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# VIRTUAL REALITY FOR MANUFACTURING SIMULATION

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## ABSTRACT

Graphical animation has been of great benefit to simulation practitioners as a communication tool. Virtual reality, or virtual interface technology, a new technology that creates the illusion of an interactive three-dimensional environment, holds promise as the "next step" in expanding simulation's role in communication. This paper describes a joint software engineering project between the Human Interface Technology Laboratory and AutoSimulations, Inc., initiated to explore how virtual reality might impact simulations and to gain insight into bringing the technology to current, commercially available simulation software packages. We constructed a manufacturing simulation based on part of an actual factory's production line and asked both workers and managers from the facility to evaluate the virtual factory. We chose AutoSimulations' AutoMod and AutoView manufacturing simulation software packages as our representative commercial system. Our evaluation results were generally positive; however, there are more issues to be addressed before this exciting technology can be proven as an alternative to existing screen-based systems.

## 1 INTRODUCTION

Last spring, the Human Interface Technology Laboratory (HITL) initiated a project with AutoSimulations, Inc. to explore how virtual reality might impact simulation by literally bringing a new dimension to animation. Our goal was to give people a way to experience a running simulation through a virtual interface, where they would feel as if they were actually in a three-dimensional environment, rather than simply watching an image of one on a flat computer screen. We wanted to understand what advantages and drawbacks such a system would have over a more traditional screen-based one, especially in terms of enhancing the communication of information. Our results, while suggestive of the potentials of virtual reality, raised a number of issues that will have to be addressed before virtual reality can be properly evaluated against traditional animation. In this paper, we give a brief overview of animation in simulation, looking at how animation facilitates communication, and introduce the technology of virtual reality. We describe our project and its evolution, goals, and software structure. Lastly, we describe the problems and limitations we encountered and discuss the testing and evaluation of the project.

## 2 SIMULATION AND ANIMATION

The primary objective of a simulation study is to improve the quality of managerial decisions [Shannon, 1975]. Therefore, for a simulation to be useful to managers it must be *relevant*, *valid*, *usable*, and *cost-effective*: it must deal with problems of importance, have a high degree of confidence associated with its results, provide solutions that are acceptable, and produce benefits that outweigh the costs of modeling [Shannon, 1975].

Simulation is addressing these criteria more effectively as software becomes more sophisticated. One particularly desirable feature of simulation is graphical animation, especially for modeling manufacturing processes [Law & Haider, 1989]. Animation has been called "an excellent means of establishing the credibility of a simulated model" [Seevers, 1988].

After a thorough review of the literature regarding simulation and human-computer interfaces, we found no specific studies that clearly defined and proved the benefits of animation. However, much of the literature revealed observed benefits which generally fall into two categories: those realized during the creation of the simulation model and those coming from enhanced comprehension when animation is used as a communication tool. During model creation, animation has been found useful to [Smith & Platt, 1987]:

- Show gross errors in the logic of system.
- Uncover design flaws inherent in the layout.
- Make complex interactions between systems within the simulation more apparent and understandable.
- Involve other decision-makers besides the simulation analysts in the development and verification process, often resulting in a more accurate model.

Once the model has been created and simulation studies are conducted, the results need to be conveyed to the parties responsible for decision making, often managers who traditionally have little or no simulation background. Animation can be very useful for communicating results to people who have no technical background, as well as to those who do. In this respect, animation can:

- Simplify the presentation of results to upper management as well as to technical engineers [Seevers, 1988].
- Serve as a catalyst for imagination and help resolve conflicts in decision-making, since each individual can show their point of view [Hawkins, et al., 1986].
- "Dramatically [illustrate] the alternatives" in a course of action [Morrison, 1991].
- Provide engineers and operators with valuable visual information to help schedule and control the system [Kunder, 1989].
- Serve as a training aid for line foremen or supervisors dealing with new facilities or working methods [Hawkins, et al., 1986].

