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A CASE STUDY IN MULTI-DISCIPLINARY DISTRIBUTED COLLABORATIVE DESIGN

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ABSTRACT

Researchers at the University of North Carolina at Chapel Hill and the University of Utah participated in a collaborative, remote, rapid design and manufacturing experiment. Several domain experts at widely distributed geographical locations worked on a challenging multi-disciplinary design problem producing a rugged, compact and light-weight housing for a ***Video See-Through Head-Mounted Display*** *to be used in image-guided surgical procedures. This was used as a case study to validate and motivate ongoing research in a distributed engineering design and manufacturing system.*

The hypothesis was that Net-based use of a highly supportive integrated, collaborative design and manufacturing environment would dramatically expedite the design and manufacturing process. Using the already existing Alpha_1 design and manufacturing environment as a platform, we embarked on a project to collapse the normal six-month cycle of design and prototype iterations into a single three-week period of collaborative design. The lessons learned demonstrate the potential success of the hypothesis, and also provide a basis for further research into tools and environments needed to support integrated collaborative design, engineering, and manufacture.

We discuss the results of the experiment, application of the existing distributed design system, the supporting system architecture, and possible future research issues brought to light by the experiment.

Keywords: CAD/CAM, Collaborative Design, Multi-disciplinary Design, Distributed Design

PROBLEM STATEMENT: THE EFFECT OF A MULTI-DISCIPLINARY COLLABORATIVE DISTRIBUTED DESIGN ENVIRONMENT ON THE DESIGN PROCESS

Researchers from the University of North Carolina at Chapel Hill and from the University of Utah participated in a study of the design process in a collaborative, distributed engineering design and manufacturing environment. Working at widely distributed geographical locations, experts from several engineering disciplines collaborated on the rapid design and manufacture of a **rugged, compact and light-weight housing** for a Video See-Through Head-Mounted Display developed at UNC for use in image-guided surgical procedures. Our 8-10 member team collapsed the normal six-month cycle of design and prototype iterations into a single three-week period of collaborative design. This housing design experiment serves as a case study for our analysis of the effects of multi-disciplinary collaboration, and specifically rapid collaboration at a distance, on the design process in a highly supportive design environment.

Collaborative design is defined as the activity of designing through the interaction of designers and the environment (Saad and Maher, 1996). Our research objective for the collaborative experiment was to determine how the design and manufacturing process itself was affected by the environment we constructed and the design goals we set. Aspects of the process under investigation fall in three broad categories: issues relating to the interactions of design team members in the collaborative environment, issues associated with the evolution of the design itself and the systems supporting it, and issues relating to manufacture and the systems supporting it. Our research addressed problems arising from competing and sometimes contradictory forces at work in these three areas of distributed, integrated collaboration.

As far as the collaborative environment was concerned, we wanted to investigate the ability of geographically dispersed team members from different disciplines to work together. A collaborative system that supports team work at the same time in different places is known as a synchronous distributed system (Saad and Maher, 1996). Believing that one is in some physical environment where one is not requires a sense of presence or a willingness to suspend disbelief. When participants are at remote locations, a medium of communication is required to convey this sense of presence, known as telepresence (Steuer, 1992). In our experiment telepresence was provided by video-link and the InterNet. Problems associated with this collaborative environment include:

- experts from different disciplines and at different geographical sites, who do not necessarily know each other, have to use telecommunication and design tools with which all team members are not necessarily familiar
- team members have to become familiar with each others' fields to the point of being able to understand the impact of other disciplines on their own
- the experimental environment exposes certain limits of current experimental CAD systems: while use of the InterNet makes it possible for team members at different sites to view the same CAD model, communication protocols do not yet exist to allow both teams to make simultaneous changes to the model; another limitation is that viewing can at the moment be controlled either locally (at each client site) or globally (from the server), but switches from one control mode to another are not possible during a collaborative session.

