# Virtual Assembly Using Virtual Reality Techniques


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## ABSTRACT

Virtual reality is a technology which is often regarded as a natural extension to 3D computer graphics with advanced input and output devices. This technology has only recently matured enough to warrant serious engineering applications. The integration of this new technology with software systems for engineering, design, and manufacturing will provide a new boost to the field of computer-aided engineering. One aspect of design and manufacturing which may be significantly affected by virtual reality is design for assembly. This paper presents a research effort aimed at creating a virtual assembly design environment.

## INTRODUCTION

The complete integration of 3D design and manufacturing tools is an important goal of the designers and creators of CAE (Computer-Aided Engineering) systems. Achieving this 3D engineering process will provide a means to envision, refine, and develop a product or process with significant cost and time savings. Technologies that allow 3D assembly evaluations are not yet fully utilized by industry, even though virtual manufacturing technologies are regarded as viable and valuable. Obtaining a true concurrent engineering effort requires a cohesive and comprehensive solution that supports both product and process views. Virtual reality (VR) is a new technology which can assist with this integration.

Virtual assembly crosses multiple domains and it is important that the related technologies develop synchronously to enable industrial applications of virtual assembly. It is envisioned that the distinction between CAD (Computer-Aided Design) and virtual reality systems will converge as new design systems will encompass features from each of the technologies.

The work being described here is part of a larger effort called “Design by Manufacture” (Angster, 1996). In a “Design by Manufacture” environment, the designer has access to manufacturing processes and tools (e.g. machine tools, assembly tools, transfer lines, etc.) in the form of virtual environments. These virtual environments will allow the designer to “virtually manufacture” the product while designing it. This paper describes feasibility work in using virtual reality for design for assemblability, the design of a virtual assembly environment and preliminary results from the use of this environment. For this paper, virtual reality (VR) is defined as the use of computer-generated virtual environments and the associated hardware to provide the user with the illusion of physical presence within that environment and virtual manufacturing (VM) is defined as the use of virtual reality in all types of manufacturing scenarios.

**Virtual reality**

Virtual reality is a technology which is often regarded as a natural extension to 3D computer graphics with advanced input and output devices. This technology has only recently matured enough to warrant serious engineering applications. Several companies and government agencies are currently investigating the application of virtual reality techniques to their design and manufacturing processes. The state of the technology is appropriate for undertaking projects which demonstrate the feasibility and usefulness of using virtual reality for facilitating the design of a product.

In very simple terms, virtual reality can be defined as a synthetic or virtual environment which gives a person a sense of reality. This definition would include any synthetic environment which gives a person a feeling of "being there". VR generally refers to environments which are computer generated, although there are several immersive environments which are not entirely synthesized by computer. Examples of these include the use of video cameras for tele-presence or the use of hardware augmented immersive environments..

The exposure most people have to the concept of virtual reality is through reports in the media, science magazines, and science fiction. However, to the researchers involved in the actual science of virtual reality, the applications are much more mundane, and the problems are much more real. A good discussion on virtual reality has been presented by Machover and Tice (1994), and Ellis (1994).

**Research Goals**

The overall goals of the research described in this paper are 1) to develop models, tools, and environments supporting assembly of mechanical components; 2) to aid in design for assembly, design for maintainability, and assembly planning; and 3) to assist in the development of assembly relevant standards. A sub-goal is to investigate requirements for effective assembly modeling in utilizing the STEP[1] standard, and to participate in the development of STEP extensions.

## PROBLEM STATEMENT

The capabilities and functionality of the next generation of CAD systems will undergo vast changes due to technological advances in: 1) *high-performance computing and communication*, 2) *the focus on the conceptual design phase*, and 3) *the use of advanced technologies such as VR.*

**High-Performance Computing and Communication (HPCC)**

With the emergence of high performance computing, communication, and visualization, new avenues for improvement are opening up to the design engineering community. This improved communication has lessened the impact of physical distances on design tasks and has resulted in reconsideration of design projects where design tasks are geographically dispersed. Computationally intensive analysis and visualization models that were previously considered unwieldy and too complex to be used are being re-examined. The rapid evolution of high-performance computing and communication clearly puts increasing pressure on design application developers and users to maintain pace to ensure the greatest positive impact on the product design process.

**Focus on the Conceptual Design Phase**

Marketplace pressures are forcing decreased product life cycle costs, maintained/improving product quality, and reduced time to design and fabricate the product. This requires that the product design take place in an environment which supports collaboration between multiple functional disciplines and provides access to advanced design tools. Few design tools address methods to assist the designer in the conceptual stage of design, yet companies are now

[1] STEP - Standard for the Exchange of Product Model Data

acknowledging that conceptual design not only determines 70% of the product costs, but also effects product delivery schedules.

**Use of Advanced Technologies**

A new technology that is being explored by industry, academe, and federal agencies is the application of virtual reality to design engineering problems (Jayaram, 1996). A natural evolution of CAD technology is the addition of virtual reality functionality to design systems. This new functionality will provide designers with methods that will extend their ability in the development of new and variant products. The design process itself will change to accommodate this new view of the product and the processes that are used to fabricate it. It is purported that once virtual reality technologies are used widely in industry, new approaches to design, as well as the associated business and engineering processes, are likely.

