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Enhancing Collaboration using an Internet Integrated Workbench

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ABSTRACT

We report on our experience using an Internet-based collaborative environment to enhance the design and manufacturing process of a custom-designed artifact transport system (ATS). Specifically, we focus on overcoming the hurdles associated with exchanging heterogeneous information that includes text, graphics, and computer-aided design (CAD) data among 15 to 20 geographically-separated project participants, each with his own unique workstation and operating system. To share this heterogeneous information among the team's members, which included designers, physicists, manufacturers and managers, we implemented a collaborative workbench (CW) that was designed specifically for platform-independent design and manufacturing collaboration. The workbench consists of two principal parts: an Internet-accessible portion and a platform-specific collaboration notebook. The Internet-accessible portion runs on a local server and consists of a Project Area that contains project-specific information such as drawings, specifications, and schedules, and a Document Vault, which stores files of any type that can be uploaded via client World Wide Web browsers. Based on specifications from the physicists, designers created and represented ATS components and assemblies on their respective CAD systems. The designers published their designs on the CW and informed project team members of the newly available CAD drawings via automatic email. Team members then commented directly on the CW representations of the CAD drawings, and those comments were republished with the drawings. This process continued until team members reached a consensus, or until face-to-face meetings helped resolve conflicting issues. Similar processes occurred with documents such as reports and schedules and with digitized photographs of manufactured components. We conclude that environments like the CW can be effective in helping teams overcome the problems associated with diverse computing environments and heterogeneous data formats, and can be effective in facilitating consensus-based decision making necessary for collaborative design.

INTRODUCTION

Recent research in design methodology, and recent practice in industry, have shown that collaboration among multidisciplinary teams benefits the time and cost to design and manufacture, and, perhaps more importantly, improves the quality of the end product. To varying degrees, collaborative engineering (CoE) has become the *de facto* methodology for developing products [Lawson & Karandikar, 1994], [Sriram & Logcher, 1993]. In general, design and manufacturing (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; Martin, 1997].

Considerable IAD issues must be resolved before CoE can be applied generally and ubiquitously in unconstrained settings. In particular, environments with diverse computing environments (e.g., hardware platforms, operating systems, networking infrastructures) and heterogeneous data formats such as CAD models, graphics and text. Limited academic models have been established and implemented for uniform workstations in synchronous collaborative design [Maher and Rutherford, 1997] and in synchronous collaboration among data producers and consumers [Frivold, *et al*., 1997]. However, Kumar, *et al*. [1994] and other researchers have shown that shared application tools have difficulty when operating among different platforms. 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 how well project participants collaborate when representing DM information to different team members using different platforms and operating systems? Exploring the answers to this question is the focus of this paper.

This paper describes a case study in using a collaborative workbench (CW), called ipTeam[1], for the design and fabrication of a prototype artifact transport system (ATS) for atomic artifacts [Tsai, *et al*., 1998; Silver, *et al*., 1998]. After briefly describing the rationale behind the ultra-high vacuum ATS project and the associated DM process for it, we highlight the characteristics of the CW that make it amenable to collaboration on this project. We then show how this collaborative tool was 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.

NOMENCLATURE

ATS	Artifact Transport System
CAD	Computer-Aided Design
CE	Concurrent Engineering
CoE	Collaborative Engineering
CW	Collaborative Workbench
DM	Design and Manufacturing
IAD	Internet-Aided Design
MBE	Molecular Beam Epitaxy
NAMT	National Advanced Manufacturing Testbed
NIST	National Institute of Standards & Technology
STM	Scanning Tunneling Microscope
SSL	Secure Sockets Layer
UHV	Ultra High Vacuum
VRML	Virtual Reality Modeling Language

DESIGN PROJECT DESCRIPTION

The present work was carried out as one of a series of National Advanced Manufacturing Testbed (NAMT) projects being carried out by the National Institute of Standards &

[1] **Disclaimer:** Certain commercial products are identified in the paper to facilitate understanding and clarity only. NIST does not judge, recommend or endorse these products.

Technology (NIST). This research program supports the development of solutions to the standards and metrology issues of new, information-based manufacturing. (A description of NAMT can be found at 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 program has created an environment wherein scientists and engineers from industry, NIST, academia, and other government agencies work together to solve measurement and standards issues in information-based manufacturing. The program also develops the needed tests and test methods for industry that are part of NIST's mission, which is to work with industry to develop and apply technology, measurements and standards.