An objective relating to the evolution of the design was to determine the design tools required, as well as the communications capabilities needed to support the use of a CAD system over the InterNet and via tele-video. Problems in this area:

- the experimental environment exposes certain limits of current experimental CAD systems: while use of the InterNet makes it possible for team members at different sites to view the same CAD model, communication protocols do not yet exist to allow both teams to make simultaneous changes to the model; another limitation is that viewing can at the moment be controlled either locally (at each client site) or globally (from the server), but switches from one control mode to another are not possible during a collaborative session

Issues relating to manufacturing revolved around the integration of design and manufacture, so that manufacturing considerations would influence the design at all times:

- time pressures require that the normal six-month cycle of design, prototype, and iterations be collapsed into a single three-week concurrent design period
- despite the reduced time period, a reliable, high-quality product has to be manufactured
- the manufacturing process has to allow for making several dozen additional copies

The goal of our paper is to discuss each of these problem areas as they relate to the evolving design process. Unlike collaborative design reviews that focus primarily on evaluation of the final model and product, we discuss the effects of the integrated, distributed, rapid design and manufacturing environment on the structure of the design and design process themselves. Our discussion of this process will be grouped under the three categories delineated above, namely the design team at work in the integrated collaborative environment, design issues, and manufacturing issues.

1. The Design Process and the Integrated Design and Manufacturing Collaboration Environment

A research goal of our experiment was to investigate the effect of an integrated collaborative design environment on the design process as it relates to the historical gap between design and manufacture, and also to the separation among different design disciplines, for example video-optical and mechanical design. Although computer aided design (CAD) and computer aided manufacture (CAM) have in recent years speeded up product design and manufacture, the historical division between the design engineer at his drafting desk and the manufacturing engineer in the machine shop has not yet been overcome. When putting a vision on paper, designers often fail to consider cost or manufacturability, while manufacturers' modifications violate the designers vision. Costly and time-consuming design iterations are required to bridge the gap between the designer's intent and manufacturing realities.

Traditionally the design to manufacture process for this kind of product would have had a linear structure with three stops. The optical design would have been passed to a mechanical engineer, who would have laid out an encasement. This design would then have been given to a manufacturing engineer.

After putting together a proof of concept design using off the shelf components, researchers at UNC decided that a custom designed and built casing would be necessary to meet the design requirements. Our collaborative experiment was driven by UNC's need for a casing, as well as by Utah's interest in investigating whether the design and manufacturing environment could be enhanced by collaboration integrating the resources of different engineering disciplines and by the use of research-level design tools. Using Utah's Alpha_1 research test bed, our collaborative effort would integrate design considerations from the video-optical, electro-mechanical and manufacturing disciplines into the design process of the VST-HMD instrument.

While providing the benefits of an integrated collaborative environment, our experiment's use of the Net would allow researchers to remain in their local environments where they are most productive and effective, avoiding the disruption of co-location. Even though the designers on our project were geographically separated by the width of a continent, telecommunications devices allowed us to interact face to face in real time. We used a dedicated T-1 compressed video-conference link between UNC and Utah. A parallel design channel was provided by workstation computers at both ends, linked through the InterNet and running the Alpha_1 research test bed software developed at Utah. Alpha_1 has a client server architecture that lends itself to collaboration at a distance. The workstations at UNC and Utah displayed the computer model of the design to participants during design discussions. Team members at different sites were able to view the same CAD model, and each site had independent control of its own viewing. This ability enabled optics experts and mechanical engineers, for example, to examine different features of the model at the same time. If distributed teams needed to look at the same orientation of the model simultaneously, the telephone or video link was used to ensure that the viewing was coordinated. When changes needed to be made to the model during collaborative sessions, the Utah team retained control of modifying the model. Existing communications protocols require that control remains at one of the remote sites since protocols for switching control do not yet exist. As the model evolved in real-time, the incorporated changes were immediately propagated from the server to clients at all sites via the InterNet link. By using telecommunication facilities to compensate for the lack of switching protocols, we were nevertheless able to successfully integrate the entire design-to-manufacture process.

The integrated environment enabled designers to discover early in the design process which tools, materials, and manufacturing processes were available. In a constantly evolving process, we went directly from concept to three-dimensional models, while at all times considering the overlapping requirements of the video-optical, electro-mechanical, and manufacturing areas. The structure of the Integrated Collaboration Environment is detailed in Figure 1.