Other areas that will drive the development of the next generation of CAD systems and which are important considerations for assembly functionality are listed below:

- **New representations** - Much of the information that a designer uses is in unstructured, non-computerized representations, such as textbooks, file folders, journal articles, or micro-fiche. This information is, for the most part, stored away and is not easily accessible for timely retrieval and use. Communicating product design information effectively between stakeholders requires design information beyond nominal product shape and contextual features. Enhanced design information must capture design constraints (i.e., Design for "x" considerations), rationale, and functionality in addition to structure. This must all be done with little or no effort on the part of the designer. New tools and technologies should force an evaluation of the current design process and promote design process evolution. This evolution is a natural consequence to support the capture of enhanced design information and the retrieval of information appropriate to the user and the task at hand. A design system which minimizes information acquisition overhead while maximizing information content is needed.

- **Design alternatives** - Of particular interest is the review of alternative designs against problem constraints and definitions early in the design cycle where maximum benefits can be achieved. Evaluating several choices will expand the "design domain" and often will serve as a catalyst to induce innovation and creativity. 'This is similar to the concept of "brainstorming" except that the "design domain" may be derived from a library of designs accessible by queries or a knowledge-based application rather than from a true brainstorming session with co-workers. Often, when a designer feels comfortable that an acceptable solution has been found, alternate, more innovative designs can be evaluated that may entail more risk associated with successful completion, but have far greater benefits to the product.

- **Integration issues** - The emergence of enhanced CAD systems has introduced new integration issues because these new technologies are not coupled tightly with current design applications. This is demonstrated by the fact that VR systems employ very different methods to visualize and manipulate the underlying product model. This results in multiple product models.

- **Design data management -** To be effective, a designer must manipulate and transform large amounts of design knowledge and information throughout the design process, while considering constraints from all the life cycle domains (including customer requirements). This requires the use of their acquired knowledge about engineering, materials and spatial relationships.

- **Access to knowledge -** With the competitive pressures facing companies today, designers are confronted with time constraints that, with current business practices, are forcing decisions to be made before a designer has been able to effectively explore key design options and alternative designs that may be critical to the product's success. Crucial decisions are made throughout the design process and each of these decisions has an impact on the final product definition. By making design knowledge more readily accessible, the designer is able to make better design decisions. Providing access to other experts' knowledge also extends the designer's knowledge and is key to increasing the designer's flexibility to better respond to today's changing environment.

- **Access to services -** Due to the large development, capital, and maintenance expenses associated with many design support functions the availability of these services for a fee is very attractive and benefits both the provider and the user of the service. Most small to medium size companies are unable to adequately attain such services as: - i) assembly dynamic analysis, ii) manufacturing and assembly tolerancing analysis/approaches, iii) assembly sequencing optimization, and iv) design for produceability knowledge/applications. Companies that are considering the addition of specific support services can use this “new way of doing business” to develop better justification requests by inclusion of expected fees from services provided to external users. These fees can help offset the development and maintenance costs of the specific support service.

# LITERATURE REVIEW

To initiate the definition of a virtual assembly environment, several key research areas were identified. These areas are: virtual environments and geometric modeling of the objects within that environment, real-time collision detection, incorporation of geometric constraints, and swept surfaces and volumes used to represent a path during assembly.

## Virtual Environments

A virtual environment currently in use is described in a paper by Bayliss et. al. (1994). This paper describes a virtual manufacturing system in which machine tools and component parts are represented as geometric models that can move but not change shape. The workpiece being machined is also represented as a solid model, but it has the ability to change shape through machining operations. This manufacturing system was designed to be used with any geometric modeler, provided the modeler can calculate the swept volume of the cutting tool and perform the calculations to subtract this volume from the current workpiece.

Schroeder et al. (1994a) have discussed a procedure for designing for maintainability. Along with the accessibility of parts and fasteners, the issues of part paths and swept volumes are also addressed. Path generation was first performed manually and then by a Random Path Planner developed by Stanford University's Robotics Laboratory. Since swept volumes are hard to create analytically, Schroeder et al. chose an innovative method for the creation of the swept volume.

Another example of virtual prototyping can be found in the paper by Dai and Göbel (1994). The primary goal of the virtual prototype was to eliminate the need to physically prototype a product, and thereby reduce the cost and time to production. Often, physical prototypes have the limitations of restricted geometric accuracy, the required use of special materials, the size of manufacturable parts, and the relatively high cost. With these limitations in mind, the use of a virtual prototype is advantageous. It allows people from differing technical backgrounds to directly interact with the design of a product and to evaluate its functionality. One consequence of the reusability of the virtual prototype is that, in the early stages of the design process, a virtual prototype can be generated quickly and modified frequently. This allows for the consideration of other alternative designs throughout the design process, thus enabling better design decisions.

