

Collaborative Mission Design at NASA Langley Research Center

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Abstract

NASA Langley Research Center (LaRC) has developed and tested two facilities dedicated to increasing efficiency in key mission design processes, including payload design, mission planning, and implementation plan development, among others. The Integrated Design Center (IDC) is a state-of-the-art concurrent design facility which allows scientists and spaceflight engineers to produce project designs and mission plans in a real-time collaborative environment, using industry-standard physics-based development tools and the latest communication technology. The Mission Simulation Lab (MiSL), a virtual reality (VR) facility focused on payload and project design, permits engineers to quickly translate their design and modeling output into enhanced three-dimensional models and then examine them in a realistic full-scale virtual environment. The authors were responsible for envisioning both facilities and turning those visions into fully operational mission design resources at LaRC with multiple advanced capabilities and applications. In addition, the authors have created a synergistic interface between these two facilities. This combined functionality is the Interactive Design and Simulation Center (IDSC), a “meta-facility” which offers project teams a powerful array of highly advanced tools, permitting them to rapidly produce project designs while maintaining the integrity of the input from every discipline expert on the project. The concept-to-flight mission support provided by IDSC has shown improved inter- and intra-team communication and a reduction in the resources required for proposal development, requirements definition, and design effort.

1.0 Introduction and Background

NASA’s Langley Research Center (LaRC) has a long history of innovative support for important agency research. In 2002 and 2003, LaRC’s Systems Engineering Directorate (SED) began developing two facilities focused on improving the mission requirements and design processes. These facilities were created by LaRC engineers with several years experience in the design, creation, and operation of spaceflight missions to offer engineers like themselves versatile environments where they could easily interact with their colleagues to quickly create robust designs, analyze them thoroughly, and easily incorporate improvements and modifications at the earliest stages of the project.

The Integrated Design Center (IDC) was conceived in response to a request from LaRC center management to improve the proposal process, and was inspired by the research of Dr. Knut Oxnevad from NASA's Jet Propulsion Laboratory (JPL) in Concurrent Design [1]. The IDC is a collaborative environment in which expert engineers from a diverse set of engineering disciplines can work together, using state-of-the-art tools, to rapidly create complex project designs. With the support of Dr. Pat Patterson and the NASA Engineering Training (NET) office, the IDC was planned and implemented in just five months.

The Mission Simulation Lab (MiSL) is a Virtual Reality (VR) lab employing head-mounted displays (HMDs) and virtual environments to create a simulation-to-flight capability for LaRC spaceflight projects. Like the IDC, this lab was developed in response to a request from LaRC center management. LaRC has a well-established history of applying the sim-to-flight approach in aeronautics [2, 3, 4] – a research development concept to reduce costs and increase confidence in aerospace efforts. However, since aircraft-based projects and spaceflight projects have different requirements constraints, the existing sim-to-flight facilities were not a good fit for the new requirements. MiSL was designed and built as a VR-based facility which could rapidly convert engineers' Computer-Aided Design (CAD) files into full-scale three-dimensional virtual models, which could then be experienced by the engineers in order to analyze their instrument designs in a simulated real-world environment.

As the IDC and MiSL began operating, the synergistic nature of the two facilities became evident, and IDC-developed designs were used to create virtual models in MiSL. Engineers and researchers who had participated in IDC design sessions were invited to MiSL to further analyze their projects using VR, and were uniformly impressed by the enhanced visualization capabilities. In early 2005, both facilities were moved to a new location, where they were collocated in order to take full advantage of the relationship between them. While each facility remains an independent entity fully capable of operating independently, the combined functionality of the two is known as the Interactive Design and Simulation Center (IDSC), a powerful "meta-facility" offering users a wide variety of advanced tools and techniques that can be used to simultaneously streamline their design process, increase the quality of their designs, and improve inter-team communications and understanding.

2.0 Collaborative Engineering

The concept of Collaborative Engineering (CE), also referred to as Concurrent Design, is a relatively new approach to system and project design which has been growing steadily in recent years, particularly in the space industry [5, 6, 7]. Essentially, the idea of CE is to bring together expert engineers from several related disciplines (i.e., structures, electronics, orbital analysis, software, etc.) in a single facility where they can perform their regular tasks, using all of the same tools that they normally employ, while working together with other experts in a structured collaborative environment. In this environment, these engineers can work together directly, in real time, to create and refine design concepts, analyze issues and trades-offs, and improve the communication of ideas and decisions.

