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COLLABORATING ON THE DESIGN AND MANUFACTURE OF AN ATOMIC ARTIFACT TRANSPORT SYSTEM: A CASE STUDY IN VRML AS A VISUALIZATION TOOL FOR CONSENSUS BUILDING

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ABSTRACT

We report on our experience using the Virtual Reality Markup Language (VRML) to collaborate on the design and manufacture of an artifact transport system (ATS). Specifically designed for the purpose of transporting nanometer-scale dimensional artifacts at pressures ~10^{-8} Pa, the ATS consists of a transport cart and an ultra-high vacuum (UHV) system. As its name implies, the ATS is to transport an atomically-accurate specimen created in a molecular beam epitaxy (MBE) laboratory to a scanning tunnel microscope (STM) laboratory across the NIST campus, where metrologists verify atomic-scale measurements. The project team involved between 15 and 20 participants – designers, engineers, physicists and manufacturers – and each individual was involved with the design and assembly of the ATS to varying degrees. After the project engineers developed their assembly models with their CAD tools, we exported the components and assemblies to VRML files. These representations were made available, via web browsers with VRML viewers, for feedback to project team members on their own workstations, which included PCs, Macintoshes and Suns. The port involved characterizing the simulation's performance over a range of parameters such as processor capability, file size, VRAM available and graphics card capability. After meeting with the fabricators and physicists to determine the approximate assembly sequence of the ATS, we used CosmoWorlds to edit, augment and animate the VRML files on a high-end workstation. By visualizing the animation sequence in a common facility with a videowall, participants were able to reach a consensus for the design and assembly changes needed. We conclude that VRML did help our team collaborate in the design and fabrication processes, although the technology supplemented, rather that supplanted face-to-face meetings. Our experience with VRML on multiple workstations leads us also to conclude that the language needs to be characterized to enhance easy development of engineering models and to achieve true and complete platform-independence.

INTRODUCTION

Recent research has shown that simulating design and manufacture (DM) activities has a beneficial effect on the overall DM process. For example, Choi *et al*. [1995] have shown that Simulation-Based Design (SBD) is useful for obtaining realistic product performance without necessarily creating prototypes of the product under consideration. From a manufacturing perspective, simulating the assembly process has the effect of studying – and perhaps modifying – shop-floor operations *before* they take place [Jones and Iuliano, 1997]. One clear benefit to simulating DM activities is that doing so makes meaningful collaboration possible, even among participants who are geographically separated. Collaboration among project team members is a key factor in reaching a consensus on how to best design and fabricate a particular product. This is especially true in the ATS design, where physicists have the experience and expertise in the design of *permanent* vacuum laboratories, and where fabricators have the expertise in creating *portable* containers for standard reference materials.

Collaborative engineering[1] (CoE) is a systematic approach to product design and manufacture. The approach is intended to cause product team members to consider *from the outset* all elements of the product life cycle from conceptual design through disposal [IDA, 1988]. To varying degrees, CoE has increasingly become the *de facto* methodology for developing products [Lawson & Karandikar, 1994] [Sriram & Logcher, 1993]. In general, DM personnel have increased their CoE activities as technology has allowed them to do so. A prime example of this is the recent proliferation of Internet-Aided Design (IAD), where DM personnel use the World Wide Web (WWW) for providing information services on the Internet [Cannon, *et al*., 1997, Cutkosky *et al*., 1996].

One difficulty associated with the increase of CoE activities and technology is quantifying the benefits and the drawbacks to designing and manufacturing collaboratively. Evaluating how people perform, how products perform and how software performs is important in guiding future directions of CoE activities and technology. Generally, questions concerning platform-independence, product representation and standards are three among the many critical issues in judging the efficacy of a given CoE methodology [Zdenek and Domingue, 1997]. In this study, we specifically asked: 1) How well does simulation help make or modify DM decisions? and 2) How well do collaborative tools perform when representing DM information to different team members using different platforms and operating systems? The answers to these questions are precisely the reason for this paper.

This paper describes a case study in using CAE and collaborative tools for the design and fabrication of a prototype transport system for atomic artifacts. We first describe the National Advanced Manufacturing Testbed (NAMT) project, entitled “Nanomanufacturing of Atom-Based Dimensional Standards,” which created the need for an ultra-high vacuum artifact transport system (ATS). We then describe the DM process for the ATS and how collaborative tools were used to make and modify decisions during the design and assembly process. We conclude with our assessment of the benefits of – and the bottlenecks to -- the collaborative DM process.

