An Experiment in Supporting Geographically Distributed Engineering Design

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Engineering Design Research Center Technical Report

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Abstract

Many of the research projects currently underway and being considered for the future at the Engineering Design Research Center involve geographically distributed project teams. The extent of interaction within this distributed team may vary from that of distant vendors who are not members of the project team but whose performance and synchronization with the project are vital - to members of the design team actively collaborating on a project to the extent of discussing detailed design, systems interface issues, and joint authoring of documentation. This report presents issues encountered in creating and operating an infrastructure to support such a distributed design team. Our approach is to identify requirements for supporting collaboration in an engineering design project from the perspective of types of information used and interactions between participants involved in the process, examining the set of available tools from this framework, as well as the changes in the design process necessitated due to constraints imposed by geographical remoteness of team members and limitations of existing technology. Recommendations are made for future engineering design projects considering the use of computer supported collaboration tools.

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1.0 Introduction

Here at the Engineering Design Research Center (EDRC), many of the current and planned research projects include some aspect of geographic distribution of the project members. The extent of interaction within distributed teams may vary from that of distant vendors who are not members of the project team but whose performance and synchronization with the project are vital, to that of team members actively collaborating on a project to the extent of discussing detailed design, systems interface issues, and joint authoring of documentation. Some of these projects include the VuMan/Navigator project to develop a wearable computer and the Rapid Design Through Virtual and Physical Prototyping project whose goal is the creation of a rapid design and prototyping infrastructure. In the former case, the VuMan/Navigator team must deal with vendors as well as clients who are located at geographically disparate points throughout the country. Similarly, the Rapid Design project consists of a consortium of educational institutions which allows its members to make use of design and fabrication technologies located at the different members' sites via the Internet. A very important part of this initiative is a plan to allow students from the participating institutions to collaborate on design projects offered in the context of a sophomore level design course. We envision that the level of collaborative learning might extend to allow students from participating institutions to use the new technology and facilities *(e.g.,* manufacturing systems, software, and analysis tools) available at other institutions remotely.

The interest in supporting collaboration and communication of geographically remote work-groups is not limited to the research institutions and academia. There is a general interest within industry and the general public which is reflected in the increasing availability of commercial products for networked multimedia interaction. Examples of commercial products for networked collaboration are document and screen sharing applications which are currently on the market, as well as workgroup support environments incorporating real-time video and audio capabilities which are beginning to appear [1] [2] [3]. Bannon *etal.* have remarked [8] that it is a confluence of events and trends; developments in technologies, and dissatisfaction with existing models of office automation, which have led to the growing interest in the area of computer supported cooperative work (CSCW) under which the current research falls. We are interested in engineering design enterprises and because design information exists in many different forms and formats, it is clear that a large part of being able to collaborate involves determining how to manage, exchange, and access a distributed network of information.

In recognition of the growing importance of collaborative engineering projects involving geographically distributed participants, members of the Engineering Design Research Center have participated in an experiment in conjunction with the Mechanical Engineering Department at Stanford University. The context of this experiment is the ME210 Mechatronics design course offered at Stanford.

1.1 Related Work

This project is an experiment in using computer applications and digital networks to support collaboration in the context of a long term engineering design project using commonly available software and hardware. An important goal of the exercise is to capture the exchange between the participants. Previous work in long term remote collaboration has usually been limited to research labs using specialized facilities. Dourish *et al.* [4] examined the use of long term multimedia communication environments in supporting cooperative work from the perspective of how users adapted normal activities to their new work space. This work was done using special links between Xerox PARC at Palo Alto, and EuroPARC in Cambridge, UK. In addition, there have been several recent initiatives with the specific goal of studying distributed design teams. The MADEFAST project [5] was a demonstration exercise intended to showcase the technologies needed to support an infrastructure for providing engineering services via the Internet. The work presented here differs from this earlier experiment in that design sessions were regularly conducted over the Internet and documentation of the design process was performed by individuals actively involved in the process, during the process. The SHARE project [6] was another earlier effort to develop and deploy an Internet-based environment for collaborative design. While this project had access to a large selection of custom collaboration tools, their design exercise involved a small problem lasting only hours compared to the current project which ran for 22 weeks. The SHARE project stressed the need to focus on societal issues in the design process.

Further related work can be found in the large body of research from the area of computer supported cooperative work, some of which overlaps the current research on issues which are relevant to supporting geographically distributed design. Grudin [7] and Bannon [8] discuss the history of CSCW and provide an overview of work done in the area.

1.2 Scope of Project

This exercise was intended to identify requirements and problems to be addressed for future collaborative engineering projects involving design teams whose members are geographically distributed. We identify available computer tools and environments which support remote multimedia communication and collaboration, and examine the effectiveness of these tools in supporting distributed engineering activities by creating and operating an infrastructure with these tools in the context of a design course. The exercise also serves to provide insight into the impact on the design process of working in geographically distributed teams.

Our approach will be to learn through active participation in the design process and in this respect this exercise is an experiment conducted under as close to real life conditions as possible. Special effort has been made during the course of this project to document as much of the interaction between the people involved in the design project as possible.

2.0 Context of the Project

This research experiment was undertaken in the context of an academic course in electro-mechanical design. The course is structured to teach concepts in design theory and collaboration methodology which are then applied in an industry sponsored design project. Prior to discussing the details of the experiment, we must clarify some of the terms which will be used to differentiate these two aspects of the project. The phrase *design project* will be used to refer to the academic aspects of the project in which this experiment in distributed design takes place. The terms *design experiment, exercise* or *study* refer to the aspect of the project related to our research in geographically distributed design teams. The use of the term *project* without a qualifier will be used to refer to both aspects as a whole.

2.1 ME 210 Course

The context of this experiment is ME210, a graduate level design course lasting three quarters (30 weeks) offered by the Design Division of the Mechanical Engineering Department at Stanford University. As part of the course, students are arranged into teams of 3 to 4 students to work on an industry sponsored design project. While the focus of the course is directed towards completion of the design project in the form of a functional prototype, a high value is placed on delivery of complete documentation of the process undertaken by each team. To increase incentive for proper documentation, final grades for the course are structured to reflect the quality of the documentation, rather than solely on the artifact, as the final product. Several design reviews by the course instructors as well as by clients and peers are held throughout the design process. The course also makes a strong effort to have the project teams use the World-Wide Web (WWW) [9] [10] as a mechanism to share information, both within as well as across the different design teams.