For this particular project, one main goal was to design, build, and test an artifact transport system (ATS). The ATS, which achieves pressures less than 10^{-7} Pa (~10^{-9} torr), consists of a transport cart and an ultra-high vacuum (UHV) system. The ATS is designed to transport an atomically accurate specimen created in a molecular beam epitaxy (MBE) laboratory to a Scanning Tunneling Microscopy (STM) laboratory located in a separate building about 600 meters away. The atomic-scale dimensional artifacts created by MBE technology are to be verified by physicists using the STM. By doing so, more accurate standards (with errors on the order of nanometers) can be used by the semiconductor industry to manufacture more reliable components.

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 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. Even under normal high vacuum conditions, 10^{-4} Pa (~10^{-6} torr), a monolayer of gas could be absorbed on the surface in a few seconds, contaminating the artifact. During transfer, which may take several hours, artifacts must therefore be kept in the UHV range (less than 10^{-7} Pa or ~10^{-9} torr). This design requirement necessitates 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. Hobson and Kornelson [1979] and others developed similar transport systems; however, the present design allows for the transfer of artifacts up to 150 mm in diameter.

The design process began with MBE and STM physicists setting the requirements and brainstorming with the designers to generate an initial conceptual design. This lead to a conceptual ATS that included a custom transport cart and the UHV system, which included two ion pumps weighing over 1800 N (400 lbs.). Designers used two commercial CAD tools, ProEngineer (ProE) and CADKEY, to generate geometric representations of the ATS. After some geometrical layout on ProE, the UHV concept was redesigned, in part, to employ only one ion pump and a lighter turbopump for the preliminary vacuum stage of the transfer. Other principal components, most of which are stainless steel, standard vacuum components, include a linear and rotary feedthrough transfer mechanism, a linear transfer rod, tees and cross connectors, valves and bellows. The entire UHV system, including power systems, controls and electronics, weighs about 2500 N (550 lbs.). The entire UHV system was modeled in ProE, and exported to a Virtual Reality Modeling Format (VRML) representation where it could be viewed by the project team via the Internet. 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, provide shock isolation, be adjustable in height, allow fine motion adjustments and have easily interchangeable wheels (for clean room transfers). The cart was designed in CADKEY and the completed model was also exported to VRML format. Figure 1 shows a VRML representation of the assembled model; Figure 2 depicts the actual prototype.