[1] Concurrent Engineering (CE) is a common term for the approach described above. We opt for Collaborative Engineering (CoE) in our work for two reasons. The first is to dispel the notion CE carries that DM activities occur at the same time. More importantly, CoE more precisely conveys the view that product development is a team effort built on consensus.

BACKGROUND

To support the development of solutions to the standards and metrology issues of new information-based manufacturing, the National Institute of Standards and Technology has initiated a research and development program called NAMT. (A web-based description of NAMT can be found at the following URL: http://www.mel.nist.gov/namt.) In brief, this program is intended to be a showcase for the future of manufacturing, demonstrating how machines, software and people can be networked together to achieve interoperability at all levels of a manufacturing enterprise. The NAMT contains a facility in which scientists and engineers from industry, NIST, academia, and other government agencies work together to solve measurement and standards issues in information-based manufacturing and develop the needed tests and test methods for industry that are part of NIST's mission.

The four original projects within the NAMT are characterized by: (1) collaborative industrial partners, (2) leading edge technologies, (3) development or use of advanced measurement technologies, (4) development of standards for manufacturing applications, (5) use of information technology, and (6) tasks and processes at multiple sites on-line. The results of the NAMT will be metrology techniques, interface standards, and other infrastructure technologies and standards.

NAMT is intended to accelerate efforts to develop components of a common information infrastructure to manufacturing, extending the capabilities of advanced computing, communications, and control technologies to multiple manufacturing applications and domains. It will leverage pools of manufacturing resources, including physical facilities, equipment, expertise, and software. Within the context of information technology-based manufacturing, the current technical thematic focus of the NAMT projects is support to *distributed and virtual manufacturing.*

- By *distributed manufacturing*, we mean cooperating in the overall manufacturing process among functionally-specialized facilities at a variety of geographically-separated sites by means of computer and communications systems.

- By *virtual manufacturing*, we mean: 1) *real* manufacturing by *virtual enterprises*, which come together by means of computer communications to produce a product or aspect thereof; and 2) *virtual* manufacturing by means of comprehensive and realistically predictive simulation of designs, processes and resulting products by means of computer quantitative modeling and qualitative animation.

This particular project, which involves more than 15 team members – physicists, designers, engineers, and fabricators – concerns the *Nanomanufacturing of Atom-Based Dimensional Standards* and is focused on the distributed design, fabrication, and use of nanometer-scale dimensional artifacts. It also uses and supports the technology of the following:

- computer modeling and simulation of mechanical systems and components;
- remote Teleoperation of Scanned Probe Microscopes (SPMs); and
- links to collaborating institutions in industry, government, and academia by means of computers and communications for high-speed video, voice, and data transmission.

There are two major industry trends that are driving forces for this project. First is the ever decreasing dimension and tolerances posed by the semiconductor and data-storage industries. The Semiconductor Industry Association's National Technology Roadmap projects that by 2001 the requirements for critical level wafer metrology of CDs will be +/- 4 Si lattice constants. Less than five years away, the line from SRM 473 shown in Figure 1 is among the best calibration artifacts that industry and NIST can now produce in reasonable quantities.

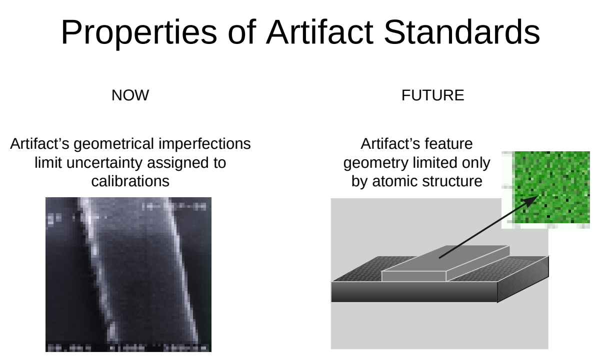

Figure 1. Current and projected artifact standards and their demands on manufacturing and metrology.

The imperfections in the line, its edge roughness, non-straight edges, and irregular wall geometry, produce calibration uncertainties that are typically much greater than that of NIST's and industry's measurement instrumentation. This in turn results in limiting NIST's ability to meet the pressing needs of industry.

One of the project's goals is to fabricate artifacts with feature geometry that are limited only by the atomic structure of matter and whose dimensions are determined by atomic diameters and lattice constants. Collaborating with industry, NIST hopes to develop such standards and to develop and put in place documentary standards to support their development. With such standards, NIST will be in a much better position to meet the future needs of industry.