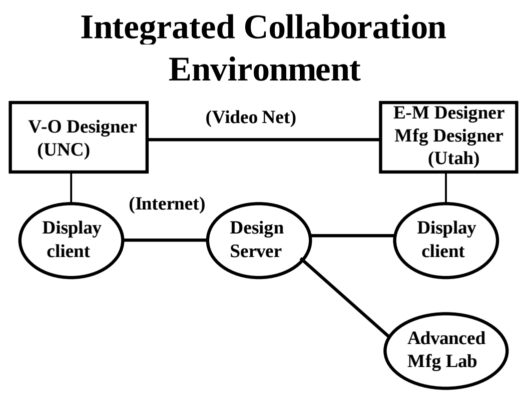


Figure 1. Integrated Collaboration Environment

2. The Design Process and the Evolution of the Design

Our design goal in collaboration with the UNC group was to provide housing specifications for an extremely light-weight, rugged, compact **Video See-Through Head-mounted Display (VST - HMD):** UNC's VST - HMD project is aimed at creating a device to be used during medical augmented-reality procedures. Augmented reality superimposes virtual reality displays onto a real-world environment. Information obtained from diagnostic tools such as ultrasound is superimposed on the surgeon's *actual* view of the patient during surgery. In the diagnosis of breast cancer, for example, the video see-through feature of the VST - HMD will capture a portion of the surgeon's visual field with two cameras and pass it through stereo displays, one for each eye. Software and special purpose computer hardware created by UNC will allow information about what's happening inside the patient, as relayed by real-time ultra-sound imagery, to be superimposed as if it were being seen directly inside the patient. With the aid of this technology, a more accurate diagnosis of diseases such as breast cancer through ultra-sound image-guided needle biopsies will be possible.

UNC's optics design goal was to provide a unit with an optically correct overlay. In earlier video display units available to surgeons performing image-guided procedures, the depth perception was off by 6 to 8 inches. This was caused by a discrepancy between the optical path lengths from the primary mirror to the user's eye iris, and from the primary mirror to the camera iris.

By the onset of our project, UNC had already developed an initial video-optical design in which the optical path was folded to ensure equal optical path lengths. The design incorporates a newly available commercial miniature video camera and display components. In addition to ensuring correct depth perception, the design was based on requirements arising from the product's intended use during surgery, and included considerations such as the intra-ocular distance and the inclusion of a mechanism to adjust depth perception for individual users. In the ongoing evolution of the design, we never migrated from the requirements of an optically correct design. Although modifications were made to accommodate design and manufacturing considerations, at each stage the working design was an optically correct variant of the initial optical solution. The Alpha_1 modeling system was instrumental in maintaining the optical constraints while mechanical design considerations were being incorporated into the design.

Video-Optical Issues in the Evolution of the Design

At Utah our manufacturing and design goal was to produce a compact, lightweight housing to hold the components in place in accordance with the optical solution. Two parallel and sometimes conflicting considerations guided the design at this stage: the housing had to be the smallest possible size while still allowing for a configuration of components that conforms to the optical solution. The two main functions of the housing are to protect the optical components and to hold them in place. Accurate placement of the components is critical to the optics, since small errors can affect the optical path. Already at this early stage we solicited input from the manufacturing engineer about lightweight materials, and discovered that the shrinkage of molded plastic upon cooling was another obstacle to be considered in the correct placement of the components. In addition to its main functions, the housing has to provide a mechanism for the user to adjust the distance between the eyes and the angle determining where the images will converge. A major optical consideration that figured into the housing design was the constraint imposed by the VST (video see-through) feature requiring equal optical path lengths from the primary mirror to the user's eye iris, and from the primary mirror to the camera iris, along the view-center rays. This configuration requires an angular distance similar to that of a computer monitor at arms length. In addition the unit should cause minimal obstruction of peripheral vision.

Figure 2 shows the preliminary layout of components in accordance with an optical solution that provided the starting point for the mechanical design.

Components required by the initial optical design had already been developed at the onset of the project. After the collaborative process had already started, the team became aware that newer, smaller cameras than the ones in UNC's initial design had become available. UNC incorporated this new technology in the design, and the feature-based Alpha_1 model was updated to reflect the new parameters. This includes a 12 mm. diameter video camera, a .7 inch diagonal display system, and a patent pending cube whose components, including lenses, mirrors and prisms, are shown in figure 2. The entire optical display system can be contained in a space with biggest dimension of 20 mm.