Attitudes have changed significantly concerning simulation's role as a tool in various situations. Whereas simulation in the past was called a "last resort" tool - mostly because it was a time-consuming process that required significant programming and computer processing time - it is now referred to as the "premier technique" in industrial engineering [Pritsker, 1992].

## 3 FUTURE OF SIMULATION

A new technology, called virtual interface technology or virtual reality (VR), is extending animation one step further. Virtual reality attempts to improve the human-computer interface by recognizing and taking advantage of our natural sensory and perceptual abilities; thus, VR attempts to adapt the computer interface to the human, rather than requiring the human to adapt to the computer [Furness, 1987].

A key attribute of most VR systems and the one that was most important to our project is their visual three-dimensionality: typically, a virtual environment consisting of objects and processes is presented in such a way as to give the user a feeling of being present in the environment [Sheridan, 1992; Zeltzer, 1992].

In our system, the user dons a head-mounted display (HMD) which conveys visual information to each eye via two separate video screens. A tracking device allows the VR system to monitor the user's head position and orientation at all times. A computer with special graphics hardware continually renders for each eye a perspective image of the virtual environment from that eye's instantaneous viewpoint, based on the user's head location. When the user sees these images through the HMD, the images fuse to form a single, stereoscopic view of the virtual environment [Ellis, 1991]. The user can turn in any direction and see objects in the environment in the same way that you can turn your head and discover what is behind you. Additionally, the user can move or `fly' through the environment by means of a hand-held joystick. The joystick contains a tracking device identical to the one monitoring head movement. The joystick appears in the virtual environment as a handle with a triangular arrow attached. To move, the user points the arrow in the direction in which she wants to move and holds down a button on the joystick.

Conceptually, virtual reality covers an almost unlimited arena of possible applications. As simulation and animation become more commonplace in and integral to manufacturing, managers and engineers have turned their attention toward virtual interfaces. A number of recent articles in trade journals have discussed virtual reality and its application to manufacturing. In the extreme, some see it making a dedicated factory obsolete [Park, 1992], with VR design systems feeding their specifications into NC machines for rapid prototyping [*Manufacturing Engineering* 1992]. Others have a vision in which "workers will be empowered by [having] a tool that allows them the ability to participate in the decision making process" [Norman, 1992].

## 4 THE VIRTUAL FACTORY PROJECT

The Human Interface Technology Laboratory (HITL) initiated a collaborative project with the Industrial Engineering program at the University of Washington and AutoSimulations, Inc. (Bountiful, Utah) to create a "virtual factory" and explore how virtual reality might impact simulation by providing a new approach to animation. HITL chose to make this investigation in the context of a current, commercially available simulation software package with the hope of sparking interest in the industrial sector. AutoSimulations provided licenses and source code to their AutoMod and AutoView simulation software, as well as customer and software engineering support to HITL and the Industrial Engineering program. HITL provided the virtual interface hardware, software, and necessary software engineering support.

The VR software we used was actually two components of a suite of virtual reality software developed at HITL: VEOS (Virtual Environment Operating System), a distributed database and data transport package created for research and rapid-prototyping of virtual environments, and the Imager Library, a platform-independent graphical rendering library created for research into VR-related rendering issues [Cygnus, 1993a].

VEOS gave us the flexibility to distribute our processing requirements over several computers on our network, thus isolating conceptually distinct tasks such as simulation and graphical rendering [Coco, 1993]. In particular, the philosophy of HITL's system allows a very open design: instead of having to re-engineer all the software intelligence of a simulation system inside a single "VR program," we can take advantage of a preexisting software package for simulation computation and concentrate on interface design instead. Thus, the intent of this project was to utilize AutoMod's computational and logical processes for building and analyzing a simulation model while enhancing the experience using virtual reality [Jones, 1992].