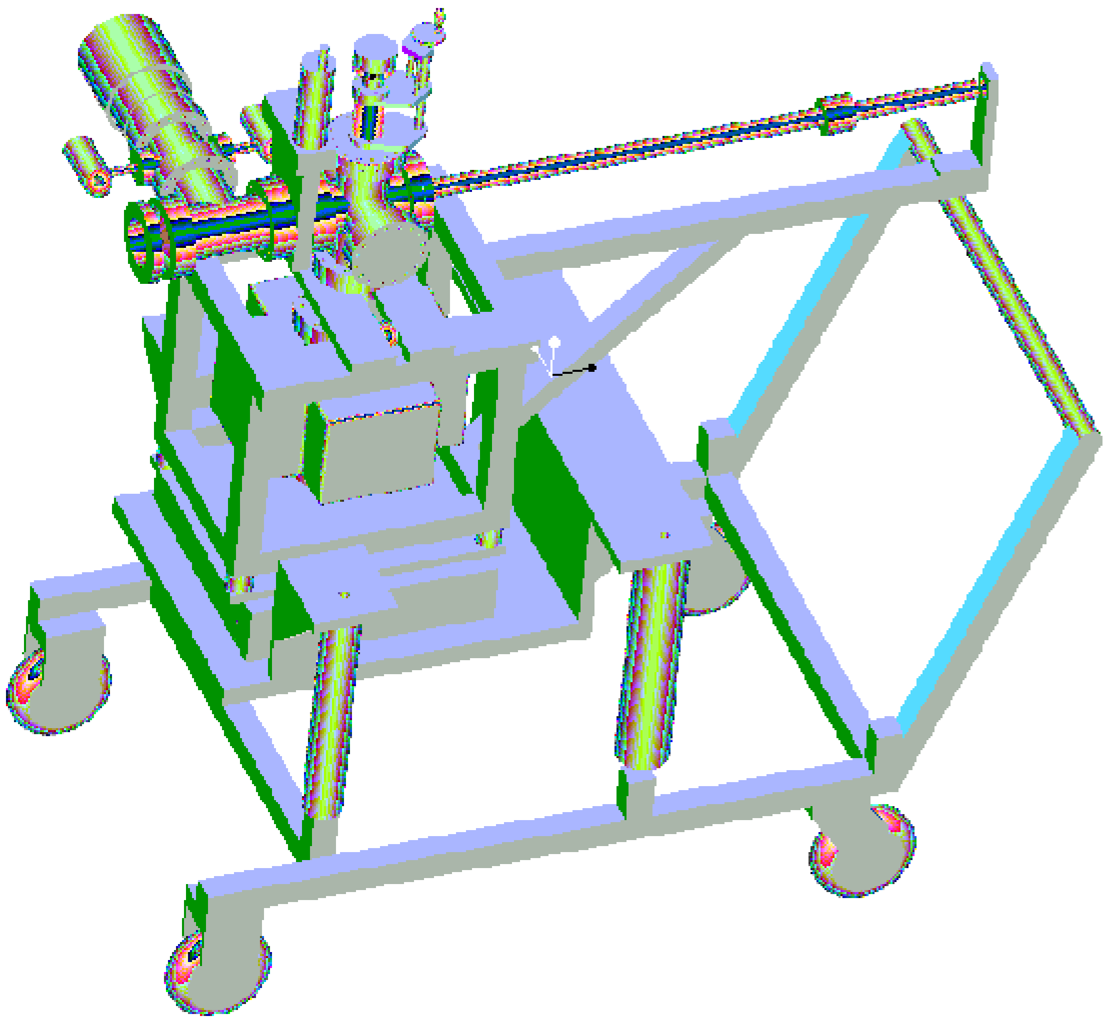

Figure 1. One VRML representation of the assembled Artifact Transport System.

The reasons for exporting to VRML were threefold: (1) To overcome the project team's diverse computing environments, where each member had a unique workstation and operating system environment, (2) To develop assembly sequence simulations, combining two distinct sets of CAD geometry, and (3) To provide the capability of representing assemblies of parts as inline files that could be browsed (not unlike linked webpages). Allen *et al.* [1998] describe more technical aspects of the ATS design and discuss the experience of using VRML in a collaborative effort.

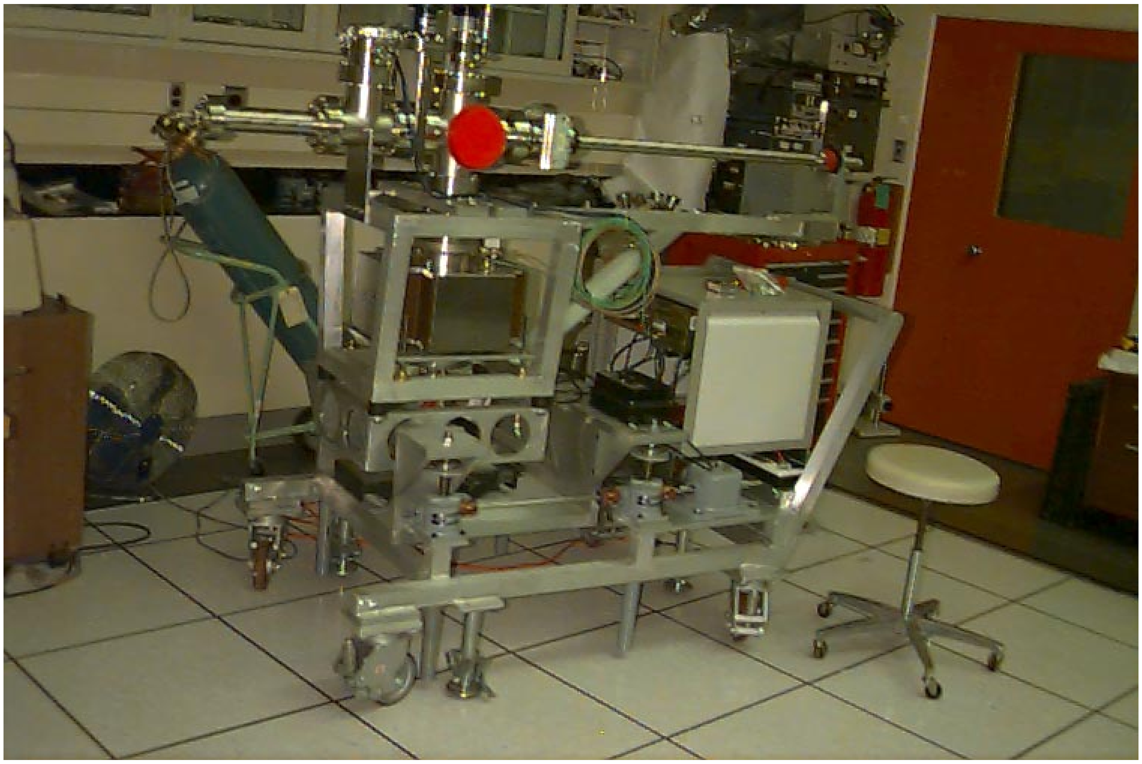

Figure 2. Photograph of the constructed cart and UHV systems in the STM Laboratory.