2.0 Context of the Project

The design project portion of the course is structured to follow the phases of a simple product development model. Such a model of the design process for a product will typically include the following stages: perception of a need or technical opportunity, organization assembly, conceptual product, design of the design process, customer feedback, configurational design, detailed design and simulation, detailed design of the manufacturing process, manufacture of the artifact, and final delivery. The process begins with the recognition of a need or technical opportunity. In the context of ME210, this first stage has been replaced by presentations made by the corporate sponsors to the class. Design teams are then formed by the students based on common goals and complementary skills and personality traits to bid on the design projects. A series of design documents and peer reviews correspond with the remainder of the benchmarks in the design process. The relation between stages in the product development process and events in the ME210 course are shown below in Table 1.

TABLE 1. Phases in a simplified model of the design process mapped to ME210.

Phase	Phases of Product Development	ME210 Course Benchmark
1	Perceived need or tech. opportunity	Sponsor project presentations
2	Organization design	Negotiation of team membership
3	Conceptual product	Critical function prototype and critical functions briefing
4	Design of design process	Autumn Design Requirements Documentation
5	Customer feedback	Peer review and Face-to-Face with instructors and outside consultant
6	Configuration design	Benchtop reviews
7	Detailed design and simulation	Benchtop reviews
8	Detailed design of manuf. process	Benchtop reviews
9	Manufacture/Fabrication	Winter Design Review Document
10	Project Deliverables	Functional Prototype and Final Design Documentation

The effect of undertaking the current study in distributed design within the framework of the regular ME210 course bears elaboration. It must be recognized that the needs of the design study did to some extent drive the direction of the design project. As an example, we cite the fact that all the team members at CMU were primarily interested in the research aspect of the project and were not receiving academic credit for the course. Consequently, some decisions on organization of the design team were made to increase interaction between the CMU and the Stanford based members of the team. In contrast, the members at Stanford were taking the course for credit and were less interested or concerned with the research aspects of the project. Another exception was the lateness of the decision to go ahead with the design experiment near the end of the first quarter of the regular ME210 course. One effect of the late insertion of the study members into the ME210 curriculum was that they missed early instruction in and exposure to the use of the computational environment available to students in the course, as well as missing lectures where the overall philosophy of the course was discussed.

2.2 The Design Project

The project selected as the goal for this experiment was sponsored by FMC Corporation and involved modification of a cooling system for AC induction motors for use in hybrid electric drive automobiles. An added complexity to the design project was the presence of essentially two clients with slightly different goals. The corporate client (FMC) was interested primarily in proving a conceptual cooling design it was pursuing for application in large 200 to 700 horsepower motors and in obtaining information on the state-of-the-art in thermal analysis methods and tools. The second client, Stanford Hybrid Automobile Research Project (SHARP), was primarily motivated by a desire to obtain a working motor satisfying the requirements for entry into an annual hybrid electric vehicle competition. FMC had sponsored a similar project in the two previous academic years. In the first year (1992-93 academic year) the ME210 team had designed and built an electric-motor, transmission, and cooling system. The second year (1993-94 academic year) saw modifications to the 1992 motor to address manufacturing and cooling problems.

The FMC/SHARP project team consisted of seven graduate students from the two institutions (three at Carnegie Mellon and four at Stanford) of varying levels of academic and industrial experience as well as varying degrees of involvement in the project. As a group of seven, the size of the FMC team was double that of most other teams involved in the ME210 course. Each ME210 team was also assigned a coach, who in the case of the FMC/SHARP team was also the project leader for SHARP as well as a member of the 1993 FMC/SHARP Motor project team. Based on an initial design project description, team members were selected who had an interest and/or experience in heat transfer and fluid dynamics analysis, and machine design. The duration of the project was a little over five months.

Due to the distributed nature of the design team, it was recognized early in the design process that a formal communication protocol needed to be established. An infrastructure for communication and collaboration to support this protocol also needed to be developed. Furthermore, since the prime goal for the research aspect of the project was to study the design process, the communication protocol and infrastructure were designed to facilitate capture of the design discourse. Most importantly, the project members were encouraged to document the process. The distributed nature of the team was exploited to maximize the level of design discourse via the communication protocol and thus to capture the design information. Responsibility for the subfunctions of the design was intentionally divided across the two locations (i.e., Pittsburgh and Palo Alto).

Financial constraints drove the selection of the Internet as the most suitable communications infrastructure due to the relatively cost-free access for educational institutions, rather than conventional satellite-based telecommunications facilities. While corporate sponsorship provided approximately $8,000 for use in the project, much of this budget was expected to be used for normal parts procurement and fabrication services. Additional costs associated with the distributed nature of the team were expected and an attempt was made to minimize costs associated with the project by using existing facilities and resources when available, and free or donated tools and services where possible.

3.0 Forms of Information and Interaction

Design is an information intensive activity. The transmission of information in a useful form and in a timely manner is critical to the efficient and successful solution of a design problem. For this reason facilitating communication is an important role of the infrastructure which supports any design project. In colocated design, meeting rooms equipped with whiteboards and audio-visual presentation equipment, team rooms, sketches and mock-ups, and most importantly the physical proximity of the members of a team are methods and technology which can be used to facilitate communication. The need for a communication infrastructure is greater still when the design team is geographically distributed and the informal mechanisms for exchange of information are no longer available.

Design is also an activity which requires substantial interaction within a design team, as well as with people outside of the design team. Because design information is transmitted during these interactions between design participants, it is important to examine and characterize the types of interactions found in the engineering design process and to identify the mediating effects of the collaboration environment on these interactions.

It should be noted that in the course of the exercise it was not possible to directly capture video or audio interactions between the design team members. This was due primarily to technical limitations, specifically the lack of equipment to record and store 5 months worth of video and audio tapes. As a consequence, only text and still images/ pictures used in the design process were captured. We feel that this does not affect the value of the study due to the care taken to promptly and methodically document summaries of all meetings and the extensive use of electronic mail in communication between team members.

3.1 Design Information

In this section we define a framework from which to evaluate computer mediated support for our geographically distributed design team. The framework tries to include some notion of a characteristic of information and the form or media in which that information is best communicated which combine to identify a set of necessary requirements for a collaboration tool. A discussion of this experiment from the perspective of supporting the building and reuse of knowledge in design projects is given by Reddy *et al.* [11] - they present several quantitative measures of types of design information, the use of tools and media, and the role of types of knowledge in the design process.