This is a radical departure from the typical mode of operation for such projects. In the past, projects have been designed using a "work-and-meet" method, where engineers meet to determine the proper next steps for each team member, then go back to their isolated work areas to perform their piece of the work. The engineers reconvene at some later date to discuss what was accomplished, inform each other of new issues, and assign more work, before returning to their offices to work some more. In addition, team members spend large amounts of time attempting to arrange side meetings and discussions, or holding these side meetings without including all team members. The results of these sidebar talks, and the alternatives discussed in them, are often not shared with the rest of the team, if they ever occur at all. Frequently, two or three team members will agree on a decision on a topic which affects the entire project, with no one else aware that such a decision has been made, or why. This method of designing

projects is very time-consuming, and often causes important information to be lost, or viable alternative solutions to be ignored.

When working in a CE environment, engineers can receive immediate feedback on their ideas, have instant access to all team members affected by their discussions, and arrive at decisions that are understood by everyone affected. In addition, team members are better informed on what trades were performed, which alternatives were considered, and why certain ideas were accepted or rejected. The result is typically a robust design, with great detail in a number of aspects, and which was formed in far less time than using the “work-and-meet” method.

When implemented, the CE concept consists of several key elements, as listed in []:

1. A well-defined set of standard information products
2. Network-linked tools
3. Well-understood procedures for real-time collaboration
4. A standing multidisciplinary team skilled in the tools and methods
5. A facility supporting the hardware, software, and human resources

The LaRC IDC was designed and implemented to offer all of these components to the project design process, as detailed in Section 3.0. In addition, the CE design approach involves more work than simply gathering a team and telling them to work. A typical CE design study consists of three phases: study planning, session work, and post-session activities. Major tasks in these phases include:

1. Study Planning (1 to 8 weeks)
 - Customer, project manager, and CE systems engineer scope the study
 - Identify required disciplines and assign experts to them
 - Subsets of the team & customer meet to work specific issues and identify trades to be performed
2. CE Session (2 to 10 half-days)
 - Mission and customer introduction
 - Customer describes mission goals, needs, and known issues
 - Concurrent design process
3. Post-IDC session activities
 - Document results in comprehensive design report, including contributions by each team member and the customer, and detailed descriptions of design decisions made and rationale, trades performed, technical considerations, etc.

The LaRC IDC encourages every design team to follow these phases, in order to receive maximum benefit from the CE design methodology.

Experienced engineers and customers who are used to the “work-and-meet” approach are often amazed with the improvement in overall productivity they observe as a result of using CE methods. Customers have estimated a reduction in development time in the early project design phases at factors between four and ten [].

The IDSC, LaRC’s meta-facility formed by combining the IDC and MiSL, extends the traditional concept of CE by including VR simulation functions in the CE model to offer design team members the opportunity to employ another powerful analysis tool: three-dimensional (3D) visualization. By allowing project teams to view and interact with their designs in full-scale 3D at any point in the design process,

the information gained from that visualization can be used to identify potential problems or further refine their designs. In this way, the IDSC enables engineers and customers to maximize the amount of information analyzed and considered during the earliest stages of their project. This ability, in turn, reduces overall project cost and schedule overruns and reduces project risk.

The following sections detail the individual capabilities and characteristics of the IDC and MiSL, and then list the additional functions made available through their collocation and interaction in the IDC. A brief IDSC case study is also included, as well as explanations of some current IDSC work in areas for future development.

3.0 The Integrated Design Center

NASA Langley's IDC [8] is a multi-user CE-based facility that permits experienced engineers to work together, making full use of their individual expertise and knowledge while employing the tools and processes with which they are already most familiar and comfortable. The IDC also offers these engineers a number of hardware and software tools which enable them to collaborate more easily. Available hardware tools include twelve high-end Windows workstations and six ceiling-mounted video projectors, to enable team members to easily hold collaborative discussions on design issues. Various sets of software tools are installed on each IDC workstation, and the workstations are located within the facility so that disciplines who frequently work together using similar software packages can be situated at adjacent IDC locations, with each person using the most common tools for their area of expertise. Figure 1 shows the current IDC layout, including locations of projection screens and key software packages installed on the IDC computers. The discipline labels shown for each station indicate a typical distribution of assignments and workstations; however, each design team is free to decide the disciplines needed for their particular study and customize workstation assignments accordingly.