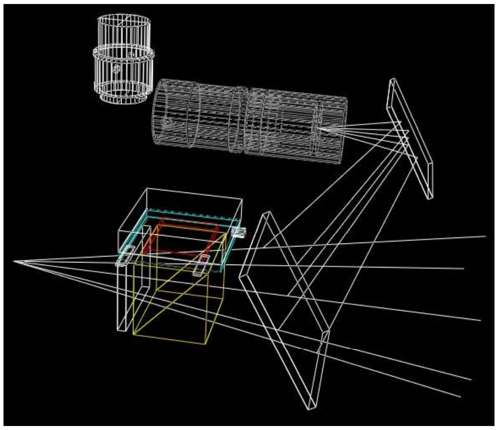


Figure 2. An optical solution

The Overlap of Video-Optical and Electro-Mechanical Issues in the Evolution of the Design

Considerations relating to the product's intended use during surgery also influenced the ongoing design. The unit has to be compact, rugged, and weigh less than a pound. It has to be comfortable to wear and easy to flip out of the way when not in use. With these issues in mind, Utah's electro-mechanical designers provided ergonomic adjustments to the design while preserving the features of the optical model relating to the provision of an optically correct image overlay.

Using the constraint propagation characteristics of the Alpha_1 CAD modeling system, basic dimensions could be changed interactively while maintaining overall design constraints. In order to explore different configurations of component placement inside the housing, accurate models of the selected components were made at Utah to serve as design constraints. The spatial dimensions and relationships among the components were parameterized to represent the optical path. When, for example, we discovered well into the design process that the cameras could be shortened, we changed the camera dimensions in the model, and used optically correct variants of the initial solution to determine the change in location of the patent pending cube. We needed to change only a single parameter, and the system automatically calculated all of the consequent changes.

Parametric layout

- Earlier headsets (using the larger cameras then available) had to have the cameras mounted on the outside of the headset. UNC's initial solution allowed for new shortened cameras to be mounted inside the housing, against the user's forehead, and allowed the Alpha-1 modeler to be used to devise a class of optical solutions that solved the depth perception problem in the old headsets. During the design process the optical team noticed that the camera could be shortened by a further 15 mm. This change in camera length was once again entered into the model, and Alpha_1 calculated the consequent changes in the positions of the cameras and mirrors while still ensuring that the image plane of the camera matched that of the eye.
- The three-dimensional locations of the components were parameterized to exactly represent the optical path constraints. To ensure that the camera would see exactly what the headpiece wearer's eye would see, mathematical constraints in the computer model ensured that the virtual optical path from the primary mirror to the user's eye iris was kept the same length as the real path that reflects from the primary mirror into the camera iris
- The optical relationships were reflected in the geometric model with each change of dimensions. During the entire design process every intermediate design was a correctly working variant of the initial optical design.

Compacted optical path

- To achieve the goal of a small and lightweight product, we used the Alpha_1 modeler's constraint-maintenance capability to develop the compact envelope containing the volumes of the components and adhering to the constraints of the optical design. After the modeler determined the optimum placement of the components in accordance with the optical solution, we started to take into consideration the structures required to hold the components in place. We now wanted to design and incorporate space for the fixed fins and webs required to hold the components in place. We also had to allow space for flexible components such as wires, which are not represented in any CAD models. Since we did not have the specifications for these elements, but only the actual physical objects to work with, we resorted to a traditional process: "to-scale" modeling and the use of calipers to determine component dimensions. During this stage designers assumed rotational camera symmetry in designing the fins and webs to hold it. At the end of this stage a compact yet manufacturable and optically correct design for the casing had been created.

Initial housing profile designed

- Once we had a computer model of the housing, it was evident that its exterior outline was very complicated. The manufacturing engineer contributed the important insight that all the components are the same width across, except for the one mirror that was wider. A separate rectangular volume was added to provide the required space for the mirror.

New optical requirement added

- When UNC reviewed this design from an optical point of view, they realized that their original specifications would result in a casing that would let in too much light. The casing was open in front so that the view of the patient would not be obstructed. As a result of working in an integrated environment, they were able to use the feedback they received to request a change to the housing profile to prevent exterior light from getting in. In a solution arrived at jointly by the teams, we added a light baffle to the front of the casing that would prevent most exterior light from getting in and yet cause minimal obstruction of the wearer's view of the real environment. Without the close coordination of mechanical and optical teams and the ability to view the model at every stage, this problem would probably not have been discovered until after the first pass through the manufacturing process.