We differentiate the information transmitted between the participants in the design exercise by *level ofdetail* and by *form.* While the notion of information having a level of detail is usually associated with theories of design methodology and its ideas of a hierarchy of abstraction from conceptual to detailed design; we apply the notion of detail to information dealing with organizational, infrastmctural, and technical issues as well as the artifact design. Clearly, there is a connection between the level of detail at which we discuss a subject and the amount of time we have spent discussing it. Initially, few details are known and therefore ideas are discussed in abstract terms. Over time, a common understanding is fleshed out between participants and both abstract and detailed information can be meaningfully used in an interaction. For instance, functional design information about a product generally consists of high level statements of what a product will do. It tends to be descriptive and adequately represented in a textual form. On the other hand, geometrical design information is inherently numerical, precise and oftentimes most useful in a graphical representation (or in a format which the user can convert to a graphical representation). In terms of technical issues, discussion of the use of file transfer protocol (FTP) for moving files across data networks might begin at a low level of detail *(e.g.,* the above statement) and develop into a detailed tutorial on the mechanics of moving files use a particular FTP utility.

From the perspective of level of detail, the information used in the course of the design exercise was transmitted between the participants at one of the following levels of detail:

- ***Functional:* Almost purely textual. States what the artifact must do from the viewpoint of the user.**
- ***Behavioral:* Can be represented as text and/or equations. Possibly graphical.**
- ***Configurational:* Spatial information, can be represented as sketches. Not necessarily exact.**
- ***Geometric:* Precise, numerically-oriented information, often best represented by drawings or computer models.**

The design information involved in developing a product is recorded, stored, and generated in a variety of forms and formats, and on multiple types of media. Requirements documents and meeting notes often contain a mix of textual and graphical information. In electronic media those same documents can also incorporate video and audio recordings. Whereas pre computer-mediated collaboration only needed to deal with paper documentation, one of the results of the use of computers is an increase in the types of media that can be incorporated into documentation. This has also had the effect of increasing the types if information which need to be captured to include electronic mail, online information from vendors, network locations of software archives and electronic documents to name a few. In addition, storing the information (or a record of it) in a digital form allows a greater variety and improved methods of

searching for and retrieving the information at a later date. The form in which information is best communicated is not solely determined by the current stage of the design process. Drawings can be both abstract (sketches) or detailed (engineering drawings). Within the individual activities of the design process, information is communicated in many different forms and over various media. Table 2 below shows the different activities in the design process and some of the types of design information generated during the particular activity.

TABLE 2. The activities in the design process and their associated design information.

Design Activities	Design Information
Conceptual Design	Brainstorming notes/sketches, meeting notes, product specifications from vendors, contact information for sources., general communications between team members and with others.
Configurational Design	Meeting notes/sketches, vendor specs., drawings, rough mock-ups and physical models, and general communications.
Detailed Design	Meeting notes/sketches, vendor specs., detailed engineering drawings, 3D solid models, detailed mathematical and numerical models, and general communications.
Manufacturing	Meeting notes/sketches, detailed engineering drawings, computer files of drawings (e.g., *.DXF and *.DWG files), general communications.
Testing	Testing data, photos, videos, reports, and general communications.

3.2 Characterization of the Interaction

We differentiate two levels of interaction between the individuals involved in the project: global context and local context. The global context deals with the broader parts of the entire project whereas, the local context differentiates interactions which might be considered simple actions that can build into a complete exchange *(e.g.,* a proposition and a response might be considered to constitute a single act of interaction in a verbal exchange). However, since some of the forms of interaction which occur under the mediation of computers are inherently asynchronous and might not even require a response, we have identified them here as complete acts of interaction.

3.2.1 Perspectives of Interaction from Global Context

From the electronic mail and other on-line documentation we have recorded, the following high-level types of interaction have been identified between the three participant groups: the project team, the clients, and the teaching team; as well as within the project team itself.

- *Organizational Administration:* Administrative issues related to the overall organization in which the project is taking place *(i.e.,* ME210, Stanford Mechanical Engineering Department). Examples of issues were phone charges for the Stanford team, course requirements and credits, *etc.*
- *Project Administration:* Administrative issues directly related to the project that the team is working on. Some issues we dealt with were individual responsibilities of team members for specific parts of the design process such as taking notes, design of particular components, testing, *etc.*
- *Design Issues:* This category of interaction deals with issues directly related to the evolving design solution such as the proposed coolant flow path through the motor or a method of containing coolant around the endturns.
- *Direct Technical Issues:* Technical issues directly related to the design problem at hand, such as how motors work, techniques for heat transfer analysis, *etc.*

- *Indirect Technical Issues:* Technical issues which are concerned more with tasks that support the design process such as how to transfer files over the data network or use specific software.
- *Miscellaneous Personal Messages:* Information about the current status of an individual's work or schedule, conveyed to the group to keep everyone informed.

3.2.2 Perspectives of Interaction from Local Context

The following types of interaction are defined at the level of local context.

- *Proposition:* A new piece of information is submitted by an individual; a proposed solution or course of action.
- *Question to group:* An individual needing a piece of information but not knowing of a source will ask a general question to the group. This is analogous to broadcasting by shouting a question out one's office so that one's coworkers in their offices can hear.
- *Clarification/Response:* A team member will respond to an earlier question or proposition. While this type of interaction is common in conversation, it is less often found in written media. We are able to capture this because of the use of electronic mail as a medium for asynchronous dialog between the project participants.
- *Technical Tutorial:* Often, an individual is tasked with obtaining specific information for the rest of the group. Examples include explanations of analytical methods for heat transfer analysis, requirements of the client, vendors and sources of equipment, *etc.*
- *Meeting Minutes:* Summaries of meetings are recorded to ensure that all members of the project team are up to date on the latest developments.

4.0 Technology to Support Distributed Design

As previously noted in Section 2.2, financial constraints limited the set of applications which could realistically be considered for use in this experiment. Consequently, the groupware and collaboration support applications discussed in this section are limited to relatively inexpensive commercial software and academic shareware or freeware. Table 3 below summarizes the characteristics of some of the software considered for use in the project, including: the type of application, the type of technology supporting the application, the highest level of detail it is able support, and its strengths and weaknesses. More detailed explanations of the applications and terms used below are provided in Appendix A.

One widely used classification scheme for software supporting collaborative work uses the notions of space and time to categorize applications. An application is typed as supporting a particular kind of activity according to its location in a 3 by 3 matrix where one axis is in terms of space *(e.g.,* single place, several known places, irregardless of location) and the other in terms of time *(e.g.,* real-time, predictable but different times, unpredictable). However as Grudin [7] points out, this particular scheme overlooks the fact that most real activities do not fall into a single category. Rather an activity will involve some face-to-face meetings, and some distributed and asynchronous exchange of information.