The second major trend in industry is the demand (resulting principally from the first trend) for cleaner and highly controlled manufacturing environments. Currently these trends are being manifested in the move from clean rooms to mini-environments to clean machines and the use of standard mechanical interfaces (SMIF) or their pods for transferring materials between the manufacturing tools. As is now found in advanced technologies such as x-ray lithography, facilities for the various manufacturing and inspection steps are generally geographically separated. In addition, the cost to bring expert staff, facilities, and materials to a common site is expensive.

Based on this trend, and the awareness that atom-based artifacts will probably live most of their lives in UHV, or at least highly controlled, environments, Figure 2 illustrates our vision of future distributed Nanomanufacturing in the microelectronics and data-storage industries.

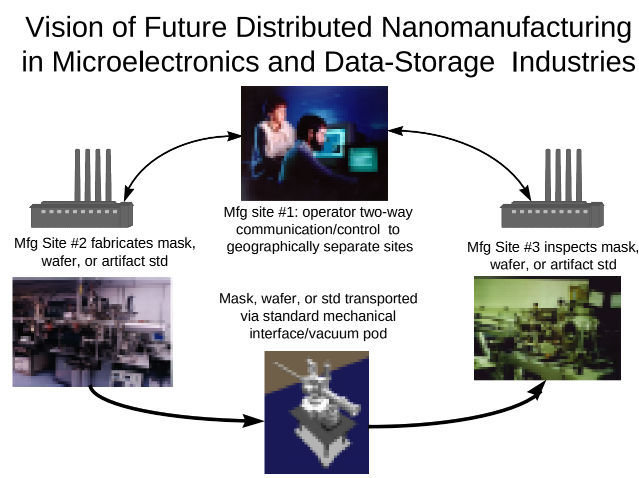

Figure 2. Nanomanufacturing in the near future.

Here we show the use of mini-environments/clean machines for fabrication and inspection evolving to the use of fabrication and inspection in UHV system environments with an artifact-transport system for transporting materials between the various manufacturing and inspection tools and geographical sites.

As a result of this vision, the second major goal of this project is to develop a standard artifact-transport system along with standard mechanisms and artifact carriers for transferring artifacts between UHV systems. Such systems will enable using geographically distributed facilities, as shown in Figure 2, and will enable the development of a database on the impact of various environmental conditions on the stability of atom-based feature geometry and dimensions. This data is needed for determining the final design of the artifact-transport system.

THE ARTIFACT TRANSPORT SYSTEM

Based on the needs described above, the main goal of the ATS is to perform three critical functions: 1) To remove artifact samples from the MBE laboratory, 2) To transport the samples about a kilometer under UHV conditions, and 3) To place artifacts in an STM while maintaining the vacuum conditions. Mitigating damage or degradation to the artifacts during transport is of primary concern to this project. Even under normal high vacuum conditions (about 10^{-4} Pa), a monolayer of gas could be absorbed on the artifact surface in a few seconds. When attempting to establish standards with uncertainties in the nanometer range, the effect of one monolayer can be significant in some cases. During transfer, which may take several hours, artifacts must therefore be kept in the UHV range ($<10^{-7}$ Pa). This design requirement necessitates having onboard pumping, and all metal seals, as part of the ATS. The second vital part of the ATS is the internal mechanism or manipulators that actually handle the artifact inside the vacuum chamber and move it between the ATS and host system. For UHV systems, these mechanisms have to be designed to avoid affecting the vacuum quality.

With the requirements laid out, fabricators and physicists brainstormed to generate an initial conceptual design of the ATS that included a custom transport cart and the UHV system, which included two ion pumps weighing over 1400 N (300 lbs.). After some geometrical layout on a CAE tool, ProEngineer [http://www.ptc.com/], the UHV concept was redesigned in part to employ one ion pump and a lighter turbopump for the preliminary vacuum stage of the transfer. Other principal components, all of which are stainless steel standard vacuum components, include a linear rotary feedthrough transfer mechanism, a linear transfer rod, tees and cross connectors, valves and bellows. The entire system weighs less than 1400 newtons. The entire UHV system was modeled in ProEngineer, and exported to a VRML representation. Figure 3 shows one VRML view of the UHV system.