## Collision Detection

Youn and Wohn (1993) describe a method which "exploits a hierarchical object representation to facilitate the detection of colliding objects." These hierarchical objects (HO) are composed of multiple segments, each of which is related to the others and to the whole. The first task of the algorithm is to determine a list of pairs of nodes which are highly probable to collide. After this determination, the algorithm determines whether the shapes contained within these nodes actually collide.

Cohen et al. (1994) present an algorithm for exact collision detection in interactive environments. A two-level hierarchical collision detection system is presented which selectively computes the precise contact between objects in a multi-body environment. As opposed to a collision detection and avoidance system designed for robotic applications, the proposed system makes no assumptions about time-dependent part trajectories or their derivatives.

## Geometric Constraints

As stated by Fernando et al. (1994), "a common weakness of the existing virtual environments is the lack of efficient geometric constraint management facilities such as run-time constraint detection and the maintenance of constraint consistencies during 3D manipulations." The approach discussed in this paper is capable of handling under-constrained geometry by using a directed graph which maintains the assembly relationships and constraints between the modeled objects.

## Swept Surfaces and Volumes

Swept surfaces and volumes are generated by an object as it moves through time and space along an arbitrary, time-dependent trajectory. There are several references on the topic of swept surfaces and volumes. In one of these, Schroeder et al. (1994b) have applied this concept to the problem of maintainability of jet aircraft engines and "safe" path planning in robot applications. In the context of maintainability, the swept volume, or service envelope, is the volume occupied by the part as it is either removed or installed in the aircraft engine. The swept trajectory is specified as a series of rigid-body transformations, both translations and rotations. The model is then incrementally stepped through the transformations to produce the desired 3D volume. In the last step of this process, the swept surface is extracted from the swept volume.

## VIRTUAL ASSEMBLY

Technologies that allow for virtual assembly evaluation and analysis are not yet fully utilized by industry. Although this emerging technology is not completely understood in regards to applications within commercial industries, the technology as a whole is viewed as viable and valuable. Virtual assembly (VA) is a key component of virtual manufacturing and is defined as:

> *"The use of computer tools to make or "assist with" assembly-related engineering decisions through analysis, predictive models, visualization, and presentation of data without physical realization of the product or supporting processes."*

As with most technologies undergoing rapid growth, supporting technologies, infra-structures, and standards are not keeping pace and, as a result of this, problems are being encountered. Virtual assembly, although defined as a technology, is actually a combination of several technologies such as advanced visualization, simulation, decision theory, assembly and manufacturing procedures, and assembly/manufacturing equipment development. Since VA technologies cross multiple domains and organizational structures, there is a need to maintain an awareness of each of the technologies that support VA and promote lagging technologies to keep all of them in synchronization.

The acceptance and use of VA rely on five issues:

1) how the virtual assembly applications enable engineers (design, manufacturing, assembly, maintenance, etc.) to gain a cohesive view of assembly issues,
2) how the system aids the engineer in making decisions,

3) how these technologies can be applied to real design and production needs today and in the future,
4) how easily the system can be used by engineers on a regular basis (e.g., ergonomics of VR hardware and human/computer interface issues) , and
5) how easily and accurately information can be exchanged between virtual assembly and supporting engineering design and manufacturing systems.

Pilot case studies at industry locations will assist in identifying areas where standards and/or new technologies and methods can be deployed. These results will provide the supporting documentation to assist in directing further research in VA and serve as the first step in the development of "next generation" CAE tools, methodologies, and technologies necessary to meet the criteria established for VA by commercial industries. An example of use of VR technologies in the creation of assembly process information is discussed below.

> ***Example**: An advanced design system allows for the creation of certain "soft zones" which are defined as zones that specific components travel through to be assembled. These zones must not be violated without initiating approval from the person or organization that defined the zone. This zone might be required for maintenance, yet not be a problem for assembly personnel due to its incomplete state when it is initially assembled. Selection of the assembly process (manual or automated) might be very dependent on this issue and this information needs to be made available to the person who designs and implements the assembly/automation lines in a way that is meaningful to assist the decision at hand.*

## VIRTUAL REALITY FOR VIRTUAL ASSEMBLY

Some important aspects and benefits related to the use of VR for virtual assembly are described below.

### VR-to-CAE data exchange

The emergence of virtual reality systems has introduced new integration issues. This new technology is not coupled tightly with complementary applications such as CAE (e.g., CAD, CAPP systems). VR systems can be viewed as a natural extension or enhancement to current CAE systems, although very different methods to visualize and manipulate the underlying product model are currently used. This results in data and information that can not be shared by other engineering and manufacturing systems. This incompatibility is highlighted when engineers, working with a product model within a VR application, generate important information that assists in defining assembly processes or results in modifications to the product model. Successful application of VR technologies where significant impact can be shown is lacking. Until these barriers are addressed and solved there is little likelihood of acceptance of VR technologies.