No attempt is made here to identify a single software application which supports a design activity. Instead, various tools are mixed and combined to support different types of interactions within an activity. Asynchronous applications like PENS (Personal Electronic Notebook with Sharing) which support a behavioral level of detail and a WWW browser can be effectively used in conjunction with a real-time video conferencing tool like CU-SeeMe to share

TABLE 1. Comparison of available software and data-models for supporting collaboration.

Name of Application	Type of Application	Supporting Technology	Level of Detail	Strengths and Weaknesses
World-Wide Web (WWW)	data-model for sharing information asynchronous	multimedia, file search and transfer, hyper-media	Geometric	Facilitates the search and retrieval of files. Available for wide range of platforms. No support for real-time audio or video.
MBone	data-model for communication synchronous	virtual multicast backbone, bandwidth-efficient broadcast	Configurational	Supports communications, with limited ability to display postscript files. Most available tools are based on Unix environment. High entry cost for hardware.
CU-SeeMe	video-conferencing synchronous	point-to-point video and audio conferencing, can be used for one-to-many with use of reflector.	Configurational	Free. Robust desktop conferencing available over a wide range of platforms. Color not available.
nv	network video-conferencing synchronous	video conferencing tool for use with MBone. can be use for point-to-point	Configurational	Free software. High cost of entry (hardware). Only available for the Unix platforms. Requires MBone connection for multicast.
vat	visual audio-conferencing synchronous	audio tool for use with MBone, can be use for point-to-point	Functional	Free software. Only available for Unix platforms. Requires MBone connection for multicast.
wb	shared whiteboard synchronous	whiteboard tool for use with MBone, can be used for point-to-point	Configurational	Free Only available for Unix platforms. Requires MBone connection for multicast.
Collage	data sharing synchronous	combines communications tools with scientific visualization	Configurational	Free Requires use of NCSA's suite of data visualization software.
PENS	document sharing asynchronous	transparent publishing of text documents on WWW	Behavioral	Facilitates publishing simple HTML documents. Single level of topics for published documents. Research software, limited support. User still needs to know HTML to do anything interesting.
Hypermail	shared hypertext mail archive asynchronous	archival and automatic hyper-text linking of electronic mail	Behavioral	Archives by date, subject, thread, or author. Only supports text.
Netscape Navigaor (or any other browser)	WWW browser asynchronous	same as WWW	N/A	Included here because it is integral to the functionality of PENS and Hypermail.
Timbuktu	application sharing synchronous	automatic file transfer and remote screen sharing	Geometric	Supports any application. Commercial software. No apparent compression techniques used in transmitting screen sharing data.

scanned images and notes from previous meetings. Even the ability to work with shared applications and screens needs to be supported by some sort of conferencing communication link; if not video conferencing then even simple POTS (Plain Old Telephone System).

5.0 Limits of Technology and Its impact on the Design Process

5.1 Effects of Geographic Distribution

In any group activity where one person's work is dependent on another's, each participant relies on others to supply him or her with the information necessary to complete his or her tasks. Geographical remoteness compounds this effect by creating a physical barrier between team members and resources. Unless identical facilities and resources are created at each remote location, even such mundane tasks as examining an earlier prototype *{e.g.,* in our case the motor from the previous year) becomes a non-trivial task requiring video-recording equipment and surface mail delivery. This section discusses the impact of geographic separation of team members on the design process.

5.1.1 Organization Design

One of the assumed benefits of distributed design teams is that it allows greater flexibility and a larger resource pool from which to assemble the expertise for a design team. Proponents argue that the competitive nature of many of today's markets *(e.g.,* reduced product life-cycles and rapidly changing technology) gives a large advantage to those who can quickly bring a product to market. The ability to work effectively as a geographically distributed product design team is considered an important capability in maintaining a competitive advantage in many of today's high-tech consumer markets. The organization of the distributed design team as well as the design process must therefore be given the same careful consideration as the design of the actual product. The following anecdotes show the possible consequences of giving insufficient consideration to organizational and process issues early in the design process.

The initial kickoff meeting was held at Stanford on January 12-14, 1995. As part of this meeting, one day was spent at the offices of FMC to discuss FMC's vision of what the design project would entail as well as general background information on the project. The remainder of the time at Stanford was spent in team building exercises, discussion of organization, and trying to come to a consensus within the team about the scope of the design project. Unfortunately, due to scheduling conflicts only one member of the CMU part of the team was available to attend the January meeting at Stanford.

The effectiveness of the preliminary meeting was diminished by a lack of familiarity of team members with the problem domain area (AC induction motors and heat transfer), as well as the general structure and requirements of the ME210 course. As a consequence, much of the preliminary organizational infrastructure and background research had to be setup and obtained remotely after the CMU member returned to Pittsburgh. This problem was exacerbated due to the unfamiliarity of many of the team members with the use of basic Internet resources and protocols. Familiarization of the entire team with collaboration tools and Internet resources involved approximately one month.

Decision on a team leader or coordinator for the project remained unresolved until late in the project. Due to the large size of the team and its distributed nature, this role is especially important to ensure the successful and timely completion of the project. Since the clients, vendors and suppliers were likely to be located in the Palo Alto area or at least the Bay Area, a coordinator from the Stanford side of the team would have seemed the most logical choice. Such an individual would have been in the best position to follow the progress of the project. No individual was ever formally appointed to the position and in the end, a single person ended up carrying the additional workload associated with managing and ensuring scheduling of the work. This situation led to an unequal distribution of workload which had a negative affect on the team dynamics.

5.1.2 Design of the Design Process

Meetings between CMU and Stanford were conducted as video-conferences using the CU-SeeMe video-conferencing application from Cornell University. During the early stages of the project, speaker-phones and fax were used to support personal communication and computer files were exchanged using file transfer protocol (FTP). The latter method was used primarily to exchange FrameMaker files for collaborative document authoring. However, not far into the conceptual design stage of the project, it became apparent that some sort of shared whiteboard application was needed to allow real-time sharing of notes, drawings, and sketches. Several commercial and freeware packages were considered[1] and a commercial screen sharing and file transfer application, Timbuktu Pro by Farallon Computing, was chosen as it seemed to promise the most transparent operation along with the greatest functionality. The addition of Timbuktu to the suite of collaborative applications in late February was expected to improve the quality and ease of future collaboration. Unfortunately, this did not prove to be the case. Attempts to use Timbuktu were plagued by problems which are thought to be due to a lack of bandwidth between CMU and Stanford. Attempts to share screens between Stanford and CMU were characterized by very slow update times (long enough to cause time-outs of the connection) and frequent crashing of the computers. The effectiveness of Timbuktu was degraded to the point where it was no longer a viable option. During our tests, we attempted to use Timbuktu with several different applications including Power Point, Word, AutoCAD, and MacDraw Pro. Attempts to use Timbuktu within the local area network of Carnegie Mellon were successful and did not pose any problems.