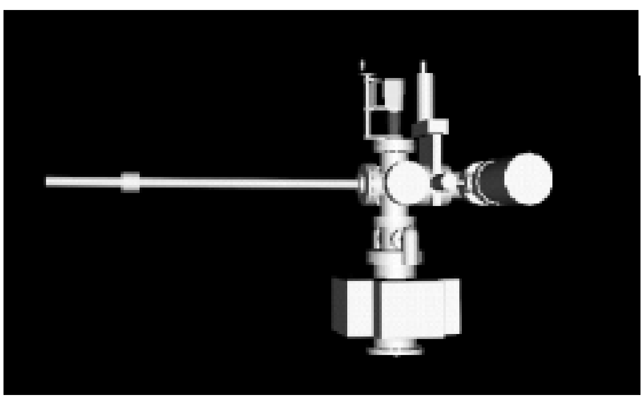

Figure 3. UHV system to maintain vacuum on artifact.

The sheer weight and size of this ATS necessitated the design of a custom cart to transport it. The requirements for the cart are that it support the ATS, and control its monitoring components, as rigidly as possible, provide shock isolation, be adjustable in height, allow fine motion adjustments and have easily interchangeable wheels (for clean room transfers). With input from the NAMT team, the project engineer provided the conceptual design and specifications to the cart designer. The resulting design is a cart made of 6.25 mm (¼”) thick aluminum square tubing 50 mm (2”), with base isolation pads for the main frame that supports the UHV system. One motor controls four jacks that can raise the cart off the ground (for changing wheels) and raise the UHV system (for final assembly and vertical positioning). The 20 cm. (8”) diameter pneumatic wheels are interchangeable with comparable clean room wheels by removing one bolt. The cart was designed in a PC-based CAE tool, CADKEY [http://www.cadkey.com/], and the model exported to VRML format when completed. Figure 4 shows one view of the VRML representation of the completed cart.

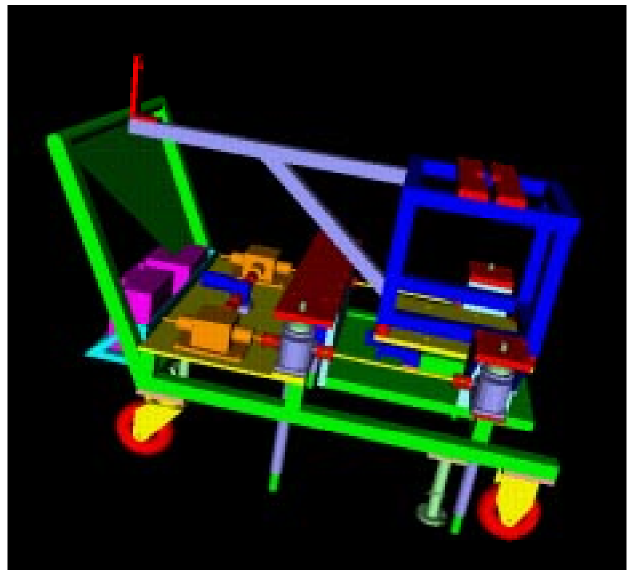

Figure 4. Cart to carry the UHV system. The ATS is complete assembly of cart and UHV system.

ATS DESIGN PROCESS

The core ATS design group consisted of two principal teams. The physicists served as both *customers* in need of a prototype, and *experts* (with >40 years combined experience) in fixed UHV system design. The engineers (with ~25 years of generic DM experience, but no UHV design experience) served as designers and fabricators of the system. As customers, the physicists provided engineers specifications needs of the ATS, and as experts they helped provide initial conceptual solutions. As a result of this atypical design process relationship, collaboration among physicists and engineers was a critical link for the success of ATS design, and often required consensus building. Several face-to-face meetings among engineers and physicists took place for consensus approval of ATS functions, of the ATS detailed model and on future development (including strategies) of ATS design.

This design process provided us the test bed to see how far we can develop a collaborative environment that would best help the team build a DM consensus. Our work focused on three stages across the DM spectrum: simulation of the conceptual artifact transfer mechanism, graphical representation of the ATS, and simulation of the final assembly of the UHV system on the cart. Our efforts included providing synchronous and asynchronous collaboration among the teams and their members. The following three sections discuss each of the efforts associated with the three DM stages.