**Assembly modeling and analysis**

As mentioned earlier, it will become increasingly important that designers develop new products that are, early in the design phase, thoroughly analyzed for "producibility" without committing the high capital required to produce physical prototypes. This capability requires the user to have high confidence that the virtual assembly systems can accurately represent physical realization of the product.

**Trajectory/swept volumes functionality**

To address assembly and maintainability concerns of a system/subsystem earlier in the product realization process, new techniques are being developed to define the assembly/disassembly trajectories and component orientation (at this point, process independent) for assembling a system. This will allow for the creation of swept volumes that will depict the volume (soft zone) of space that the component or subsystem travels through during assembly (or removal process required for maintenance).

**Assembly process planning**

As the virtual assembly models are developed, key information is both derived and appended to the model providing for downstream use by other personnel. The exploitation of this knowledge and information will require mapping VR and CAD descriptions to assembly plans; that is, a reliable transformation (manually assisted or automatic) from the assembly's virtual description to a plan to physically realize the assembly. These abstract assembly plans would contain sufficient process information such as component sequencing (with alternatives), feature datums, assembly trajectories, component orientation, and tolerancing data to support decisions in process selection (manual or automated) and enabling more detailed process definition.

**Assembly-based design**

There has been increased activity in exploring assembly theory and methods to dramatically improve the product realization process. Some researchers have recommended that assembly serve as an "integrator" for the design process, stating that this effort will result in better methods for partitioning system level requirements into subsystems and mapping these into component geometries, and designing production systems and techniques to support flexible production. When developing a complex system, decomposition of the system into optimal sub-systems, then defining assemblies and components is critical in determining its cost and build time.

## THE VIRTUAL ASSEMBLY DESIGN ENVIRONMENT

The primary objective of the research being described in this paper is to demonstrate the feasibility of creating valued design information using VR tools and exchanging this information with other engineering applications such as a CAD application. A prototype "Virtual Assembly Design Environment" (VADE) has been defined and implemented to address a specific assembly scenario representative of actual issues facing an industry assembly facility. VADE consists of a virtual environment which allows an engineer to consider assembly issues of mechanical systems earlier in the design cycle. In performing virtual assembly tasks the designer creates product and process information. An initial study of this type of assembly system is presented by Connacher et. al. (Connacher, 1995).

The virtual environment consists of virtual reality hardware and software, which will allow the designer to be immersed in the environment. A head-mounted display is used to provide the engineer with high-quality, stereo-scopic graphics. Electromagnetic positioning devices are used to monitor the head movements of the user and the display in the helmet will be modified automatically to allow the person to "look around". Additional positioning devices are used to track the movements of the hands of the user. This information is used to create and manipulate a model of the hand in the virtual environment. An instrumented glove is used to monitor the movements of the fingers and the wrist. The engineer will be able to use this virtual assembly environment to evaluate tolerance issues, select optimal component sequencing, generate assembly/disassembly process plans, and visualize the results.

This research was intended to be a pilot project in the area of VR-based virtual assembly tools. A successful demonstration of the feasibility of using VR for virtual assembly will provide commercial industries with the confidence to apply this technology to their own design processes. The success of the research being described in this paper relied on the various technical aspects described below.

**<u>Creation of the virtual environment</u>**

The requirements of the overall virtual environment software that will form the backbone of the virtual assembly system needed to be carefully analyzed using object-oriented analysis (OOA) methods. The use of object technology makes the resulting software system more flexible and easy to extend. It allows for easier alignment with the next generation of standards for multimedia software (e.g. PREMO[2]). A complete object-oriented design (OOD) needed to be performed based on the OOA. The user interface for the virtual assembly environment was then implemented.

**<u>Transfer of information from a parametric CAD system (Pro/ENGINEER™) to the virtual assembly environment</u>**

Methods for creating a direct interface between a parametric CAD system and the virtual assembly environment needed to be created. In this research, the CAD system used was Pro/ENGINEER™. Methods for storing and displaying the CAD model information at varying levels of detail needed to be investigated to obtain the optimum performance in the virtual environment. These display models were chosen to be polygonal models. These methods have been tested by automatically transferring Pro/ENGINEER™ models of mechanical assemblies to the virtual environment. The CAD system contains information which will assist in the creation and use of the virtual assembly tools. Other standards such as STEP and "de-facto" standards (e.g. the Open-Inventor format from Silicon Graphics) needed to be evaluated for the data transfer between the CAD system and the VR environment.

**<u>Creation of component trajectory information</u>**

In the virtual environment, the trajectory of the component needs to be recorded as it travels through space during the assembly process. This trajectory gives rise to "soft zones". Methods to create, store, and display these soft zones needed to be implemented. Simple collision detection algorithms were needed to detect collisions between components during the assembly process.

**Transfer of virtual assembly data to the CAD system**

Valued design information will be generated when the engineer uses the virtual assembler. The amount of this information that can/should be sent back to the CAD system needed to be investigated. The transfer of information related to the sequence of assembly, the soft zones, the trajectories, etc. are particularly important.