Additional support for documentation of the design process and communication between team members was provided by the Hypermail and PENS applications, in conjunction with the World Wide Web. While Hypermail essentially archives electronic mail by creating hyper-text links between related messages, PENS allows the user to define a single level of categories, and publish simple notes under these categories. This allows better, though still limited, classification of documentation for future retrieval. At the time of publication of this report, a newer release of PENS, which allows sketching, is under development.

5.1.3 Customer Feedback

Video-conferencing was the preferred mechanism for real-time communication between the CMU and Stanford participants. Bi-weekly meetings with the client were initially held at Stanford to make use of the facilities there since FMC did not have easy access to the Macintosh platform, on which the video-conferencing application ran, at its offices. However, this procedure broke down very early on in the process when the client expressed an unwillingness to use video-conferencing in the bi-weekly meetings. The client reportedly felt that video-conferencing slowed down these meetings and did not feel it made for an effective use of his time. For the remainder of the project, the client held scheduled meetings with members of the team located at Stanford, and the results of these meetings were then relayed to CMU either in the form of meeting summaries on PENS or verbally during the course of the regular meeting of team members.

5.1.4 Configuration Design

AutoCAD with Advanced Modelling Extension was chosen as the application to be used to create part and assembly drawings. There were two reasons for this decision: (1) legacy drawings from the previous year's project had been created using AutoCAD, and (2) this software was the only solid modelling capable package readily available to both the CMU and Stanford groups. Expectations of possible difficulties in collaborating during configuration and detailed design was another reason for the decision to purchase the Timbuktu screen sharing application over less expensive alternatives. The rationale was that AutoCAD models of the proposed design could be modified in real-time by shar-

1. Other applications considered were NCSA Collage and Face-to-Face by Crosswise.

ing an AutoCAD screen between design team members at CMU and Stanford. For reasons mentioned earlier, this did not prove to be feasible.

The final solution for displaying sketches and pictures during video-conference meetings involved transmission of a video image of a whiteboard at both locations using CU-SeeMe. Unfortunately this arrangement did not allow the simultaneous display of the conference participants, so that only a disembodied voice would be transmitted when showing the whiteboard. With two cameras at a site, it was possible to quickly switch between views of the white-board and participants. To obtain an understandable image of a sketch on a whiteboard or drawing, a video camera with manual focusing was required *(e.g.,* any standard commercial camcorder). Typical video-conferencing specific cameras *(e.g.,* TeleCamera from Howard Enterprises, Inc. or QuickCam from Connectix) are inadequate since they do not allow manual focusing. Figure 1 below shows the use of CU-SeeMe in supporting preliminary configuration design using a marked up drawing of the previous year's motor design.

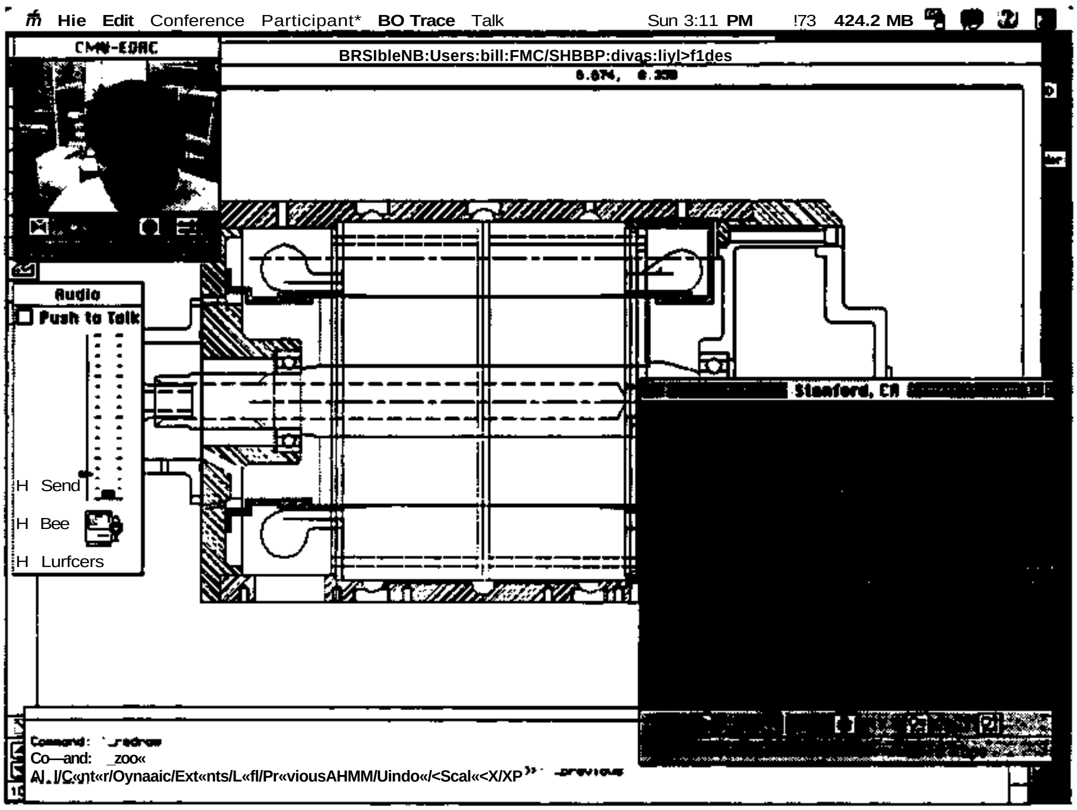

FIGURE 1. Due to technical problems with sharing applications between CMU and Stanford, discussions between the remote groups involving drawings required the use of a camera directed at a whiteboard and projected via CU-SeeMe.

While not directly related to the goals of the project, we attempted to make use of the growing number of on-line catalogue services available on the Internet aimed at providing information about services and parts. Most services like IndustryNet shown in Figure 2 and Thomas Register on-line provide a means for searching for products or industry related service via the World-Wide Web. Such services are a relative novelty at this time and as such the contents of these on-line WWW accessible catalogues is inferior in both quantity as well as quality than comparable printed catalogues. The possible benefits are high because on-line information improves the information provider's ability to

deliver more up to date information, more quickly. For the user, digitally stored catalogues provide the same level of improved search methods available with any computer database.