SIMULATING THE INTERNAL MECHANISM

Simulating the internal mechanism of the artifact transfer system is important, especially to the physicists as *customers*, because positioning of the artifact in either the MBE system or the STM is critical to the success of each system's ability to perform, and to maintain the integrity of the artifact. The engineers designed the components of these mechanisms, which must have distinct, precise linear motion and rotary motion, in ProEngineer and I-DEAS [http://www.sdrc.com/]. These are the mechanisms for removing Silicon artifacts from the MBE system and for placing them in the STM. Realistic simulation of the assembly was achieved by exporting the ProEngineer and I-DEAS models to Alias PowerAnimator – a flexible animation -- tool developed for SGI workstations--via the Initial Graphic Exchange Standard (IGES). Figures 5 and 6 show snapshots from the simulation. [http://www.aw.sgi.com/pages/home/pages/products/pages/poweranimator_film_sgi/index.html].

Figure 5: Picking the artifact from the MBE system.

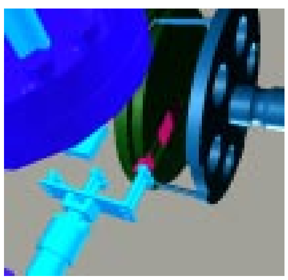

Figure 6: Unloading the artifact in the STM.

Because this simulation was developed on an SGI workstation, this particular evaluation was conducted in a face-to-face meeting in NIST's NAMT Lab [NIST, 1997]. This state-of-the-art laboratory was developed, in part, to enhance synchronous communication. The laboratory includes six SGI and Sun workstations, PCs a large display screen and videoconference links to many parts of NIST via an asynchronous transfer mode (ATM) network. By using ATM, we can switch the display screen to any terminal in the Lab or any NIST location linked to the Lab.

When the simulation was displayed in the NAMT meeting, one physicist identified lapses in the mechanism. As depicted in Figure 5 for example, the initial configuration had a support plate that could slip, possibly dropping the artifact along with it. Since the same mechanism is being used to unload the artifact in STM, as shown in Figure 6, the same problem of slipping resurfaces. This along, with other suggestions, ultimately resulted in the engineers designing a more compatible mechanism. This again was developed into a simulation that was reviewed and approved, and now is a demonstration model for visitors interested in the NAMT project. Our observations about this stage of the collaborative environment are depicted in Table 1.

GRAPHICAL REPRESENTATION OF THE ATS

Our next approach to enhancing collaboration was to present the assembled designs of the ATS to the team members so that each could evaluate, and comment on, aspects of the design he thought was important. In this effort, we chose an asynchronous approach so that the team members could perform their evaluations at different times and places. We chose the Internet as communication medium as it supports our aim by letting team members downloading simulation files at their convenience.

Table 1: Summary of observations in experiment 1.

Experiment	Experiment Aim	Experiment Needs	Environment	Design Gain
Simulation of internal mechanisms.	To display simulation of the internal mechanisms to physicists. Engineers needed feedback on the mechanism's compatibility to physicists' machines.	Computer assisted face-to-face collaboration. • All collaborators present at *same time* and, due to hardware limitation, at *same place*.	• Components created in ProEngineer and I-DEAS, exported to PowerAnimator via IGES standard. • Flipbook animation on SGI to video projected screen.	One of the physicists pointed out likely failure of mechanism for picking the Si artifact from MBE. Engineers decided to further investigate MBE to make the mechanism compatible with it. After the engineers investigated MBE interface, design changes were made to ensure compatibility.

Our tasks to make this idea successful included 1) addressing interoperability issues of combining the cart assembly developed in CADKEY and the suitcase assembly modeled in ProEngineer, and 2) presenting them over the internet independent of the member's hardware system. We chose Virtual Reality Modeling Language (VRML) [Hartman & Wernecke, 1996] as it is

- supported by web browsers for viewing [visit http://www.sdsc.edu/vrml/ for more information],
- a language that supports solid model representation and, most importantly,
- unlike existing IGES standard supported by CAD packages, in that it facilitates representation of parts of assembly as inline files that can be browsed, like a linked HTML documents, by double clicking on them.

We have used this facility of manipulating VRML part files as inline objects to complete the assembly of cart and UHV system.

We used CADKEY's and ProEngineer's built-in converters to export the assembly models the engineers developed (.asm files) to VRML models (.wrl files). Using CosmoWorlds [http://cosmo.sgi.com/] on a Silicon Graphics workstation [http://vrml.sgi.com/], we edited these VRML files to complete the cart and UHV system assembly, shown assembled in Figure 7. Our effort in these exports and transfer is summarized in Figure 8.