## SYSTEM CONFIGURATION

The workstation used for a prototype implementation of VADE consists of a Silicon Graphics, Inc. Crimson™ workstation. This workstation has a single, 150MHz, MIPS R4400 processor, with 64 MB of RAM, Reality Engine™ Graphics, and a multi-channel option board. Two head-mounted displays (HMDs) are supported. One is the VR4™ HMD from Virtual Research. The second helmet is an indigenous one which utilizes two Tektronix Model EX100HD, 1” color CRT displays. The Tektronix displays have the capability of 800 x 600 resolution. Position and orientation tracking is done by Ascension’s Flock of Birds™ with an Extended Range Transmitter (ERT). This transmitter employs a pulsed, DC magnetic field and is capable of determining 6 DOF information from each of the possible 29 receivers. Measurements can be made at a rate of 10 - 144 hertz at a range of ± 8 feet from the ERT. A CyberGlove™ was chosen for use with this system. Finally, tactile feedback is supplied by a Tactools™ feedback system which uses shape-memory alloy to provide a touch feel at the fingertips. The system configuration is shown in Figure 1.

[2] PREMO - Presentation Environment for Multimedia Objects

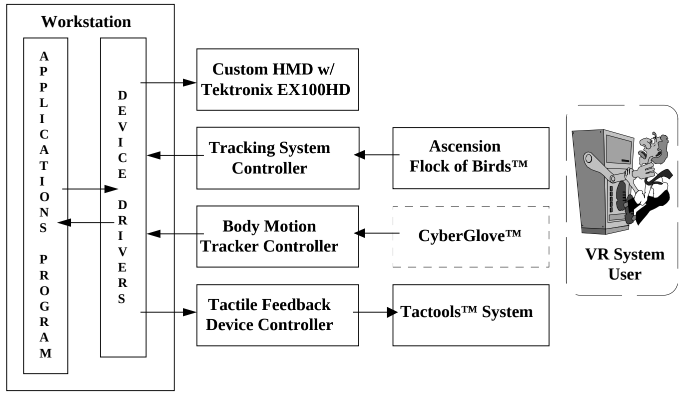


**Figure 1 - System Configuration.**

Initial prototypes of VADE and the first generation of VADE were created using Silicon Graphics' OpenGL™ graphics libraries. The second generation of VADE has been designed to take advantage of Silicon Graphics' high-performance graphics library IRIS Performer™.

# EXAMPLE OF USE OF VADE

Figure 2 shows the flow of information during the use of the virtual assembly environment. The process starts with the creation of a model of the assembly in a CAD system (e.g. Pro/ENGINEER™). This model is then interrogated by a VADE preprocessor for pertinent information. The visual attributes of the parts (e.g. color, textures, etc.) are extracted automatically. The geometry of each part is also extracted along with assembly information. Tolerances, locations and orientations of the parts, the number of instances of each part in the assembly, assembly constraints, etc. are automatically extracted and made available to VADE. In the virtual assembly environment, the user is presented with a method for "pre-planning" the assembly. This involves locating the various parts in bins, racks, on a table, etc., redefining certain visual properties (e.g. making certain parts translucent), defining the tolerances for the "snap-fit", etc. The user then enters an immersive environment and performs the assembly of the design. During the assembly process, the user has the option of storing the trajectory which was created or reject it and reassemble the part. Collision detection methods will warn the user of interference problems and tolerance problems.

The information generated by the virtual assembly process may be used in several ways. The trajectory information could be sent to an Assembly Analysis System (e.g. Design for Assembly) to allow the engineer to generate some suggested design changes which could then be fed back to the design process. The VADE information could be used to train personnel for the assembly process, sent to CAPP systems for process planning, or used to generate robot path information. The VADE system could also generate valuable information which will assist in the design of specialized assembly equipment (such as those required for the assembly of electronic components).