Suspend casing from frame

- Until this stage of the design, UNC's initial optical specifications required a separate, mirror-image working unit for the left and right eye. Our manufacturing engineer pointed out that there seemed to be no optical or electro-mechanical reason for the units to be mirror-images. If the units for both eyes were made identical, the mold design would be vastly simplified: only one mold, consisting of male and female halves, would be required. This would reduce the mold manufacturing time by half. After this solution was adopted, the design process focused on how to suspend a casing for each eye from a frame, and how to connect the left and right housings with an adjustment mechanism for the lenses.

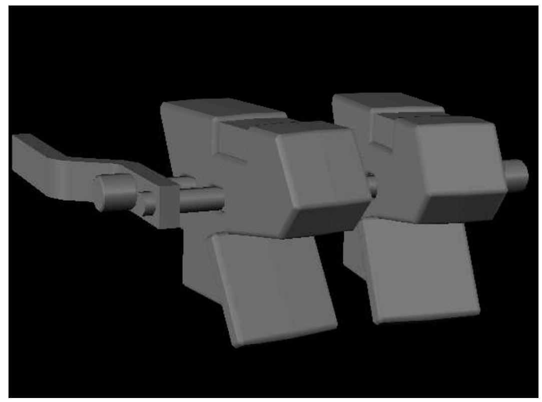


Figure 3. Housing Design

Integrate support rods through the middle

- Examination of the design for both eyes showed that support rods through the middle, between the left and right housings, could replace the adjustment mechanism previously envisioned. This would result in a slight increase in mold complexity, but reduce the overall part count.

Add assembly details

- Webs for holding the components in place were added, as were bolts to hold the two sections of the housing together. We also provided a focus adjustment consisting of a thumb knob and a screw.
- A wire path and connector placement was determined so that the *fixed* length cable could be used, and the cost of a custom cable could be avoided.

Camera variation

- After the first parts were molded and assembled, we ran into an unanticipated problem. Maintaining coordination between camera CCD scan lines and display scan lines was important. The cameras we had used as our model had opposing screw holes aligned with the CCD horizontals, so we created holes in the mold aligned with those on the camera. However, later cameras did not repeat that alignment. That is, holding the cameras in that position led to angled scan lines, with each camera different. The solution required redesigning the mold to enable the cameras to rotate the required amount to align scan and display, and still be held in place.

3. The Design Process and Issues of Manufacture

A result of working in an integrated environment was that a continuous dialogue was maintained with the manufacturing engineer from the initial stage. While the optical solution was still being refined, the manufacturing engineer was already considering materials and methods that would ensure a lightweight, compact, easily reproducible product that would be manufacturable within the time constraints. Once a manufacturable electro-mechanical solution had been reached, UNC reexamined it from an optics point of view, and further adjustments were made. The integrated collaborative environment allowed all of these manufacturing considerations to feed back into the design process despite the geographical separation between the different engineering groups.

Material and manufacturing process choice

The two primary considerations that governed manufacturing choices were the projected three-week production time and the goal of producing several dozens of the unit. Materials and processes considered were the following:

- Machined metal has the advantage of being the most straightforward and most accurate process; disadvantages are its weight and high unit cost.
- "Rapid Prototyping" plastic (STL, FDM) has the advantage that no molds are needed and that the products are lightweight; disadvantages are that the process is less accurate and slower, and that the product is less rugged.
- Injection-molded plastic (ABS) was the winning choice, since products are lighter and more rugged than those produced in the above-mentioned processes. Once the molds are machined, the cost per molded unit is low. The only negative associated with this process is the possibility of shrinkage—and we hoped to contend with it by incorporating the anticipated shrinkage into the design.

- Once a manufacturable optically correct working model had been achieved, the designers' communication with the manufacturing engineer provided insights into the mold manufacturing process that fed back into the design process. While designing the mold, the manufacturing engineer has to provide manufacturing details for removing the plastic product from the mold. The design was draft-angled to prevent it from sticking in a plastic ejection mold, and ejector pin locations were worked into the design. Slots were made wider to improve the flow of plastic.