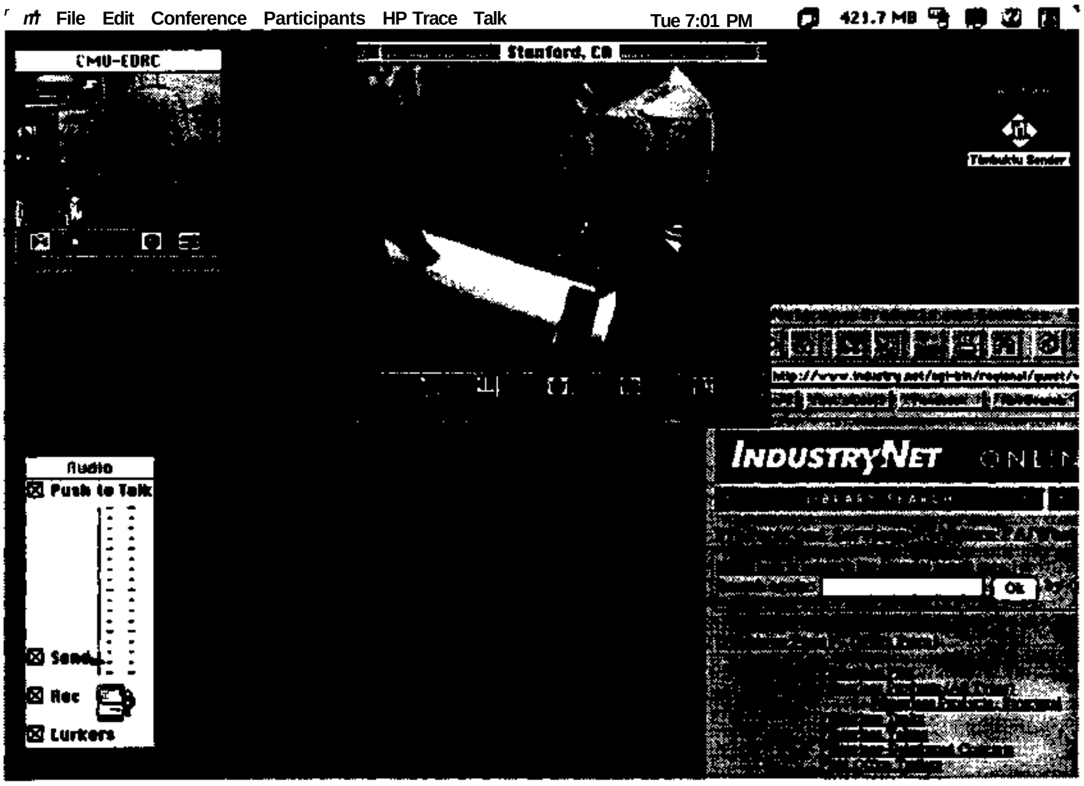

FIGURE 2. A typical design session conducted remotely between CMU and Stanford via CU-SeeMe. In this session a planned modification to the motor housing is discussed with the Stanford team member showing where the existing housing needs to be machined. In the background is a WWW Browser displaying one of many emerging on-line catalogue services.

Late in the conceptual design stage it was decided that a second visit by the CMU members of the design team to Stanford was necessary to make a final decision on the design at a configuration level. During this trip, all three members from CMU were in attendance. This event was notable in that it implicitly acknowledged that face-to-face meetings were still necessary to resolve questions about the status of the project which either could not or could not efficiently be answered via computer mediated means.

5.1.5 Detailed Design

Once the configuration design decisions had been agreed upon by the design group, responsibility for the detailed design of each component was divided between four members of the group. A protocol was devised to ensure that only one person would work on the shared copy of the detailed drawings at a time. The main drawing file was kept on a single machine, and was "checked-out" via FTP by whoever needed to work on it. An ASCII text file (a README file) located in the same directory as the drawing file was used to keep track of the current status of the shared drawing file. Whenever the drawing file was checked-out, the borrower was required to make a note that he was using the drawing file within the README file. Clearly this arrangement only worked because we were able to schedule the work such that only one person needed to modify the drawing file at a time. An engineering document management application such as Autodesk WorkCenter would have been useful in this situation however it is not know if such tools are scalable across disparate file systems across the Internet.

Also during the detailed design stage, there was a noticeable drop in interaction and even communication between CMU and Stanford. While this was due in part to the division of responsibilities for the detailed design of individual components, as well as to events in the academic calendar (notably the mid-semester break when several team members were unavailable), it seems clear that a breakdown in connection between the team was also the result of problems which arose in the use of computing resources at the Stanford site. We cite two phenomena which appeared around this time: an increase in the overall use of the pool of common use computers for the ME210 course by the class to the point where it became a problem for members of our team located at Stanford to obtain use of a computer, and the appearance of "common-use-computer syndrome".

Since communication via video-conferencing applications was integral to our group's ability to have productive meetings between CMU and Stanford, the inability to obtain use of a computer during scheduled meeting times was directly responsible for the cancellation of meetings. The second phenomena we have labelled "common-use-computer syndrome" refers to the situation which arises when one user group unintentionally disables a computer for another set of users while reconfiguring that machine for their own work. Even such seemingly minor details like a missing microphone or lack of batteries for an external speaker can be a trouble-shooting nightmare capable of cancelling a meeting. More serious acts like the thoughtless removal of files or applications are actually easier to identify. These events highlight the need for dedicated machines for individual design teams and also for the need for full time support in maintaining communications infrastructure. Both of these were present at the CMU side but were not present at Stanford.

5.1.6 Manufacturing

Manufacturing of components was split between Stanford and Carnegie Mellon to make the best use of available facilities and to minimize lead times. Final assembly of the motor was performed at Stanford and therefore ail components fabricated and materials purchased by CMU were shipped to the Stanford site. The location where the detailed design of a component was performed did not necessarily determine its location of fabrication. Since all of the fabrication processes were new to the design team, a lot of interaction was required to determine the limits of a fabrication process and the format in which the design specification was required by the fabricator. Having indirect contact between the designer and the fabricator led to misunderstandings and delays.

5.2 Challenges to the Process

This section discusses the problems encountered by the distributed design team in the course of this project. The challenges are viewed from an organizational perspective and include: lack of existing communications infrastructure and experience using this type of infrastructure (sources of experience), dissimilar computing environments (Macintosh vs. Unix), loss of familiarity between the team members (loss of team cohesion) due to their remoteness, and the effect of different time zones on scheduling. Some problems encountered, like lack of direct management, might have occurred in colocated design but were exacerbated by the geographic distribution. Other problems, like resource allocation, were the result of self-imposed constraints required for the design experiment.