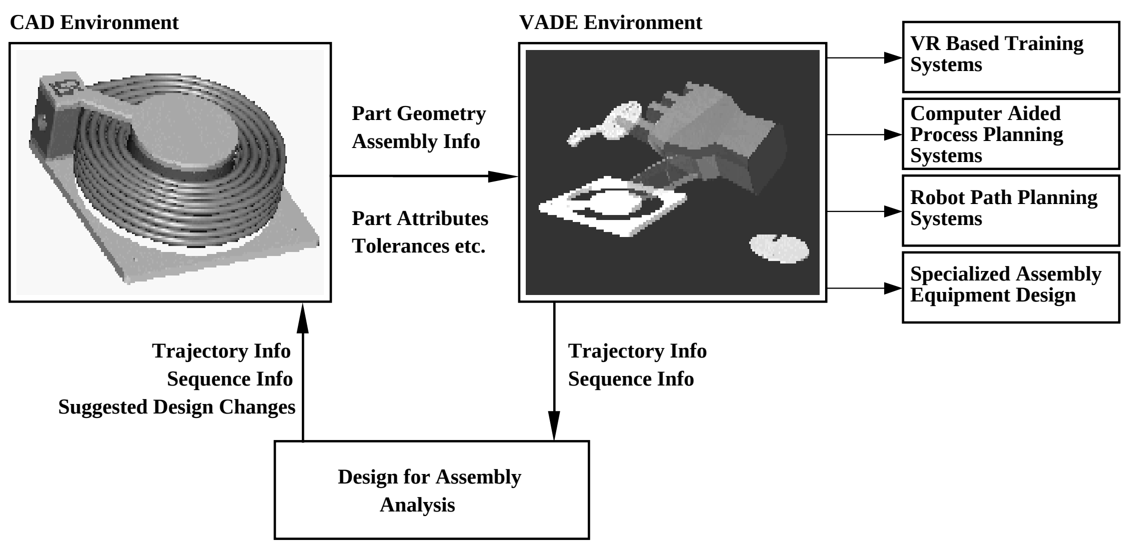


**Figure 2 - VADE Usage Scenario.**

## PROTOTYPE IMPLEMENTATIONS OF VADE

Three prototypes of the Virtual Assembly Design Environment were implemented. For the first prototype, an assembly of a mechanical system was supplied by Isothermal Systems Research, Inc. (ISR). This assembly model was generated by ISR in Pro/ENGINEER™ as individual parts and subsequently assembled (Figure 3).

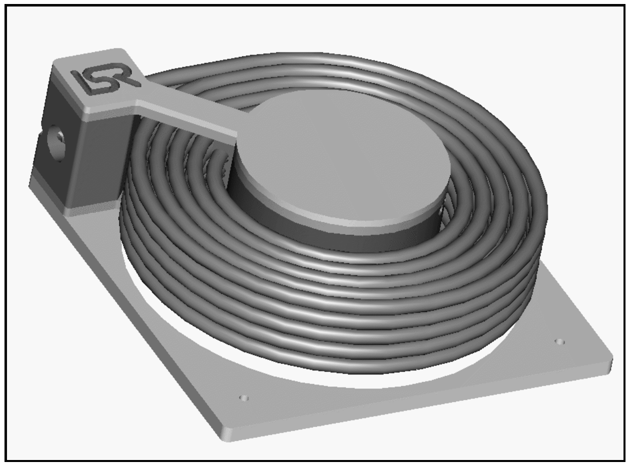


**Figure 3 - ISR Pump Assembly.**

For the first two prototypes, several different formats of data output were investigated and it was decided that stereolithography data files were the easiest to convert. When exporting a file in this manner, the output generated is a triangulated approximation of the surfaces of the part. Once this had been accomplished, it was necessary to determine the translations and rotations that would transform the part into its final assembly location and orientation. This was done by entering the Pro/ENGINEER™ CAD environment and directly determining the values for each transformation from the pump assembly. Next, it was necessary to import the parts into the virtual environment. Parts were displayed in the VR environment by means of display lists in Open-GL™. For each individual part, a display list was created and executed which allowed each part to be a unique and separate entity within the VR system.

Initially, the parts were arranged in a row, in order of their assembly sequence, in front of the user for ease of selection. In order to pick up the part, the current location and orientation of the fingertip, supplied by the Ascension tracking system, were compared to the initial, arbitrary location and orientation of the part. Once this value was within a given tolerance, the part became "attached" to the fingertip. To place the part in its final assembled location, the current part's location and orientation were compared to its final assembled location and orientation. Again, once this was within a given tolerance, the part snapped into place in the assembly and the next part was ready to be picked. In these prototype implementations, the glove input device was not used. Another version of the first prototype included a visual representation of the soft volume required to assemble one of the parts. An example of the soft volume generated is shown in Figure 4.

The second implementation of the prototype assembler also used a model generated in Pro/ENGINEER™ (Figure 5). This version used stereolithography output from a Pro/ENGINEER™ model as well. The main difference between the two implementations was the method of generating the necessary transformation values. The new model was generated with all the components of the assembly in the correct orientation. It was determined through investigation that the values required to perform the translation to the final assembled position could be extracted from the assembly stereolithography file. First the number of triangles and the vertex information for the first triangle in the surface model of each part were extracted from the part file itself. Next, the corresponding triangle in the assembly file was determined and the vertex information was again extracted. The difference between these two locations provided the needed x, y, and z values to translate the part.