The ultimate virtual factory might allow the user to build the factory and then dynamically alter variables to explore the simulation, all within the virtual environment. Our original goal was to work toward the latter characteristic, so that after creating a simulation layout and specifying some initial conditions, an AutoMod user would be able to experience the simulation as it was being calculated, and could change parameters or conditions in the simulation in near real-time. However, as with most simulation systems, AutoMod itself currently has no facility to allow changes to be made on-the-fly during an actual simulation run. By examining AutoMod's software structure, we determined that such a goal, while technically possible, was an engineering task outside the scope of this project.

We decided instead to make use of an AutoMod extension called AutoView and create a virtual factory that would allow a user to experience a three-dimensional "playback" of a simulation. The user could move around in the factory but would not be able to make changes to the simulation other than starting and stopping simulation time. AutoView allows the user to "film" a running simulation, creating a "film loop" which is used to present simulation results as a screen-based animation. The AutoView film is stored as a time-stamped, three-dimensional script of all actions within the simulated system. To play back the film, AutoView reads this file and creates an internal model of objects in the simulation; then, it steps through simulation time, updating objects according to the script and periodically regenerating an on-screen, three-dimensional picture of the simulation.

We chose to use the existing AutoView software package as a framework for development, intercepting functions that relate to graphical object display and replacing them with ones that communicate relevant information out into a virtual environment. Our modified package, called AMVE (AutoMod Virtual Environment), is essentially the functionality of AutoView packaged into two major functional elements, named **av-init-model** and **av-step-animation**. These elements are modules written in the 'C' programming language that appear as LISP calls (another language) in our VR prototyping system. Figure 1 shows the conceptual functionality of AMVE.

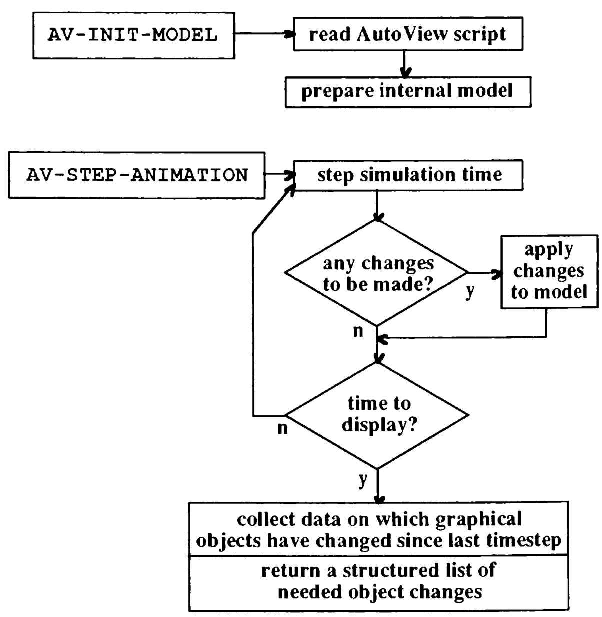


Figure 1: Conceptual Operation of AMVE's Two Main LISP Calls

The first function, **av-init-model,** is called only once. It reads the desired AutoView script, generates initial geometries and attributes for all objects in the model, and performs other internal initializations.

The next function, **av-step-animation**, embodies the heart of the animation loop. It steps through simulation time until it reaches the next display time, then it traverses its internal hierarchy of objects, collecting information on all attribute or position changes. It returns this information in a list to the LISP software layer, which applies the proper changes to objects in the virtual environment through VEOS. The LISP layer calls **av-step-animation** repeatedly until it exhausts the script, which signals the end of the simulation segment [Cygnus, 1993b].

## 5 BUILDING THE SIMULATION

For testing, we decided that we could gain the most useful feedback on AMVE and the virtual factory concept through responses from actual manufacturing personnel to a simulation of their production line. We constructed a simulation of the wheel assembly area of Derby Cycle, a producer of recreational and sport bicycles in Kent, Washington, and used production and manufacturing personnel as subjects for evaluating the interface. To make the model as meaningful as possible to the subjects, Derby provided some workstation cycle time data and access to their factory floor for additional time studies.