- *Communication Infrastructure:* At the start of the project, a clear vision of the communication system which would be used to link the CMU and Stanford parts of the design team did not exist. While likely candidates for parts of the system had been identified, there was no experience in how or even if the pans could be integrated. Thus, trivial tasks became non-trivial experiments based on trial and error.

- *Dissimilar Computing Environment:* **The available computing environments of CMU, Stanford and the corporate sponsor (FMC) were all different. CMU team members were most familiar with Unix-based applications, Stanford members were completely Macintosh-based, and the corporate liaison worked on a PC platform. The final solution was the purchase of a dedicated Macintosh platform with applications by the CMU group as this seemed the least expensive and easiest fix. This decision was also supported by the choice of video-conferencing application (see Appendix A and CU-SeeMe).**
- *Loss of Team Cohesion:* **"Design is a social activity", is one of the provisional rules of design on which the ME210 course is founded. Unfortunately, interaction through a mechano/electrical link-up does not support a feeling of social closeness. Since the majority of communication between CMU and Stanford members were either via electronic mail or in the context of an official video-conference meeting, a level of formality was imposed on all of the dialogue. The lack of any social context for the team prevented any feeling of team cohesion from developing (at least between the two campuses) and tended to promote an "us/them" mentality.**
- *Time Zones:* **In conducting meetings between geographically distributed groups it is necessary to consider the effects of different time zones. One of the major problems which we encountered was the 3 hour time difference between the West Coast and East Coast time zones. Since the West Coast team members were often unable to meet until 6 or 8pm PST, this meant that many meetings lasted past midnight for the East Coast members. Over the course of 4 months this proved to be a point of friction and certainly added to the difficulty of scheduling meetings.**
- *Hands-off Managing:* **Physical separation limits one's ability to manage. In one situation which developed during the project where a more experienced member of the team was managing another team member, the physical distance between the two meant that the manager was never quite sure what the other was working on. The manager had to rely on the other to know when he needed help and to ask for it. When this proved not to be the case, weeks were lost because supervision was not as tight as if the two were located at the same office.**
- *Resource Allocation:* **Unlike other teams enrolled in the ME210 course, the FMC project team did not have the opportunity to build a group internally. Membership in the project was imposed externally based on a preliminary (and somewhat erroneous) expectation of the project problem scope. One eventual result was a difficulty in modularizing the project to assign specific and independent modules to individual team members. Proper modularization of the project tasks would have allowed the remote members to work with relative independence once a clear definition of the interface between the modules was defined. This would have minimized the need for continual, detailed discussions which did not lend themselves well to the video-conferencing tools available. We acknowledge that this problem was to a certain degree self-imposed for the purpose of increasing the interaction between the team members and thus the information captured about the design process.**

5.3 Limitations of Current Tools

Limitations of the available tools for supporting distributed team work are discussed. The tool related problems we encountered were in the area of: network bandwidth limitations, inter-operability of applications and platforms, the notion that simply providing tools does not address the cultural aspects of design and in fact might give rise to new implications on how people interact, and the brittleness of the available tools.

- *Network Bandwidth Limits:* **Video-conferencing and desktop-conferencing applications use up a large amount of bandwidth. During peak hours on the Internet, this bandwidth is often not available, degrading the quality of the connection.**

- *Software and Hardware Interoperability:* Due to cost restraints, it was necessary to mix and match individual software and hardware components. Often it was discovered that these systems were not compatible. Examples included continual problems with Timbuktu Pro, and the decision of Autodesk not to support AutoCAD for the Power Macintosh.
- *Cultural Aspects:* A strong effort must be made to make people learn tools and perform tasks whose benefits are not immediately obvious to them. Simply providing someone with a tool to publish information on a WWW page does not necessarily guarantee that the person will do so, or that he/she will publish useful information. Another cultural aspect which manifested itself in the course of the project was related to the dependence of the design team on email as a communication tool. As shown in Figure 3, the CMU-Stanford team generated almost twice the amount of email as the next closest team (JPL). It should be noted that the three members of the JPL team were SITN (Stanford Instructional Television Network[1]) students. This indicates that they did not attend lectures on campus (and in fact one member of the JPL team was located in Oregon) and thus this design team was also geographically distributed. This dependence on electronic mail caused communication problems for those members of the team who either did not have easy access to an email facility or did not adopt the habit of frequently checking their email (+ once/day).

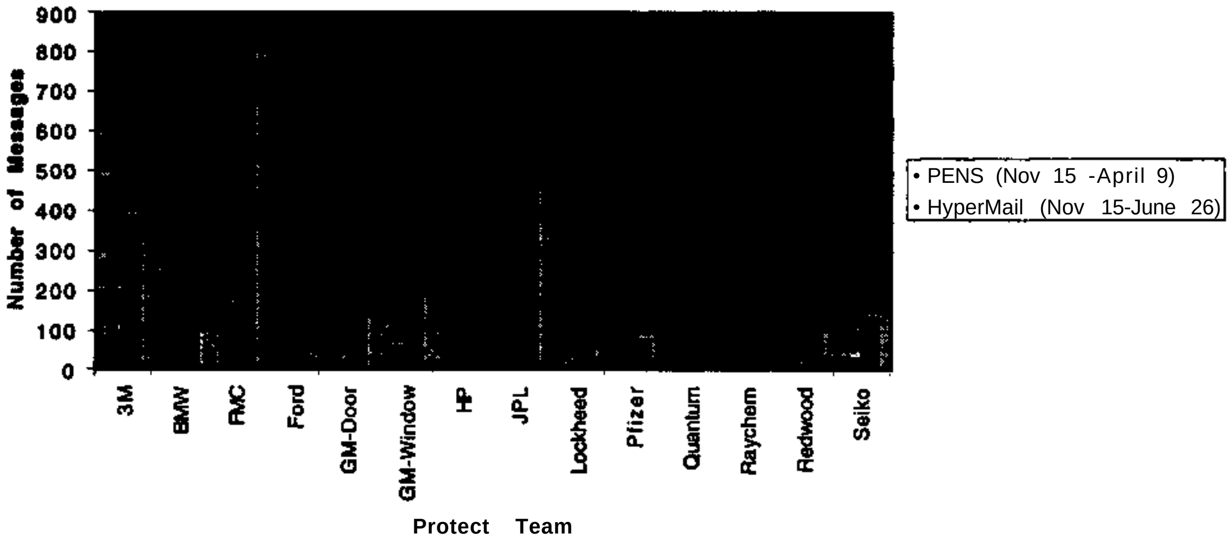

FIGURE 3. A comparison of volume of electronic mail and PENS postings throughout the different design teams in the ME210 course.

