92, also in SIGGRAPH'93 Course Notes 43: 3.1-3.10.

Cruz-Neira, C., Sandin, D. and DeFanti, T. (1993 a). *Surround-Screen Projection-Based Virtual Reality: The Design and Implementation of the CAVE*. In proceedings of SIGGRAPH'93: 135-142.

Cruz-Neira, C. et al. (1993 b). *Scientists in Wonderland: A Report on Visualization Applications in the CAVE Virtual Reality Environment*. In proceedings of the IEEE 1993 Symposium on Research Frontiers in Virtual Reality: 59-67.

Fahlén, L.E., Brown, C.G., Ståhl, O. and Carlsson, C. (1993). *A Space Based Model for User Interaction in Shared Synthetic Environments*. In proceedings of INTERCHI'93: 43-48.

Feiner, S., MacIntyre, B. and Seligmann, D. (1992). *Annotating the Real World with Knowledge-Based Graphics on a See-Through Head-Mounted Display.* In proceedings of Graphics Interface'92: 78-85.

Feiner, S., MacIntyre, B. and Seligmann, D. (1993). *Knowledge-Based Augmented Reality.* Communications of the ACM 36(7): 53-62.

Fritzmaurice, G.W. (1993). *Situated Information Spaces and Spatially aware Palmtop Computers.* Communications of the ACM 39(7): 39-49.

Fuhrmann, A., Löffelmann, H., Schmalstieg, D. (1997). *Collaborative Augmented Reality: Exploring Dynamical Systems.* In proceedings of Visualization'97.

Gröller, E., Wegenkittl, R., Milik, A., Prskawetz, A., Feichtinger, G. and Sanderson, W.C. (1996). *The Geometry of Wonderland.* Chaos, Solitons & Fractals 7(12):1989-2006.

Holmgren, D. (1992). *Design and Construction of a 30-Degree See-Through Head-Mounted-Display.* Technical Report 92-030 at the University of North Carolina, available at ftp://ftp.cs.unc.edu./pub/technical-reports/92-030.ps.Z .

Krüger, W., Bohn, C., Fröhlich, B., Schüth, H., Strauss, W. and Wesche, G. (1995). *The Responsive Workbench: A Virtual Work Environment.* IEEE Computer 28(7): 42-48.

Löffelmann, H., Gröller, E. (1997). *DynSys3D: A workbench for developing advanced visualization techniques in the field of three-dimensional dynamical systems.* In proceedings of WSCG'97: 301-310.

Nielsen, G., Shriver, B. and Rosenblum, L. (eds.) (1990). *Visualization in Scientific Computing* (Los Alamitos/California: IEEE Computer Society Press).

Milik, A. (1996). *Dynamics of Mixed-mode Oscillations.* PhD thesis, Vienna University of Technology, Austria.

Pausch, R., Burnette, T., Brockway, D. and Weiblen, M. (1995). *Navigation and Locomotion in Virtual Worlds via Flight into Hand-Held Miniatures.* In proceedings of SIGGRAPH'95: 399-401.

Rekimoto, J. and Nagao, K. (1995). *The World through the Computer: Computer Augmented Interactions with Real World Environments.* In proceedings of UIST '95: 29-36.

Sharma, R., Molineros, J. (1996). *Interactive Visualization and Augmentation of Mechanical Assembly Sequences.* Proceedings of Graphics Interface '96: 230-237.

State, A., Livingston, M.A., Garrett, F., Hirota, G., Whitton, M.C., Pisano, E.D. and Fuchs, H. (1996). *Technologies for Augmented Reality Systems: Realizing Ultrasound-Guided Needle Biopsies.* In proceedings of SIGGRAPH'96: 439-446.

Sutherland, I. (1968). *A Head-Mounted Three Dimensional Display.* Fall Joint Computer Conference, In proceedings of AFIPS Conference 33: 757-764.

Szalavári, Zs. and Gervautz, M. (1996). *The Personal Interaction Panel - A Two-handed Interface for Augmented Reality.* In proceedings of EUROGRAPHICS'97.

Taylor, R. M. et. al. (1993). *The Nanomanipulator: A Virtual Reality Interface for a Scanning Tunneling Microscope.* In proceedings of SIGGRAPH'93: 127-134.