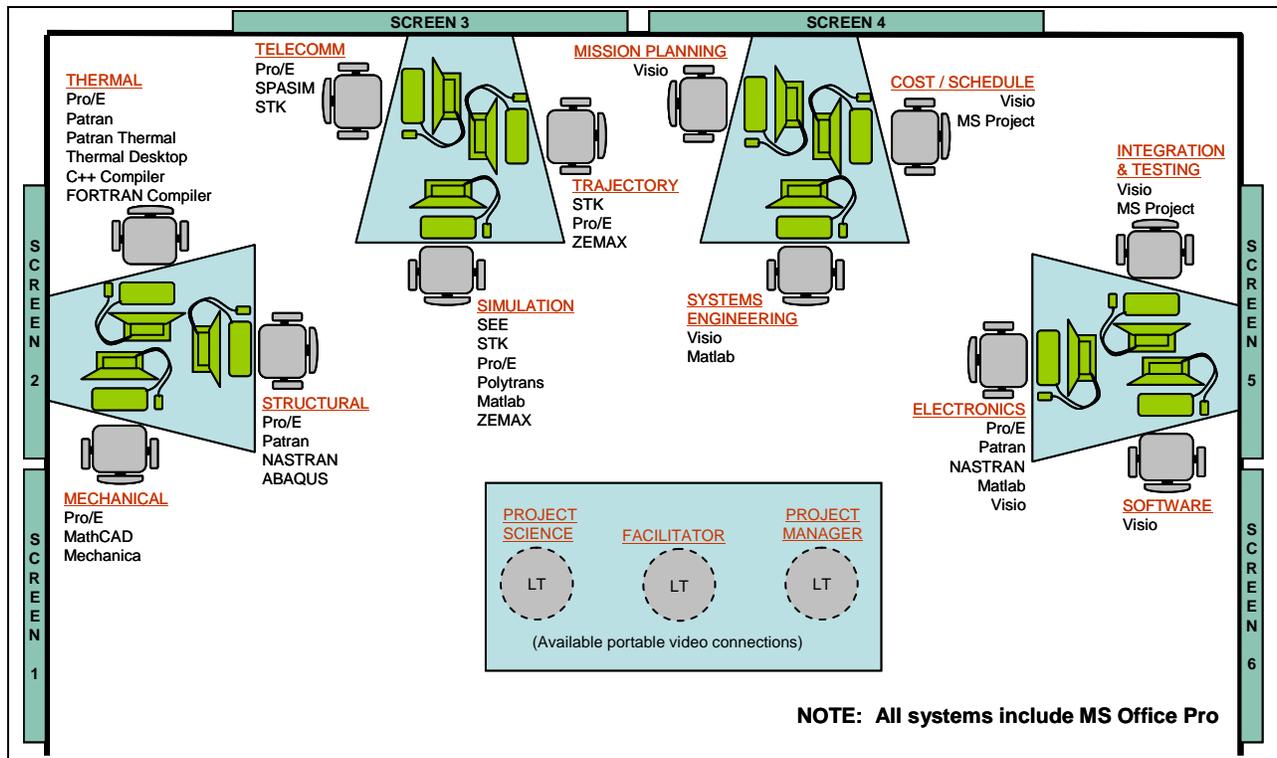


Figure 1: IDC layout showing typical discipline assignments.

Conceptually, the IDC is composed of three elements: Standard Tools, Tools for Knowledge Sharing, and IDC Personnel. These components are brought together in the IDC environment through the development of interfaces between many of the tools and through focused user training. The result is a powerful design center where teams of LaRC personnel can work together in a unique environment which allows them to produce highly robust, well-considered system designs in a very short time period, while maintaining an extremely high level of interaction and understanding between team members.

3.1 Standard Tools

The first goal of the IDC is to enable project teams to minimize the learning curve required to work in a CE environment, in order that they can quickly begin producing high-quality work products. It is our experience that engineers are reluctant to embrace a new tool or work procedure when they already have one with which they are familiar. Therefore, rather than bring engineers into an unfamiliar environment, where they will feel somewhat uncomfortable from the start, and introduce them to a set of CE-specific tools, we have chosen to maximize the use of standard tools that are already well known to LaRC engineers.