While the team benefited from using a neutral and nonproprietary representation such as VRML as a collaborative exchange format for sharing geometric models, other forms of collaboration needed to be explored. These other collaboration processes included: sharing comments in a communal environment, sharing other data formats, and maintaining a history of the design and manufacturing process. To do this, we implemented a commercial collaborative tool, called ipTeam (formerly AIMSNet), which we briefly describe below.

COLLABORATION ENVIRONMENT

Created by NexPrise, Inc., ipTeam is a suite of software tools focused on establishing a free-form virtual collaboration space that allows interaction among team members, while retaining the ability to manage heterogeneous information generated by the team. The suite consists of five integrated, object-oriented modules: Internet Workbench, Notebook, Tracking Center, Procurement Center, and Supplier Center. ipTeam employs a secure client/server architecture based on Internet protocols, that uses the Internet to link geographically-separated individuals. By combining the capabilities of a server environment with the flexibility of desktop browsers and ipTeam desktop applications, team members can collaborate over heterogeneous data formats while using different local operating systems. With core functionality and documents remaining on the Server, team members interact using a standard Internet browser and the client software, referred to as the Notebook. The Server provides viewing access to each member, while the Client provides on-line authoring and publishing, as well as a set of desktop tools for augmenting records. The Server/Client environment is depicted graphically in Figure 3.

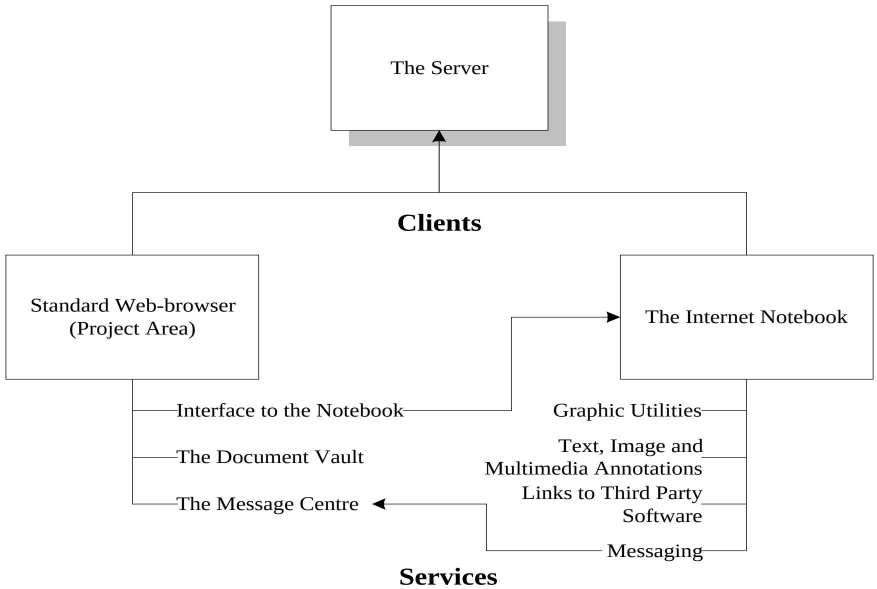

Figure. 3. ipTeam's basic architecture. To ensure security, the server is accessed using a Secure Sockets Layer (SSL) to encrypt data transmission over the network. The server can also reside behind a firewall to allow only HTTP packets to pass through.

The Server software, manageable through its own URL and port number, contains several software components that store and supply data to the clients, both Browser and Notebook. These are as follows: Project Area, Document Vault, data storage and management of notebook entries, Message Center and various administrative tools. The Server Administrator, sets up virtual teams and users associated with those teams, and provides general tool administration. Each user can create a Project Area, which contains Document Vaults and Notebooks, thus providing a protected framework for project collaboration on the Server.

Residing within the Project Area, the Document Vault is a secure data management component that provides a mechanism to control and share project information. Specifically, the Vault provides teams with 1) a sharable and secure repository of documents, files and objects, 2) document descriptions to facilitate search, 3) version control and 4) search and filtering tools. Also residing in the Project Area is the Notebook, a multimedia environment for collaborative prototype and product development. This platform-specific, information-authoring tool allows users to create entries containing text, drawing elements, graphics, audio or video. The Notebook is a collaborative tool that extends the notebook metaphor by making entries accessible to all team members, storing entries in an indexed array, and allowing entries to be changed in a way to record the rationale behind decisions. The last component to the Project Area is the Message Center, which primarily serves to automatically notify team members of changes by other users. ipTeam Suite User's Manual provides a more complete description of the environment [Nexprise98].