We used a number of related processes on different regions of the mold to make the final shape:

- Machining: the largest possible volume of metal was extracted by milling. Since the design was developed as an Alpha_1 feature-based model, the feature objects such as pockets and holes were sequenced into a manufacturing process plan model, which then automatically produced the CNC machining programs to cut the mold insert parts of the injection mold assembly
- Wire EDM: used to make ruled surfaces in confined areas
- Sinking EDM: metal removed in required shape through the use of a graphite electrode made on a 5-axis milling machine

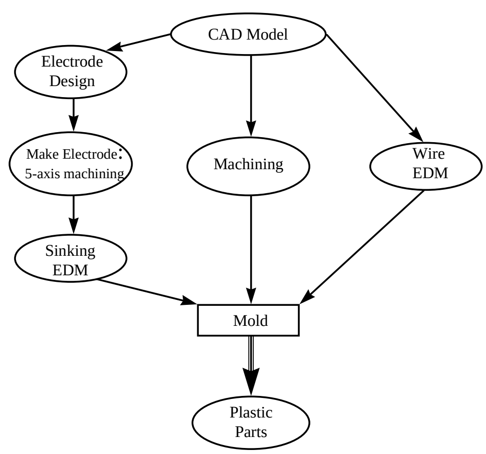


Figure 4. Complex relation between CAD modeling and injection mold manufacturing

In each of these steps errors could occur that could affect the accuracy of the design so crucial to the optics, but because of the integrated design environment we were able to address problems as we became aware of them. Figure 4 shows the hierarchical relation among modeling and manufacturing concerns.

The Overlap of Electro-Mechanical and Manufacturing Design Issues

Simplified housing concept

- Although the compact design was manufacturable, the manufacturing engineer immediately suggested that the it could probably be simplified. At this stage the casing had prismatic angles that would be hard to make. After further discussion the electro-mechanical and manufacturing teams jointly decided that a flat-sided casing would fulfill all electro-mechanical and optical requirements, and machining the mold would be easier. A casing consisting of two flat-bottomed pockets with different depths was decided upon.

At the end of this phase we had achieved a design that represented a reconciliation of the interests of the three engineering disciplines. We had moved from the concept to a choice of components, to the analysis of our graphics modeler's 3-D sketches, and on to a solid model conforming to an optical solution. In the following phases our dialogue continued to refine the product. As discussed in the previous section, examination of the design after the left and right casings had been combined showed that support rods through the middle could replace the adjustment mechanism previously envisioned. This change was incorporated into the design of the mold, slightly increasing its complexity, but reducing the overall part count.

Assemblability and repeatability

- Since at most several dozen units were to be manufactured, we weighed the time that would be saved by easier and speedier assembly against the time that would be lost in making the necessary adjustments in the mold design. We decided that assembly considerations were secondary to overall design and manufacturing time. Unfortunately, the product ended up being hard to assemble. Even though the webs were designed to hold the components in place once the casing was assembled, they did not do so prior to assembly. Further, the components slipped out of alignment as the two halves of the casing were brought together.

After the assembly of a few units at UNC, we collaboratively devised solutions to make assembly easier and assessed whether it would be necessary to make a new mold to incorporate the design changes. We decided that the current mold, processes, and materials were adequate for our present production needs. Only if much larger quantities of the product had to be manufactured would it justify the cost of making the required changes to the mold.

Results

Despite the fact that we used relatively primitive existing tools -- tools not designed with the primary purpose of working in a remote, distributed collaborative environment -- we were successful in designing a working product in only three weeks. There were however, several design features that had not been incorporated into the first manufactured version of the casing. Both the thumbscrew focus adjust and the i.p.d./convergence adjust are to be incorporated into the next version of the casing. Other desirable traits, such as webs to insure l.c.d. orientation, were not represented in the computer model. These deficiencies can be directly attributed to the three week cycle time. By using the client server architecture to enable each site to have local control over its viewing, valuable design time was saved by allowing each team to focus on the aspects of the design most pertinent to their expertise. On occasions when the design process required all teams to view the same orientation of the model, the telephone or video link provided the necessary communication tools to direct coordinated viewing. By using the InterNet to propagate design changes from the server to the client sites, all teams continually had access to the latest changes in the design.