For instance, the LaRC standard Computer Aided Design (CAD) program is Pro/Engineer™, commonly referred to as Pro/E. While other CAD programs are certainly used at LaRC, most engineers have some level of experience and familiarity with Pro/E. Therefore, several IDC workstations have been installed with the latest version of Pro/E so that IDC users can use the CAD tool that they are most likely to have knowledge of. Similarly, industry standard software packages such as Microsoft Office, Matlab®, and Satellite Tool Kit™ (STK) are installed for IDC users who need them during CE sessions. In addition, a number of LaRC-developed tools have become important elements in the center's project design community, and these tools are also available within the IDC. SPASIM, a spacecraft simulation package, and SMALLSAT, an Excel-based conceptual spacecraft analysis tool, are widely used at LaRC and have therefore been installed and used in the IDC.

An integral part of the IDC's success is the range of highly powerful software tools offered to its users. One very important aspect of this array of available tools is that many of the key packages are not simply "number crunchers". Instead, the IDC makes extensive use of "physics-based" software tools in order to allow users to perform a more detailed analysis of the issues they are responsible for examining.

3.1.1 Physics-Based Tools

Many collaborative engineering centers use tools that provide "spreadsheet-level" knowledge of the system. For example, a thermal engineer might draw on empirical knowledge and past experience to determine that two cryocoolers would be needed for a certain system, and that they would have a certain mass and power usage. However, the LaRC IDC employs "physics-based" tools rather than spreadsheet-level design, back-of-the-envelope calculations, or top-level approximations. In this usage, "physics-based" means that the tools utilize 3D true geometry, and model or simulate the true physics of the problem. Since the IDC workstations are powerful high-end systems, a physics-based tool can be used to construct a true model of the system in question and solve for the discipline of interest. In this same example, the IDC thermal engineer would actually create a physical model of the system and analyze its performance with two cryocoolers. The disciplines for which this level of tools are used include thermal analysis, structural analysis, optical analysis, orbital and trajectory analysis, telecom and communication simulation, power management, electronics design, mechanical and motion design, and laser performance simulation.

A concern in using physics-based tools is time: the models may take too long to create, or the true physics-based solution will take too long to generate. However, using electronic transfer of model data between tools substantially lessens the model creation time. With modern tools and high-end computers,

the solution times can be reduced to less than one hour for many problems, which makes them tractable in the setting of an integrated design session.

There are several advantages inherent in using physics-based tools. First, it enables the use of a single process from concept to flight and operations. Since the tools are true geometry and true physics, they can be used at any level of design. This means that the work done on a preliminary design is not discarded or passed on via hard copy, but is actually used and refined at the next stage of design. Second, it ensures a higher degree of accuracy than sole dependence on empirical data and personal experience. Third, it facilitates the transfer of data from one tool to the next, since all are using the true geometry, timeline, etc.

3.2 Tools for Knowledge Sharing

Simply installing multiple copies of popular software does not make the IDC a CE facility. In order to facilitate the collaborative design process, the IDC must create a work environment in which engineers can easily share their knowledge and expertise. There are several tools specific to the IDC that aid in the process of sharing knowledge. The DICE software, provided by Jet Propulsion Laboratory, is a web-based projection control utility that allows every IDC user to direct the projection of IDC displays. Any participant who is on the network can turn on or off any projector, and can select any IDC computer to display on any screen. This gives the participants ultimate flexibility, in that they can post their own display to clarify something to others, or they can choose to post another discipline's display near themselves in order to examine someone else's work more closely. It also encourages focus on the work at hand, since anyone doing unrelated work can suddenly find themselves posted on every screen around the room.

A key component of the IDC is a shared drive containing the archives of all previous studies in the IDC, as well as several important files for use by multiple IDC users, such as the user's guide, the process document, and training files and templates. This shared drive is accessible from anywhere within the LaRC firewall, so participants can pre-load information valuable to the whole team before the start of the study. An important feature of the IDC is that the user's guide is accessible electronically from each station in the IDC, so that any participant can access current instructions easily. The user's guide is kept updated with the recommended procedures and tools in the IDC during and after each study. Another document of great value is the Detailed Discipline Interface Guide [8]. This contains the current best practices used in each engineering discipline, as well as the details in the optimum operation of each of the electronic interfaces between tools. As better processes are developed, this guide is updated, so that it is a continual living description of the recommended way to accomplish this work. As such, it is useful for all of LaRC and all of NASA, not just the IDC, because the interface methods developed are useful when people are working at their desktops as well as in the IDC.