The wheel assembly area has four basic assembly lines, two each for the front and back wheels. The assembly occurs over the following stages: *pre-lace, build, true,* and *mount*. There are two *pre-lace* stations where spokes are attached to the center or hub of the wheel. These sub-assemblies are placed in bins and sent to one of six *build* machines that attach the spoke-hub component to the rim. The resulting assembly is sent to one of four robots that *true* the rim and adjust the tension in the spokes. Then, tires are *mounted* onto the rim and the finished wheel placed in a cart. Figure 2 gives a schematic layout of the wheel assembly area; figure 3 shows a view of the factory as it appears in the virtual environment.

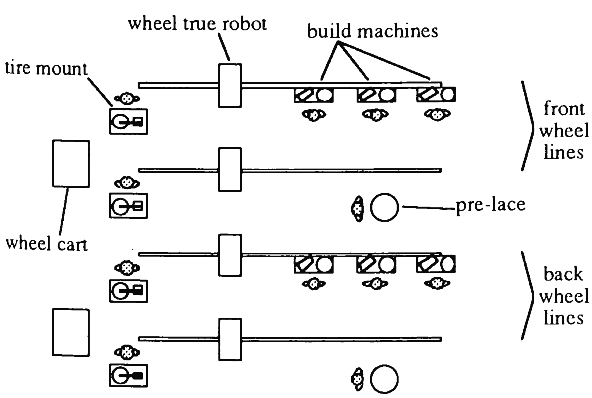


Figure 2: Layout of the Virtual Factory

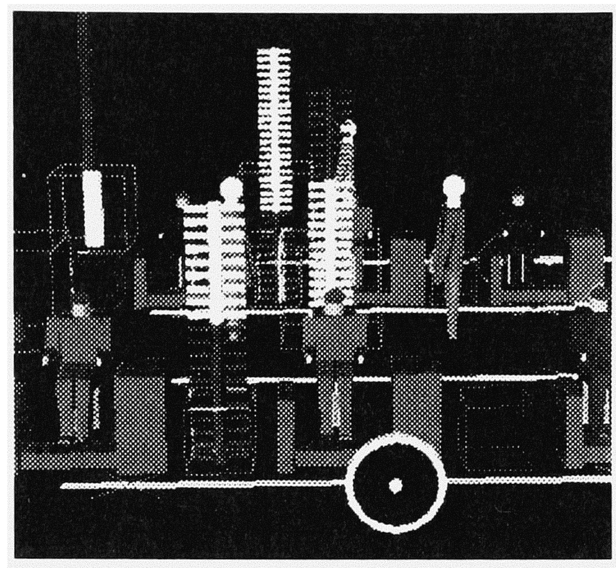

Figure 3: The Running Virtual Factory Environment

## 6 LIMITATIONS

The most distracting drawback of the prototype virtual factory was its low animation speed, measured in the number of images or frames presented to the user's eyes per second, or frames-per-second. On average, the prototype ran at a speed of two to five frames per second. For a comparative reference, most of HITL's development worlds run at ten to twenty frames per second. The slow update rate creates obvious limitations on the type and complexity of an AutoMod model that could be used for an effective simulation.

Several factors that were at the time unavoidable contributed to the low frame rates [Cygnus, 1993b]. First, the geometric complexity of the animation component of a simulation model, measured by the total number of polygons used to define all the model's geometries, can be very high in a simulation detailed enough to be useful. Also, to produce true stereoscopic images, all visible objects must be drawn twice, once for each eye. Thus, if a model contains 3,000 polygons, 6,000 must actually be drawn.

Second, VEOS, being a research tool, is not optimized completely for data transmission speed or database pattern matching. The distributed database mechanism in particular suffered from linear pattern matching performance in certain cases of data retrieval.