The complexity of the overall design process and the intermediate derivative processes is not evident when looking at the finished product or even its "blueprints." The resulting feature-based model captures the final state of the design very well, but does not include earlier design alternatives.

The successful outcome of this collaboration has served to drive Alpha_1 development of a more complete collaborative engineering design environment. An obvious development required is for control protocols that will allow a peer to peer rather than a client server architecture.

Conclusions and Future Research

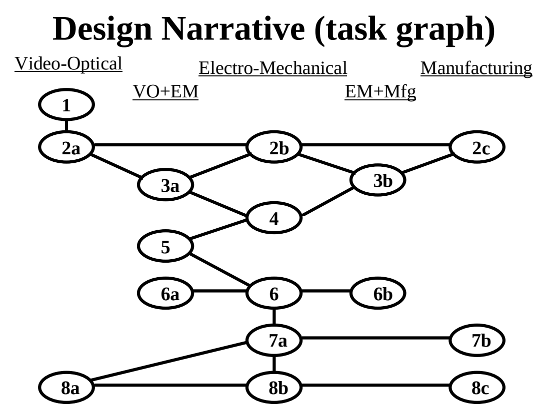
Remote collaborative design is not only exciting, but real. Our experience has shown that experts in multiple engineering disciplines working in a distributed, collaborative design and manufacturing effort can produce a viable and useful product: the VST-HMD has made a contribution to the UNC ultrasound project.

In addition to cutting down on costs related to production and manufacturing time, the remote, distributed collaborative environment can drastically reduce travel and consultation overheads.

However, our experiment brought the need for new design and communication tools to light. Communication between the various remotely located team members proved the most difficult challenge. Spontaneous brain storming, possible with co-located teams, was not possible, since the video teleconferencing had to be scheduled in advance. Some spontaneity was possible when participants discussed reviews and modifications by phone while each discussion participant ran the modeling system. Several researchers found the voice and video lag time during teleconferencing detrimental to the spontaneity of the design process. These are areas that still need considerable work before the collaborative design environment becomes a practical tool.

Insights about the structure of the design process itself will be beneficial in future collaborations. Early introduction of all interests including manufacturing seems beneficial. The requirements of each relevant engineering discipline should be actively expressed and represented throughout the design process.

The basic design process is likely to change (See figure 5). More iterations and dialogue are possible, and the iteration loops are likely to be shorter. Figure 5 provides a Design Narrative, or Task Graph, that consists of five columns illustrating the distribution of tasks among the three engineering disciplines. Note that the second and fourth columns indicate the overlap of disciplines. On a horizontal level, note the task path's layered structure -- reminiscent of a three-layer cake--that represents three contiguous and overlapping phases of collaborative design and manufacture.



Key to tasks

1 Selection of components and determination of relationships
2a Preliminary layout of components
2b Parametric layout
2c Material and manufacturing process choice
3a Compaction of optical path
3b Simplification of housing concept
4 Design of initial housing profile
5 Add light baffle
6a Integrate support rods through the middle
6b Decrease housing size
7a Add electro-mechanical details
7b Add manufacturing details
8a Accommodate camera variation
8b Assembly details
8c Evaluation of existing mold

Figure 5. Design Narrative (Task Graph) : The Structure of the Collaborative, Integrated Design Process

This multi-forked and reconvening path from concept to product differs markedly from the closed-loop iterations of traditional methods where the first prototype is frequently arrived at without intervening dialogue between design team and manufacturer.

More study is needed to determine the tools and conditions required to optimize distributed collaborative design and manufacture. Possible future areas of research include:

1. Further development of collaborative computer modeling tools.

2. Improvement of video communication tools.
3. Aspects of the remote collaborative environment that contribute to the participants' psychological comfort.
4. Aspects of the remote collaborative environment that lend themselves to distributive application, for example the ability to maintain proprietary specifications at different sites, and to combine them for viewing only for the duration of a remote collaborative design session.

The integrated, distributed collaborative environment seems capable of facilitating enormous speedup from design to manufacture. Even though we used primitive tools not explicitly designed for use in a remote, collaborative environment, we had considerable success in producing a quality product while reducing design and manufacturing time.

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