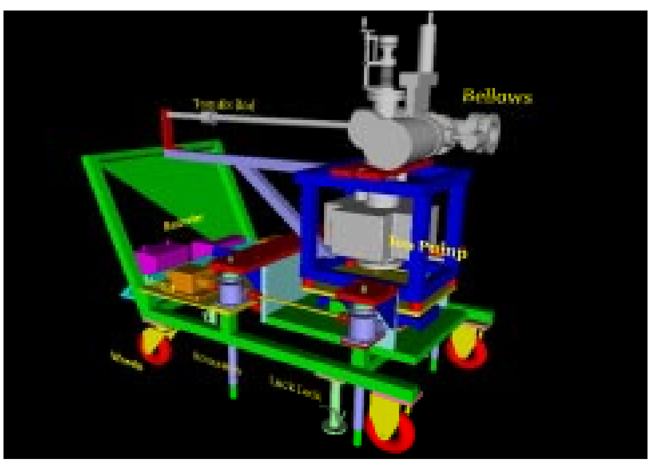

Figure 7. Assembly of cart and UHV system--as a unified VRML model.

Because VRML objects can be manipulated without losing their representation as a solid model, the final assembly still retains the CAD model rendering to help engineers to visualize space constraints such as if the suitcase fits in to the cart or not. VRML also provided the team members the feel of *virtual reality*, that is one can *feel* the VRML model using walk through supported by VRML browsers. We have used CosmoPlayer plugin to Netscape browser to present assembled model in VRML format. This allowed us to present the assembled model on SGI and PC platforms from different places at any time. (Because of the difficulties with the Sun VRML browser, the assembled model was not represented on that platform.) VRML files were placed on our server where each team member has access to browse files. Table 2 summarizes our findings.

We have also observed that PCs failed to present large VRML files effectively. Our VRML assembly file, slightly less than 4MB, nearly took 5 minutes to view it on the fastest PC available to us (32MB RAM, 166 MHz, 2MB VRAM). Navigating through this VRML file on PCs found to be very cumbersome. SGI machines suited us well to present VRML assemblies. In case of Sun workstations, browser support is lacking for presenting VRML 2.0 files.

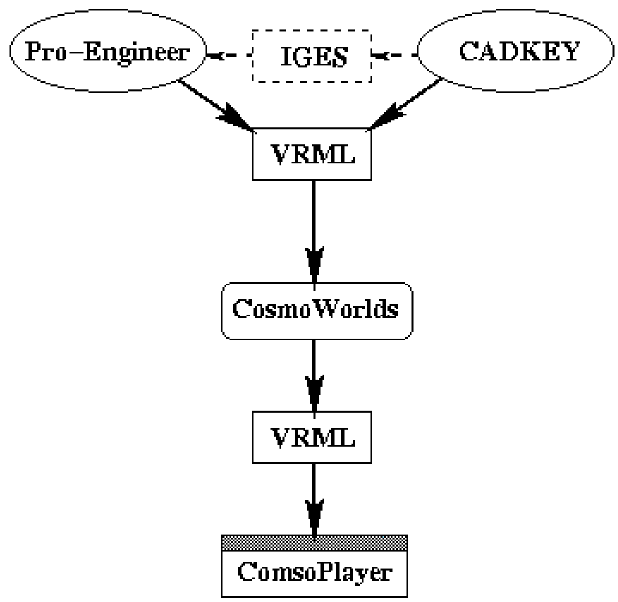

Figure 8. Development effort for VRML assembly of ATS. The dotted path (use of IGES) was only used in our effort to develop the assembly sequence simulation.

SIMULATING THE ASSEMBLY SEQUENCE FOR THE ATS

Our third effort involved simulating the assembly sequence of the cast and UHV system. Digital mock up of this assembly sequence was crucial to identify problems of assembling various components, and to save time and effort by avoiding these problems during actual assembly. The engineers needed information on UHV systems' assembly procedures from the physicists. As the ATS design is a new experience in NIST and elsewhere, any such information was greatly appreciated the engineers.

Following the success of the second experiment, we used VRML (key frame animation) for asynchronous visualization of assembly sequence. Similar to our efforts earlier, we used CADKEY's built-in converters to export the assembly models the engineers developed to IGES models, which we imported into ProEngineer. (See Figure 8).

Table 2: Summary of observations in experiment 2.

Experiment	Experiment Aim	Experiment Needs	Environment	Design Gain
Assembly of cart and suitcase.	Aimed at checking space constraints to assemble cart and UHV system. Cart and suitcase components are developed in two different CAD packages.	*Asynchronous* collaboration. • Initially the team saw the assembly at *same place* and *same time*. Later, this assembly was showed to physicists at *different places* at *different times.*	• Converting components of cart in CadKey to VRML and those of suitcase in ProEngineer to VRML • Editing VRML files for assembly of cart and suitcase (CosmoWorlds is used). • Browsing VRML files via the web on PCs and SGI machines.	Conformance check of whole assembly was successfully achieved. Both physicists and engineers were able to *visualize* the whole assembly for the first time.