Finally, 10 Mb/s Ethernet (ten megabit-per-second) was the development network used for this project; it is shared among many computer systems at HITL. The raw transmission speeds of the network and its particular response to heavy usage are nontrivial limitations, considering the large amount of graphical information a simulation animation can generate, such as object creation and destruction, object motion, and color changes.

The above limitations weakened our comparison of the AMVE and AutoView interfaces: for an ideal comparison, neither should be constrained to account for the behavior of the other. By that measure, this project fell short of the ideal. In order to have a reasonably interactive virtual factory we simplified the objects that went into the simulation model. The level of detail in the resulting model was not what one would ordinarily expect from a professional three-dimensional and graphics-oriented package such as AutoMod. However, the level of translation and data exchange that had to occur between the AMVE internals and the rest of the virtual environment software system pushed VEOS performance envelopes to their limits.

## 7 TESTING THE VIRTUAL FACTORY

The last phase of this project was to evaluate the prototype system to determine if the virtual environment is an appropriate interface for manufacturing simulation and if the potential benefits would be realized with this application. A key element of the evaluation was the participants' reaction to the technology: did they feel comfortable with the technology, was the simulation easy to understand, and could they see this tool as useful to their company. Usability testing, which has been widely used to refine and evaluate screen applications, did not transfer well to testing the virtual environment. Without documented usability testing on manufacturing simulation software packages, there is neither a benchmark against which to measure this prototype nor a methodology to guide the development of testing procedures. We determined that the best methodology would be to use qualitative feedback and discussions to compare the prototype to the existing AutoView product.

The methodology was the following: (1) a 5 minute training session, during which the subjects became familiar with the computer-generated objects; (2) a 15 minute trial session, during which the subjects were asked questions about production to assess their general understanding of the simulation; (3) a written questionnaire immediately following the session; and (4) a group discussion led by one of our researchers to assess how the subjects felt about the technology and its possible applications.

Five subjects from Derby Cycle participated: three wheel assemblers, one materials supervisor, and one manufacturing engineer. Subjects were shown either the virtual environment or the AutoView animation on a computer screen. We asked the subjects questions to determine their understanding of the virtual factory and conducted a follow-up written survey and group discussion.

The ability to look around in and navigate through the virtual world gave the AMVE subjects more freedom to explore the simulation than the AutoView subjects, who were seated at a computer terminal, without controls, to watch the AutoView animation of the simulation. We observed that AMVE subjects tended to be more engaged in the simulation, commented more, and asked more questions about the simulation than the AutoView subjects, who tended to sit and wait passively for the testers' questions before speaking.

The participants' reactions generally did not show a clear distinction between the two types of interfaces. The users of the virtual interfaces particularly liked that it was easy to point out non-operating areas and to see the process flow, and they enjoyed being able to see (visit) operation zones from all angles. However, they disliked the slowness and jerkiness of the graphics (the low frame rate), the lack of movements in the graphical people in the model, and the difficulty in navigating due to lack of experience with the controls. AutoView users cited liking the flow but occasionally felt confused about what they saw.

Written survey results indicated that both interfaces seemed equally acceptable for the suggested applications: planning purchase of new equipment, planning a new facility, planning a production schedule, presenting new ideas to a superior, presenting new ideas to upper management, facilitating communication and discussion of production-related issues between coworkers, and orientation of a new worker, supplier, or visitor.

One notable conclusion from the group discussion that fit our observations during testing was that the virtual factory *captured the imagination* of the Derby employees. Participants who viewed the virtual factory were much more talkative and involved in the exploration of the simulation than the subjects who experienced AutoView. They were able to discuss the model of their facility at length, how they could use the technology and the simulation to their advantage, and reflect on other possible applications for this technology. These intangible benefits would be difficult to quantify either in usability testing or in a cost-benefit analysis.