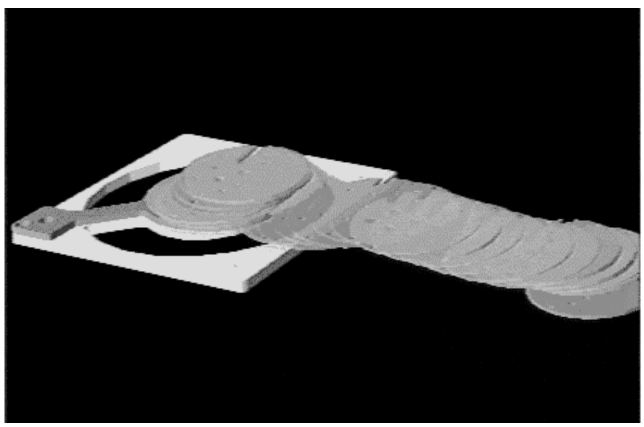

**Figure 4 - Example of Soft Volume.**

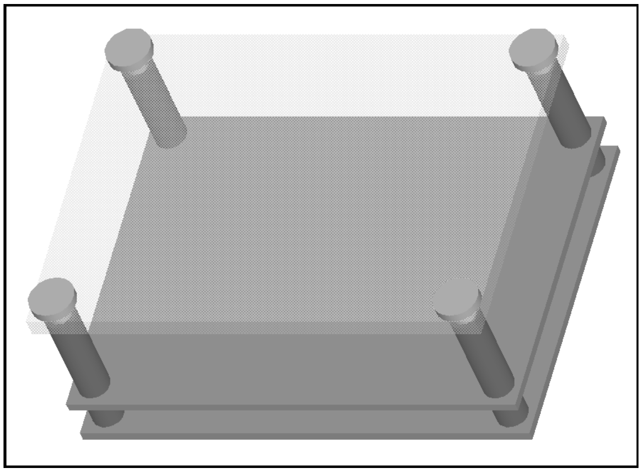

**Figure 5 - Pins Assembly.**

Figure 6 shows the parts laid out in a row for the virtual assembly environment. One drawback of this prototype implementation was the inability for a single part file to be used multiple times in a single assembly. Display lists were again used to display the surface of the model. The procedures for setting the initial location, picking the part, and placing the part were retained from the previous implementation.

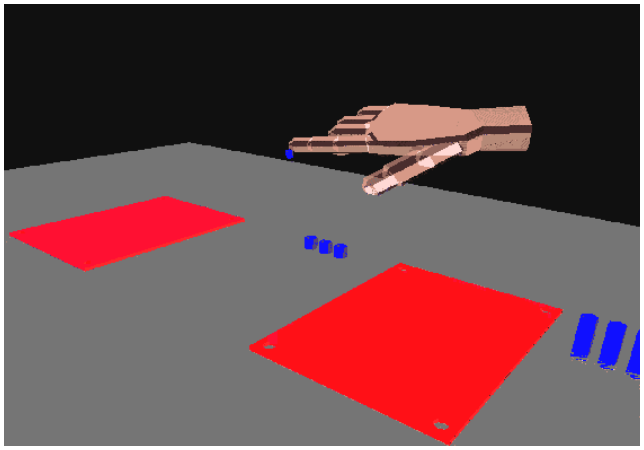

**Figure 6 - Parts in the Initial VADE System.**

After the two initial prototypes, an object-oriented analysis and design were performed for a more complete VADE system, fully integrated with Pro/ENGINEER™ (Connacher, 1996). Figure 7 shows a user's view of the new VADE environment.

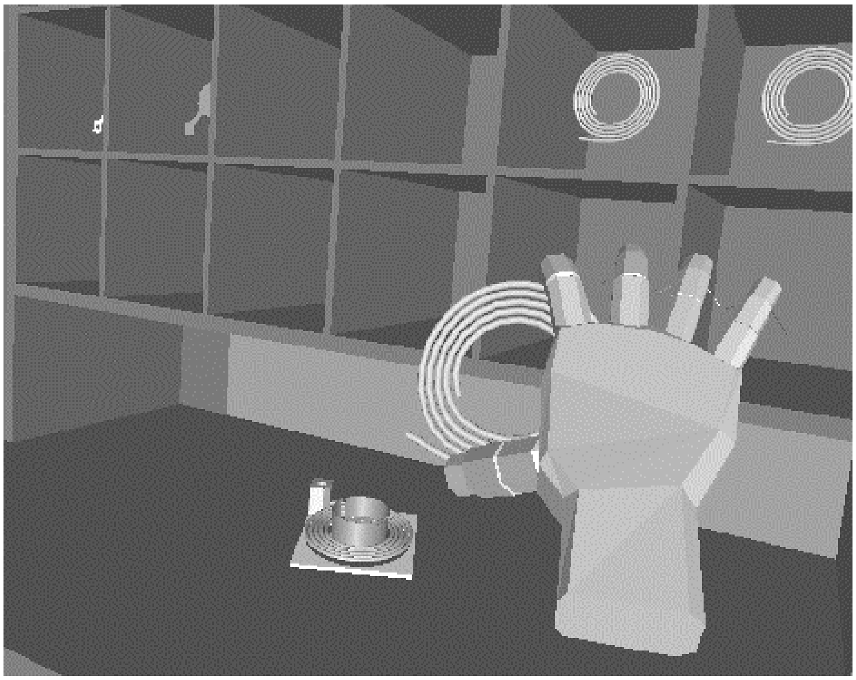

**Figure 7 - Example of the Final VADE System.**

## Associated Technical Issues

There are several technical issues which need to be resolved to enhance the usefulness of virtual assembly systems. Some of these are listed below.