The client software was installed on each team member's computer. The client software enabled direct viewing and editing of graphical information in addition to links provided to outside documents. Each notebook contains a number of folders called *entries*, each of these in turn contains the multi-media information pertaining to the design of an ATS. The entries were typically organized with respect to their keywords. Optionally they were organized with respect to their ID number or date of recent posting and revision number.

An Internet browser provides the link from the information stored on the server to the client workstation and Notebook. We installed the Notebook Client software on diverse platforms (Mac, PC, Sun) with different operating systems (Apple, Solaris, Windows NT and 95). As expected, performance (measured qualitatively by speed and robustness) varied widely across platforms; NT-based workstations performed better on average.

The ATS design process provided the test bed to see how well the CW would help the team reach consensus developing the ATS. Our work focused on two aspects of the DM spectrum: graphical representation of the ATS system and resolution of conflict during design. The results of our case study are summarized below.

GRAPHICAL REPRESENTATION OF ATS

Representing the ATS in its component and assembled forms is critical to the designers and fabricators, but equally important to the managers and physicists as customers. The reason for this is that form and position are critical to the success of linking the ATS with each laboratory -the STM and the MBE - while maintaining the ultra-high vacuum. To distribute a typical ProE part file of the UHV among the team members, one designer provided a description about the drawing in the Notebook entry, and a link was provided to the ProE file stored in a Document Vault. With this arrangement, a team member could have viewed a snapshot of the part file with his Notebook Client, or could have downloaded the actual .prt file to his workstation. (If ProE were installed on that particular workstation, the .prt file could be viewed and edited directly in ProE.) Our team preferred the Notebook entry to downloading, as it provided the opportunity for each team member to comment *separately*, either via e-mail or in the Notebook entry. A typical notebook entry is shown in Figure 4.

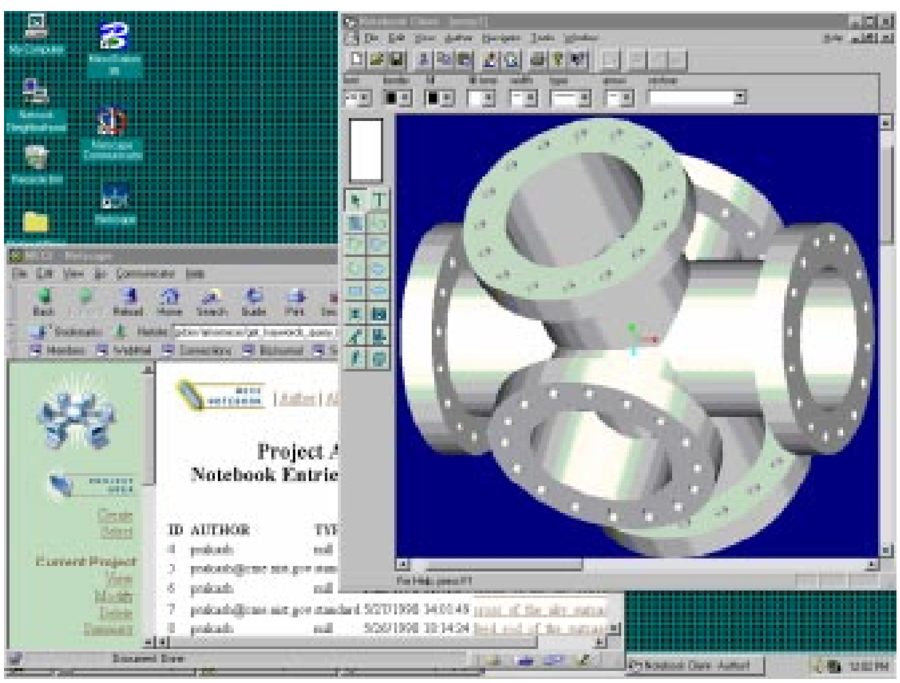

Figure 4. A screen dump showing the browser in the background opened to the NAMT Project Area. The Notebook entry, in the foreground window, shows a snapshot of a ProE file that depicts a shaded view of the main cross connection in the UHV-ATS system.