## 8 CONCLUSIONS

The appropriate next step for simulation animation software may be toward a virtual interface. Many researchers and simulation practitioners have cited the benefits of graphical animation for simulation; our results suggest that the virtual interface could improve upon traditional animation for communication of results, generating a greater interest and depth of understanding in a simulation model. There are, however, issues of performance and system integration which must be addressed before we can make a proper evaluation of the potential of VR in simulation.

We have shown the feasibility of bringing virtual reality to commercially available simulation software. We have produced a working first prototype system from which we can evolve general simulation-oriented systems. The integration pathway we chose allowed us to use the intelligence of currently available simulation systems rather than re-engineering those systems ourselves. Such an approach can also facilitate the entrance of a virtual interface product into the simulation market, by tapping into the existing product's reputation and user familiarity.

## REFERENCES


Coco, G. P. (1993). *The Virtual Environment Operating System: Derivation, Function, and Form.* Master's thesis, University of Washington, Seattle.

Coleman, J. R., et. al., Editors (1992, January). Future View: Tomorrow's Manufacturing Technologies. *Manufacturing Engineering*, pp. 76-88.

Cygnus, M. W. (1993a). *The Imager Library.* (Tech. Rep. No. R-93-4). Seattle: Human Interface Technology Laboratory.

Cygnus, M. W. (1993b). *The Virtual Factory Project: experiences in the real world of software engineering and virtual reality.* (Tech. Rep. No. R-93-5). Seattle: Human Interface Technology Laboratory.

Ellis, S. R. (1991). Nature and Origins of Virtual Environments: A Bibliographical Essay. *Computing Systems in Engineering, 2(4)*, 321-347.

Furness, T. A. (1987). Designing in Virtual Space. In W. B. Rouse & K. R. Boff (Eds.), *System Design.* New York: North-Holland.

Hawkins, R. W., Macintosh, J. B., & Shepherd, C. J. (1986). Simulation on microcomputers in the development of a visual interactive modeling strategy. In R. D. Hurrion (Ed.), *Simulation: Applications in Manufacturing.* Berlin: Springer-Verlag.

Jones, K. C. (1992). *Manufacturing Simulation Using Virtual Reality.* Master's thesis, University of Washington, Seattle.

Kunder, R. (1989, June). Simulation as a planning tool in material handling. *Proceedings of the 5th International Conference on Simulation in Manufacturing*, 13-26.

Law, A. M., & Haider, S. W. (1989, May). Selecting Simulation Software for Manufacturing Applications: Practical Guidelines & Software Survey. *Industrial Engineering*, pp. 33-46.

Morrison, K. R. (1991). Animation - A New Dimension in Computer Simulation of Automotive Assembly Processes. *Computers Industrial Engineering, 21 (1-4)*, 547-551.

Norman, V. B. (1992, July). Future Directions in Manufacturing Simulation. *Industrial Engineering*, pp. 36-37.

Park, B. V. (1992, July). The Cyberfactory: View of the Future. *AI Expert*, pp. 59-64.

Pritsker, A. A. B. (1992, July). Simulation: The Premier Technique of Industrial Engineering. *Industrial Engineering*, 25-26.

Seevers, C. (1988, November). Simulation before Automation. *Proceedings of the 4th International Conference on Simulation in Manufacturing*, 217-244.

Shannon, R. E. (1975). *Systems Simulation: the art and the science.* Englewood Cliffs, New Jersey: Prentice-Hall.

Sheridan, T. B. (1992). Musings on Telepresence and Virtual Presence. *Presence, 1(1)*, 120-126.

Smith, R. L., & Platt, L. (1987, January). Benefits of animation in the simulation of a machining and assembly line. *Simulation*, 28-30.

Zeltzer, D. (1992). Autonomy, Interaction, and Presence. *Presence, 1(1)*, 127-132.


## AUTHOR BIOGRAPHIES

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**Dr. Richard L. Storch**, a professor in the University of Washington's Industrial Engineering Department, chaired Karen Jones' thesis, "Manufacturing Simulation Using Virtual Reality."