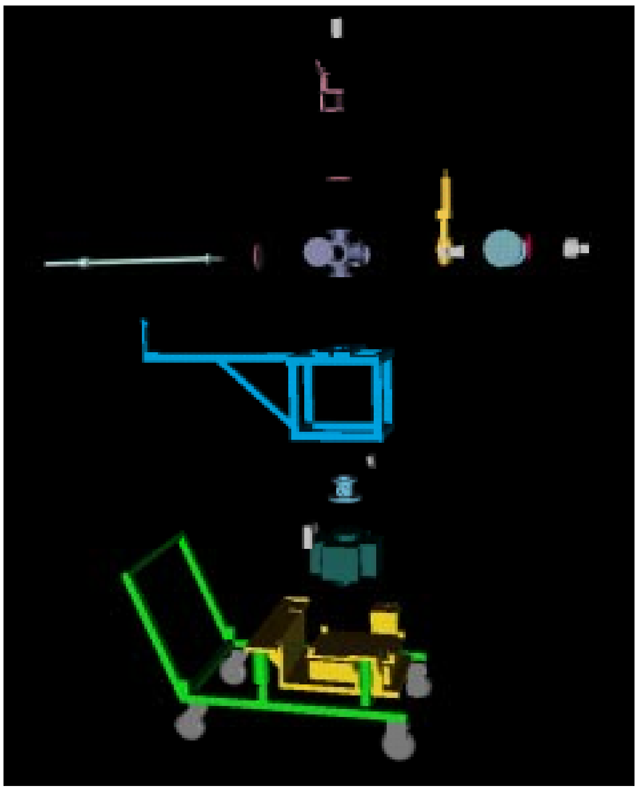

Figure 9. Exploded view of UHV system just before the start of assembly sequence animation.

Doing this allowed us to export to VRML in a uniform manner. Specifically, ProEngineer's export mechanism permits each individual component as an inline VRML file. This allows us greater control and flexibility in animating the model with CosmoWorlds. We edited these VRML files to complete the cart and UHV system animation. Figure 9 shows a sample VRML snapshot of the simulation (an exploded view of the UHV system and the cart at the beginning of the animation).

As explained at the beginning of this section, we gathered simulation details from the engineers and the physicists to generate initial assembly sequence in VRML. This sequence is then tested to browse from different places However, these files are browsable only on SGI machines. PCs no longer supported animation of several solid models (parts) of UHV system. In our earlier experiment, any PC with or above 32 MB RAM, 166 Mhz and 2 MB video RAM displayed VRML files. In this experiment the same PCs failed to show animated VRML files. This presented us serious hardware limitations to build collaborative environment, as most of the team members do not have access to SGI machines. Although, part of this problem can be solved by team members using the available SGI machines *at any time* to browse the animation sequence, truly independent collaborative environment was not realized.

Ultimately, we showed the animation sequence to key team members at the same place in the NAMT Lab. In one three-hour meeting (including 1½ hours viewing the simulation), one STM physicist evaluated the assembly sequence and suggested several modifications to it from his experience in assembling UHV systems. For example, ion pump maintenance requires underside access, necessitating a different placement of the support frame relative to the UHV system. We summarize the experiment observations in Table 3.

DISCUSSION

VRML is found to be a useful and important tool for web-based collaborative design of detailed solid models. It supported asynchronous collaboration where engineers can look at the solid model at different times. State of the art, VRML browsers allowed engineers to have virtual reality feel of the solid models and helped them reason about the design realistically. This facility allowed engineers to minimize time for ATS manufacture.

Table 3: Summary of observations in experiment 3.

Experiment	Experiment Aim	Experiment Needs	Environment	Design Gain
Assembly sequence animation.	To develop and evaluate assembly sequence for UHV system. This is a digital mockup to gain experience of assembling before actual assembly on shop floor.	Goal was *Asynchronous collaboration*, hardware limitations forced computer-enhanced face-to-face meeting. • Engineers and physicists were present at the *same time* and at *the same place*. Computer assisted collaborative experiment depended on the capability of SGI machines. Video projected screen enhanced simulation display.	• Part details designed in ProEngineer • Conversion of ProEngineer files to VRML • VRML Key frame animation (s/w CosmoWorlds issued) • Browsing VRML animation on web on SGI machines only.	Design progressed from a tentative and incomplete assembly sequence to more definitive and detailed sequence. Engineers and physicists mutually participated in the development and modification of the sequence.