To incorporate the .prt image format, the Notebook takes a snapshot of the .prt image and converts this to a .bmp image, which the Notebook can then import. (In the version of the Notebook used for this project, the software was limited in that it could only accept .bmp and .png type file formats for its graphical images.) Once one team member created an entry, other team members were notified automatically via email. The e-mail contained brief information about the project name, notebook name and the number and keyword of the entry, containing the modified design. It also contained the URL, allowing a direct link to invoke the modified design drawing via the Notebook Client software.

Resolving Design Conflicts

Many parts of the UHV ATS necessitated extended and detailed discussions by team members to finalize the design. Since face-to-face meetings had been long established prior to implementing the collaborative environment, and such meetings are part of the NIST culture, many design issues were resolved in face-to-face meetings. At times, however, some design issues were not readily resolved in the face-to-face meetings. Then, the engineers discussed and resolved those design problems using the collaborative environment.

Figure 5 shows one instance of the Collaborative Design carried out by the NAMT team members to refine some design decisions about the internal mechanism of the ATS. Once the design was almost finalized, the engineer who was looking after the preparation of the machine drawings of the parts on ProE and CADKEY posted the drawings in Notebook entries. The engineer who monitored the MBE where the artifact was manufactured noted that the ATS was designed to carry more samples (three) at one

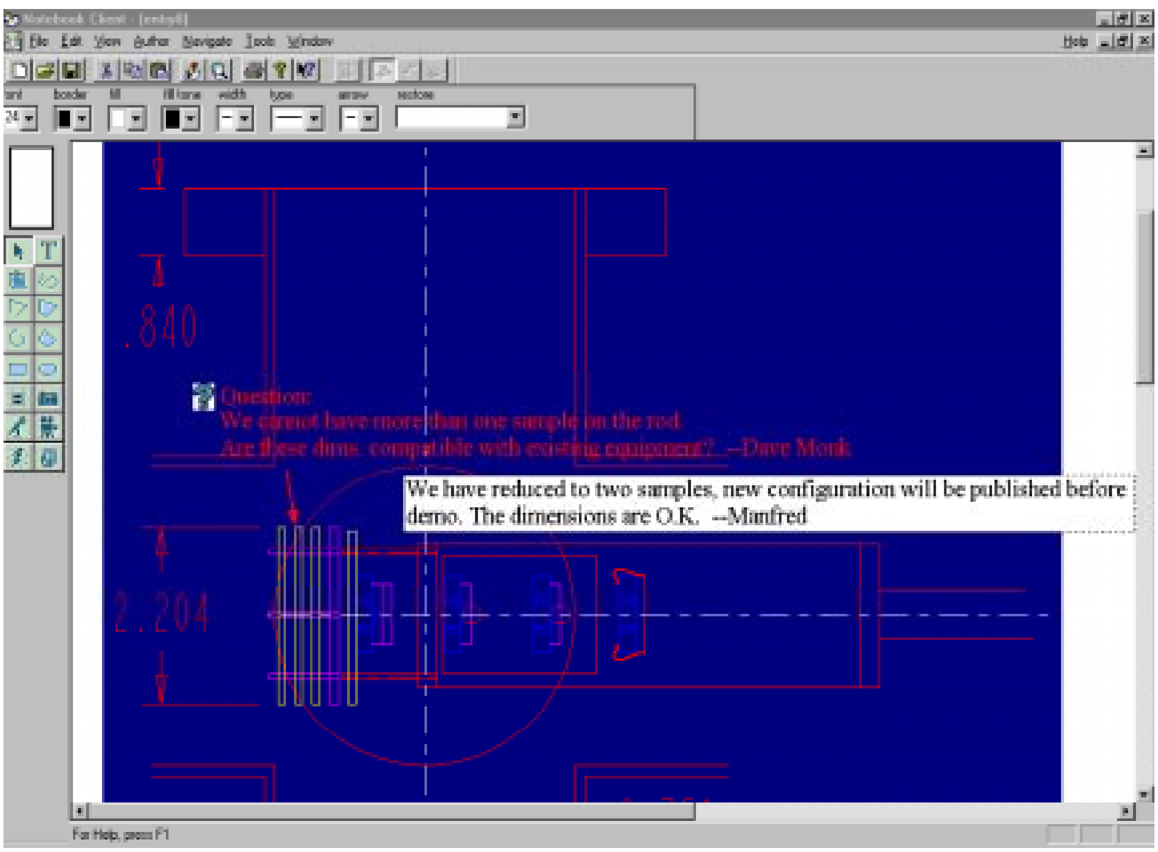

Figure 5. Sample interaction between NAMT team members over the internal mechanism design.

time than the MBE actually allowed (two). Immediately, he pointed out that the transfer rod of the ATS could retrieve only one sample. He also felt that the dimensions mentioned on the design for the sample holding plate were not compatible with those of the mating equipment. He *republished* the drawings with his comments on the Workbench, informing all the members of the NAMT group in turn. The Workbench sent an automated e-mail to all the members of the NAMT with the exact location of the *entry* mentioned as a hyperlinked URL and brought up the entry containing the design information in quick succession. The other engineers followed that hyperlink, which invoked the browser and the notebook.