One widely-used tool in any technical design is MS Excel. Engineers throughout the project team frequently use Excel for numerical processing and maintaining text-based data. The IDC allows users to share this data through IceMaker, a software tool that allows spreadsheet data to be shared using network communications [9]. This software links Excel spreadsheets from each discipline, allowing each person to see and track only the variables that are of interest to their discipline. Using IceMaker, any user can easily publish values for which he or she is responsible, so that they can be used by other team members, or request a needed parameter electronically so that another team member can publish it. When a published parameter is updated, the new value is immediately available to the entire team. This facilitates the summing of masses, powers and costs for each discipline, using the values generated by several other disciplines to determine the most accurate values. More important, the use of IceMaker ensures that there is only one version of each variable in use throughout the project team, and that each discipline is using current values. At any time, the entire state of the project can be saved off as an archive if a baseline is to be kept, or if two options are to be evaluated.

The IDC includes a video-conference system to allow outside organizations to be linked in, both visually and via audio. These outside organizations can also be granted network access to the project's Excel spreadsheets, the IDC shared drive, and even the projector control application, depending on the requirements of the type of study. Sidebar chats can be held using the installed instant messaging software.

Finally, a very simple but powerful tool is a Microsoft Word template document. This template is used whenever a project is going to produce a written report as part of their final product (which is most often the case). It has been found that when participants produce a report in Word, as opposed to slides in software like PowerPoint, the write-up has a much greater wealth of detail, such as more "what-if?" cases and trade-off results, and more of the basic information and assumptions underlying the work. A report created in Word also captures more of the caveats and ideas for the future. Typically, each team member is responsible for explaining his or her own area of responsibility in a separate Word document, and the individual discipline write-ups are merged into a single project report. In order to make everyone's documentation simple to integrate together, a template is used from which each discipline starts their write-up. The template contains the necessary styles and headings, and may even contain the sub-sections that are recommended for each discipline's write-up. Use of this template makes the job of the integrator of this work many orders of magnitude easier than if everyone uses their own format.

3.3 Development of New Tool Interfaces

An extremely beneficial aspect of the operation of a CE center is the creation of new tools, new interfaces, and new methods. Because the people in a design session are sitting "cheek-by-jowl", they can easily see the effect of their data transfer on the individual receiving it. If the data is transferred in a format that forces the recipient to do a lot of extra work, the data provider will be pressured to make alterations in their own process, in order to make the transfer smoother. Many enhancements to the current LaRC IDC process have been engendered in this way.

One of the first such enhancements occurred during the pilot study conducted in the IDC. The thermal engineer was using Thermal Desktop, a tool that was relatively new to the Center at that time. There was no existing method for easily capturing the mechanical design geometry from Pro/E and importing it into Thermal Desktop. Since LaRC analysts are accustomed to importing geometry (rather than manually creating geometry), the thermal engineer worked with other analysts to evaluate several methods for import of the geometry, in order to avoid manually entering a design geometry from drawing dimensions – an error-prone, tedious, and costly approach. When the engineers determined the best process for importing the geometry, it was documented in the IDC User's Guide so that future design teams could also use the same method. Since that time, the process has evolved, and now yields much smoother import of design geometry into the thermal tool.

In another instance, the project scientist was impressed by the variety of powerful graphical tools on display and in use in the IDC. Inspired by this, he asked for improvement of an existing tool that he had been using to predict laser performance and science instrument output, based on atmospheric conditions and spacecraft altitude. This tool had been in use, but was only text-based. In the course of two morning design sessions, this tool was refined and used to graphically predict the science impact due to various atmospheric effects and scenarios. An example of the graphical output of this tool is shown in Figure 2.