- *Brittle Tools:* The collaboration applications used in the experiment were generally not robust enough to survive use by casual users. Learning the idiosyncracies of the different applications and protocols require a relatively high amount of determination and patience which is generally in short supply when faced with a pressing deadline for a design project.

1. SITN is a program of the Stanford Center for Professional Development. SITN provides television broadcast of class lectures within the Palo Alto area.

- *Immersive Technology:* The tools we used were not designed to support a simulation that the participants were really located in the same room. It became clear during the course of the brainstorming sessions that a lot of time was being lost because people could not engage in side-bar conversations. During normal meetings where all the participants are located in the same location, many secondary discussions might be going on at the same time as the main discussion. During these side-bar discussions, individuals or small groups discuss and resolve issues which are related to the main discussion. Having come to some consensus, they might then choose to reenter the main discussion with the new piece of information. Individuals might be engaged in one primary discussion, while peripherally listening to the secondary discussions around him. The colocated meeting can thus be characterized as a parallel processing activity. Without a truly immersive technology, meetings were constrained to be serial activities only capable of supporting one topic of discussion. It was not possible to peripherally participate in multiple conversations at the other end of the video-conference connection. Side-bar discussions had to be summarized for the entire group, which tended to disrupt the primary discussion and led to long and frustrating meetings.

6.0 Conclusion and Recommendations

The confluence of trends in current models of the design process and office automation, along with advances in technology make the idea of collaboration across geographic distance an attractive and seemingly achievable goal. This experiment in performing distributed design supported by computer collaboration tools is a necessary first step in assessing the challenges and requirements for future remote collaborative engineering projects. The project discussed in this report differs from previous experiments in computer supported collaborative work in that:

1. We present experiences from a realistically complex mechanical engineering project *(i.e.,* design of a novel cooling system for AC induction motors for application in an electric vehicle).
2. The duration of the design project was 5 months.
3. The members of the geographically distributed design team participated regularly in all phases of the design process via the Internet.
4. Members of the design team were also involved in the research *(i.e.,* participatory observation).

This report has described the setting for our design problem, outlined a framework for identifying the necessary tools to support distributed engineering design, discussed the effectiveness of our testbed infrastructure and collaboration tools, and outlined our preliminary findings and observations of the protocols for communication and collaboration within a distributed design team.

We have found that the available technology, both in terms of hardware and software, is still insufficiently robust to be used by design teams without full-time support and significant training. We strongly encourage the use of dedicated communication facilities for individual design teams, rather than common use facilities which are prone to neglect and breakdown. However, deficiencies in hardware and limited bandwidth over data networks are technological problems which will undoubtedly be solved under the current market forces. The more interesting developments will be in the organization and culture of the design team members who will need to follow more rigorously the idea of designing a workable design process prior to attempting to address the actual design problem. While loose organization and informal protocols for communication can be overlooked in colocated design, interacting with others via computer mediated facilities and the attendant challenges created by geographical distance does not create a situation which is tolerant of informal models of communication.

Appendix A: Existing Tools for Design

The following is a discussion of a representative set of tools which are useful for distributed design, the technology they use and the procedure for obtaining the software *{i.e.,* ftp sites, vendors). Not all the tools listed here were used in this project.

Collaboration Infrastructure

World-Wide Web

World-Wide Web (WWW) [9], [10] is a data model developed by Tim Berners-Lee at CERN (a collective of European high-energy physics researchers), which merges techniques of hypertext, information retrieval, and wide-area networking. It uses a client-server protocol for information transfer. The World-Wide Web supports multiple media types including text, still images, video, and audio formats.

MBone

Multicast Backbone (MBone) [12] is a virtual network built on top of portions of the physical Internet. It was developed to provide point-to-many and many-to-many network service for applications requiring simultaneous communication with multiple hosts *(e.g.,* video and desktop conferencing tools). This virtual network is composed of nodes (typically running on Unix machines) that directly support IP multicast such as multicast LANs like Ethernet, which are linked by point-to-point connections called *tunnels.*

Video-Conferencing

CU-SeeMe

CU-SeeMe [13] is a video conferencing application from Cornell University specifically developed for the Macintosh platform. It is classified as a point-to-point video conferencing tool but can be used for multi-party communication by use of a reflector operating on a separate (Unix) machine. The audio facility is provided through Maven (an audio-only application for the Macintosh) which is integrated into the CU-SeeMe package. An enhanced commercial version of CU-SeeMe is currently being jointly developed between Cornell and White Pine Software of Nashua, NH.

Available via anonymous ftp: *gated.cornell.edu*

nv & vat

Nv and vat [14] are video and audio tools respectively which use the MBone protocol for communication. Vat was developed at LBL (Livermore Berkeley Labs) by Van Jacobson and Steve McCanne. The net video tool nv was created by Ron Frederick at Xerox PARC.

Available via anonymous ftp: *ftp.ee.lbl.gov 2xidparcftp.xerox.com*

Document Sharing and Whiteboards

wb

The wb application is a shared whiteboard application which can be used in point-to-point mode as well as under the MBone protocol. Also authored by Jacobson and McCanne at LBL.

Available via anonymous ftp: *ftp.ee.lbl.gov*

Collage

Collage [15] uses communication tools to support collaborative scientific data visualization. Remote users can share data visualization, electronic whiteboard capabilities, text display and editing, and screen capture

Available via anonymous ftp: ***ftp.ncsa.uiuc.edu***

PENS

Personal Electronic Notebook with Sharing [16] is designed to be a note-taking tool for the notebook computer platform. It's power derives from the ease with which notes written in the PENS application can be published in a shared workspace (i.e., the Internet WWW).

Available at URL: ***http://me210.stanford.edu/tools/indexMtml***

Hypermail

Hypermail is a utility program developed at Enterprise Integration Technologies which automatically converts mail messages into a cross-referenced archive of HTML documents. During the conversion to an HTML file, each mail message is further checked for URLs, any of which are also converted to hyperlinks. Four index files of the archive are created which sort the messages by date received, author, subject, and thread.

Available at URL: ***http://www.eit.com/goodies/software/hypermail/***

Application Sharing

Timbuktu Pro

Timbuktu Pro is a screen sharing and file transfer application for TCP/IP networks by Farallon Computing, Inc. The screen sharing feature allows remote users to observe the contents of or control the operation of another machine. The file transfer procedure allows transparent movement of files between machines.

Miscellaneous Commercial Applications

In addition to the above specialized collaboration tools, other computer applications were used to support the design project including: AutoCAD by AutoDesk, MathCad by MathSoft Inc., FrameMaker, Microsoft Project, Netscape Navigator, MacDraw Pro, and Adobe Photoshop.

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