The engineers who were designing the internal mechanism of the ATS read the comment made by the MBE team member. The two options available to them were either to modify the length of the pins of the transfer rod so that they could carry many samples, or to redesign it. They contacted the team member in charge of logistics for the project, who confirmed that a key component was already purchased. Redesign would have been expensive because many other related parts would have to be reordered or remanufactured. A little more research clarified that actually two samples could be carried on the transfer rod at a time. As for the dimensions of the sample holding plate, the engineers verified which of the two designs was more appropriate. Some modifications in the design were not reflected in the machine drawing. The subsequent face-to-face meeting of all the team members consisted of the display of the machine drawing of the internal mechanism on a wall-sized projector screen from the Notebook Client running on an NT workstation. Utilizing the zoom facility and the annotations made by engineers on the Workbench, the team came to a definitive and final design for the internal mechanism.

Another difficult design issue was the choice of proper wheels for the cart. There was an array of choices from cast iron wheels with maximum load capacity to commercially-available, shock resistant casters for industrial applications that minimize the vibrations. The goal was to optimally choose the casters that have the required load capacity yet are shock resistant. One team member suggested cast iron wheels. Another team member commented that the cast iron wheels would not be compatible with clean-room requirements and expressed doubts whether simple neoprene covered casters would be enough to take the load.

The team member responsible the actual assembly of the cart reported that the casters already had been purchased and said he was certain that the casters would serve the purpose. Ultimately the team decided to use and test the casters for their suitability and should they fail in damping the vibrations, they would be replaced. Figure 6 shows this activity in a Notebook entry.

Similar experiences arose over other aspects of the project. For example, the team explored the necessity to remotely read, record and monitor the on-cart readings pertaining to the vacuum conditions and vibrations of the suitcase. The widely accepted suggestion among team members was to design a wireless system that could offer complete remote operation. Analysis using the collaborative environment revealed that the need for a wireless remote control system conflicted significantly with budget and time constraints. In another example, one team member in the UK pointed out that the vertical alignment of the ATS and the port to the MBE was not indicated on the CAD drawings. In the span of 10 minutes in real-time, the problem was corrected along with a new bill of materials through the automated mail system.