**Calibration of the virtual space**

The use of electro-magnetic tracking devices allows a great degree of freedom for the user. However, the presence of metallic objects in the vicinity of the transmitter or receiver significantly distorts the magnetic fields. This necessitates the calibration of the workspace. The accuracy of this calibration depends on the specific application. In the case of virtual assembly, the calibration needs to be quite accurate if reach studies and any other ergonomic studies are to be performed. Several research activities are currently underway to make the calibration process more precise and easy (Ghazisaedy et. al., 1995 and Gowda, 1996).

**Graphics speed**

Although most VR-based research laboratories have access to a high-end graphics workstation, it is unreasonable to assume that all engineers will have such workstations on their desktops. Thus, the speed of response of the system becomes important. With the prototype system, dramatic improvements in speed were observed by reducing the number of polygons in the displayed image without losing detail in the model. However, this trade-off point will vary from one system to another and from one model to another. The VADE system needs to be scaleable to support the various types of hardware levels which may be available to the user. Moreover, even if the graphical representation on the display device is less accurate, the actual model used for all the computations needs to be the exact surface or solid model.

**Ease of use**

One of the goals of the VADE system is to provide a useful tool for designers and manufacturing engineers. This can be achieved only if this VR-based system is easy to use. The current state-of-the-art does not facilitate this. HMDs which have a high enough resolution are cumbersome and heavy. The use of "fish-tank" VR systems may not be immersive enough. The entire topic of user interface in a VR environment is very difficult to deal with. Several of these problems are expected to be solved or at least reduced over the next few years as research into VR hardware and software progresses.

**Physics-based models**

When performing assembly operations in a real-world environment, an important consideration is the physics of the assembly process. As with physical mockups created using a modeling material such as wood or clay, the inertial properties of the assembled parts are different from the actual properties of the real components. Similarly, in a virtual environment, the inertia of the assembled component does not come into play. Within the VADE system, a method for incorporating velocities, accelerations, etc. needs to be investigated to augment the virtual assembly process.

**Trajectory editing**

The trajectory created during the assembly of a part may need to be cleaned up before sending the swept volume to the CAD system. The number of trajectory stations may need to be decreased and the trajectory may need to be optimized. The user should be given the option of performing the trajectory modifications in both the VADE and the CAD environments.

**Virtual sssembly standards development**

To enable industries to more effectively and efficiently utilize virtual assembly technologies, standards and/or common approaches and methods are required. Within the current standard efforts there are many activities that address issues related to VA. To aid in developing a preliminary structure that can be used in developing standards in VA, portions of existing standard efforts need to be incorporated where appropriate. An example of this is the STEP project 105 for kinematics. This effort has very detailed methods which identify and define techniques to represent displacements and orientation. This combined with other such efforts can serve as a start for future efforts in structuring an application protocol (AP) for virtual assembly. There are also interest groups and committees being formed to address issues in virtual reality which are closely related, and of importance, to virtual assembly. Another related standards activity is the PREMO Multimedia API standards development effort.

**Technology validation**

Often, the reason that new technologies are not implemented is that they lack sufficient documentation and business justification to support their use in production. This documentation is required by enterprise executives to understand the impact of new processes and technologies. Before a new technology will be considered for implementation in a production setting it is important that the system undergo a series of tests to validate its capability to handle production requirements consistently and accurately. For example, one test for trajectory functionality could be the recording of trajectory information of actual assembly operation and compare this to projected trajectories using VR.

## CONCLUSIONS

This paper presented the concepts behind a VR-based virtual assembly system. Initial prototypes of this system proved the feasibility of these design enhancement tools. Initial tests of the implementation of VADE have shown promising results. Virtual reality tools are demonstrating their value in assisting the designer in creating designs which are more "assemblable". Full implementations of this virtual assembly technology can significantly reduce design cycle time, re-design efforts, and design prototypes.

It is anticipated that through the development of new design systems that use VA technologies, companies would benefit by:

1) reduced product development and fabrication time, therefore reducing time-to-market,
2) faster technology insertion of advanced design methods and tools,
3) improved product design (quality, reliability, etc.), and
4) reduced costs.

These benefits would be realized through improvements in areas such as those listed below.

- *Assemblability* can be analyzed by allowing an engineer to evaluate the motions associated with assembling a system.

- *Selection of the "process" can be delayed* to enable better engineering decisions throughout the product realization cycle to answer issues such as: "Should the assembly be out-sourced?", "What is the time taken to assemble the product?", and "What effect does my tolerancing have on cost?".

- *Electronic mock-ups* can enable the system to be analyzed more completely (i.e., inclusion in its expected functional environment) providing engineers with a detailed view of the product from which many critical decisions can be made, leading to a more predictable manufacturing/assembly and field deployment cycle.

- *Expenses can be reduced* in the development of new products. The "*producibility*" of these products can be analyzed thoroughly without committing the high capital required to fabricate the product.

- *Maintainability* issues can be addressed by VA through key factors such as accessibility (with tools, required torque), safety, field of view, and disassembly.

- *Reduction in inventory* can be favorably impacted with improved projection of design-to-product cycle times.

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## DISCLAIMER

The authors do not intend to promote any specific software or hardware systems mentioned or described in this article.

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