However, presentation in VRML required a lot of effort and time to develop the VRML model itself. We call this *authoring complexity*. Similar to the observations by Cannon et. al. [1997], engineers effort increased enormously as they developed the design from conceptual sketches on paper to CAD models in ProEngineer and CADKEY to assembly/simulation in VRML. It required two VRML specialists working for days to complete the VRML presentations. Moreover, in order to make a design change, the complete cycle shown in Figure 8 has to be reworked. For example, if a component has to be re-designed, including its assembly sequence, the engineer has to modify it in the CAD package and export it to VRML for complete rework of key-frame animation. This presents additional tasks of authoring VRML worlds for engineering collaboration.

In addition to authoring complexity, VRML solid model representation looses *engineering information* of the same model represented by CAD packages. For example, ProEngineer can represent a component as parametric solid model, which is a very useful representation for manufacturing. Once such a model is converted to VRML, the parametric representation is lost. Also VRML does not explicitly support *relative motion* of moving objects in its key-frame animation. For example, in order to simulate a valve opening with respect to the location of a particular moving piston, complex scripting and programming might be required to achieve realistic simulation. Such engineering task further increases authoring complexity.

Nevertheless, VRML is a relatively new approach to support web-based design compared to existing engineering methods and traditional across-the-table design meetings. We believe that this evolving standard should take into account the needs of collaborating engineers if it is to be considered as a viable tool for representing engineering designs over the web. In order for VRML to be truly independent of hardware systems, VRML browsers need to evolve too and they must be available on all hardware platforms from low-end PCs to high-end workstations.

SUMMARY AND CONCLUSIONS

NIST's focus on distributed manufacturing in the National Advanced Manufacturing Testbed (NAMT) project presented us an opportunity to support and test collaborative design environments for Design and Manufacturing (DM). We present our experience in providing collaborative support for engineers in the design of Ultra High Vacuum (UHV) Artifact Transport System (ATS). The ATS is required to transport nano-dimensional, high precision artifacts from their manufacturing site (MBE) to the metrology laboratory (STM). The ATS design process thus required collaborative effort from designers, engineers, manufacturers and physicists with considerable experience both in UHV systems and DM. Our effort was to provide web-based collaboration among team members for a better consensus building. We reported three such experiments during the detailed stages of ATS design.

We found Virtual Reality Markup Language (VRML) as a promising tool to present and reason about detail designs, such as assemblies and simulations, over the web. We exported engineers' design from traditional CAD tools, such as ProEngineer and CADKEY, to VRML and edited these VRML (.wrl) files to be presented to engineers to reason about ATS design. We found VRML's solid model representation to provide the feel of virtual reality. Its flexibility to refer components as an embedded inline files, and its key-frame animation to develop assembly sequences are very useful to present ATS design to engineers at any time from any place. Each experiment enhanced team members' insight into the thinking of other team members. This resulted in critical and positive feedback and minimized redesign and manufacturing efforts. However, use of VRML presented several problems to develop collaborative environment effectively. While the PCs were able to display sizeable (4MB) *static* VRML files with reasonable response, low-end PCs were unable to support high graphics requirements of VRML animations. Secondly, developing a VRML model was found to be complicated especially to make a design change and present the new version of the design to the team members. Moreover, VRML doesn't represent engineering information, such as parametric representation and relative location/movement, which is important for DM. In spite of these drawbacks, VRML, as a collaborative design tool, shows promise for enhancing the engineering design process.

NOMENCLATURE

ATM	Asynchronous Transfer Mode	ATS	Artifact Transportation System
CE	Concurrent Engineering	CoE	Collaborative Engineering
DM	Design and Manufacturing	IAD	Internet Aided Design
IGES	Initial Graphics Exchange Standard	MBE	Molecular Beam Epitaxy
NAMT	National Advanced Manufacturing Testbed	NIST	National Institute of Standards and Technology
SPM	Scanning Probe Microscope	STM	Scanning Tunnel Microscope
UHV	Ultra High Vacuum	VRML	Virtual Reality Modeling Language

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DISCLAIMER

The National Institute of Standards and Technology does not judge, recommend or discommend the commercial products discussed in this report.

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