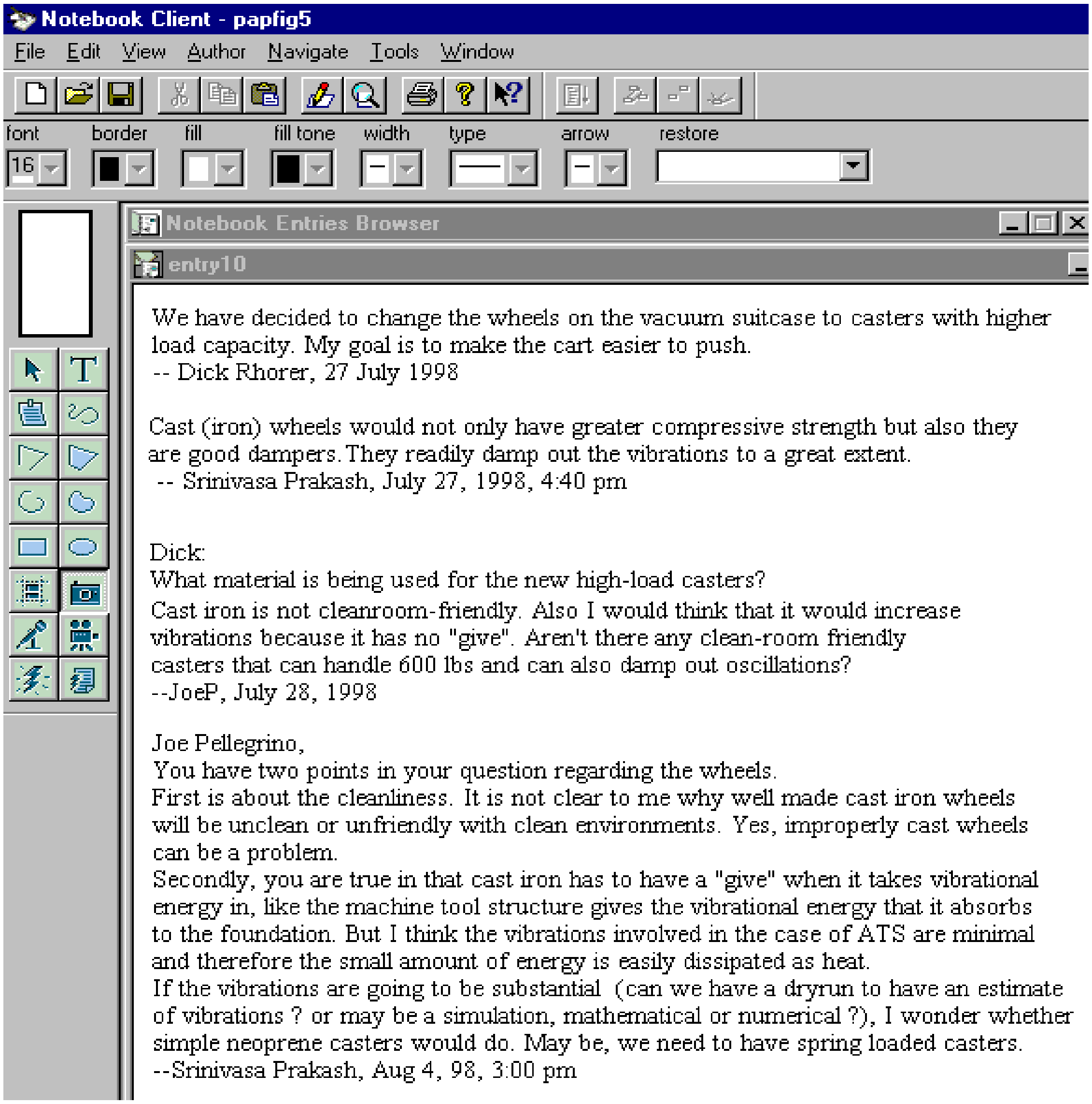

Figure 6. Discussion about the ATS cart wheels by NAMT team members using Notebook entries.

DISCUSSION

The collaborative environment was generally found to be a useful and important tool for web-based collaborative design of a complex system. It supported asynchronous collaboration where team members could create or modify a portion of the design and broadcast their input via the Internet. The tracking system allowed us to monitor how and why decisions were made. The environment also reduced the frequency of face-to-face meetings, albeit the software was used to augment an already existing, cultural practice.

As with any new technology, there are difficulties in adapting a new collaborative environment such as this one to a specific task. While collaborative environments are suitable for creative brainstorming and resolving conflicts, it is not well suited yet for setting or changing strategic directions [Carman98]. The reason for this is that such a major activity requires real-time, simultaneous input from all team members. This includes gestures and body language, which are not captured with the current form of this technology. There is also a need for a common dictionary and indexing schemes for effective filtering in data reuse. As entries became more and more numerous, the ability to search effectively for a particular design discussion became increasingly difficult. Linked with this concept of effective filtering, there is currently no event-tracking center to monitor communications or design process. This would aid in data reuse. Other improvements are less general and can easily be addressed in later releases. These include: (1) the amount of information provided on automated email should contain enough information to also suggest the particular modifications performed by a particular team member, and (2) there should be more uniform functionality across different platforms and operating systems.

Despite these drawbacks, practical collaborative tools are a relatively new technology that support web-based design, and work well in conjunction with existing engineering methods and traditional methods of communication (such as phone, face-to-face design meetings, email). To become even more viable, we believe that this technology should take into account the specific needs of collaborating teams.

SUMMARY AND CONCLUSIONS

This paper focuses on overcoming the hurdles associated with exchanging heterogeneous information that includes text, graphics, and computer-aided design (CAD) data among 15 to 20 geographically-separated project participants, many with his own unique workstation and operating system. We deployed a commercial collaborative environment to share this heterogeneous information among our team's members. We described the workbench, which consists of two principal parts: an Internet-accessible portion and a platform-specific collaboration Notebook. Using this framework, the team used this environment to display design concepts, drawings and assemblies, brainstorm creatively and resolve conflicts. Consensus was often reached within the environment, although face-to-face meetings also helped resolve conflicting issues.

We conclude that collaborative environments can be effective in helping teams overcome the problems associated with geographically-separated participants, diverse environments and heterogeneous data, and can be effective in facilitating consensus-based decision making necessary for collaborative design. Such technology increases overall productivity by improving DM processes in specific instances. As this technology becomes more robust and mature, the contrast between today's collocated teams and tomorrow's virtually collocated teams can potentially be significant.

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