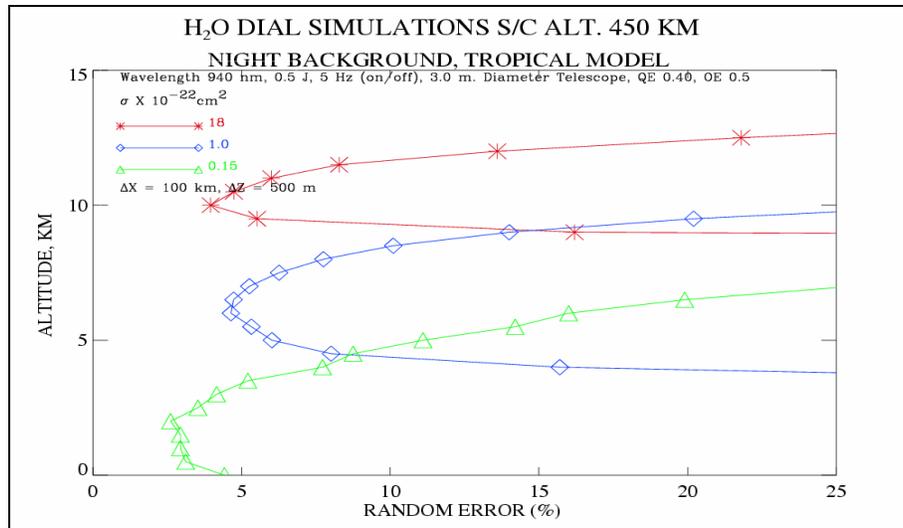


Figure 2. Example laser measurement error prediction.

Another interface was developed because of the need to transfer a highly detailed thermal distortion of a mirror to the optical analysis program. The entire sequence began by taking Thermal Desktop thermal results, mapping those to a NASTRAN mesh of the system and performing a thermal stress analysis to determine the deformations of the system. A program called SIGFIT was then used to produce a polynomial fit to the distorted shape (in this case, Zernike polynomials were used). SIGFIT then produced the input files for the optical code ZeMAX. As in all these tool interface developments, they were enabled because the personnel involved were working together in the same location, and could therefore conduct many rapid trials of solutions in a short period of time, with no delay in communication.

During the same study, the orbital analyst expressed a need to import the Pro/E-based geometry into STK in the same manner as other disciplines were able to import geometries into their tools. However, no defined method existed for performing such an import. After some collaborative research with other IDC analysts, a method was developed and documented that involved translating the Pro/E file into Lightwave format, through the use of a COTS program called Polytrans. This format could then be imported into STK for use in project orbital analysis and visualization.

One common thread in these interface developments is that they are time-consuming. The time involved to develop a new method is often the same as that necessary to use the old “brute force” method it is replacing (i.e. manually entering geometry, etc). However, as a method gains more use, it becomes more familiar and efficient, saving time for every user in the organization and facilitating further improvements in the process. Another common thread is that they must be documented to remain useful in the future, so that others can continue to use them.

3.4 IDC Personnel

While good tools and procedures are important, the primary factor in the success of any study performed in the IDC is the people who are tasked to work on it [10]. Specifically, a design team should consist of engineers who are experienced in the concepts of the discipline to which they are assigned, familiar with the tools necessary to perform their assigned tasks, and capable of working with others as part of a team. In addition, there are certain key design team leadership roles that must be performed as well, in order to maximize the team’s productivity. These key leadership roles include a customer representative, a project manager, and a design study facilitator.

3.4.1 Discipline engineers

Before starting a design study, IDC personnel meet with the project management requesting the study to determine what disciplines should be represented, and to assign individual personnel to each of the areas identified. While there are a number of CE facilities which employ a dedicated staff of engineers who can perform the duties for one or more disciplines, the LaRC IDC currently does not. Instead, IDC studies are manned by a combination of personnel from the project being studied and engineers and discipline experts with experience in both a particular discipline and the IDC environment. This allows LaRC to draw from a large pool of experts, and allows more LaRC engineers to become accustomed to using the CE approach to designing projects.

Projects requesting IDC studies typically have several engineers available who are already a part of the project team and have begun identifying and addressing project issues. Frequently, however, some engineering areas have not yet been addressed (often no one has even been assigned to these areas). Therefore, IDC personnel can help projects identify these areas and find experts who have participated in past IDC studies and can take part in the upcoming sessions. This ensures that design team members are familiar with the most current methods in their area of expertise, and have recent experience working on projects in their field.

3.4.2 Customer Representative

Direct participation of the customer is an important part of the IDC vision. In a non-CE environment, projects frequently experience difficulties in refining high-level project requirements into design decisions because of difficulty communicating effectively with the customer. Often, customers face numerous requests for their time and input from a variety of sources, and they simply cannot effectively respond to all of the telephone calls, emails, and conversations asking for information. In the IDC, the customer is strongly encouraged to attend and participate in the design sessions – as an advisor, instead of actively performing design work on an IDC workstation – so that project personnel can quickly and easily present them with issues to be resolved, possible solutions, trade-offs inherent in various choices, and so on. Customers often find that by having a number of brief conversations in the IDC, project engineers have significantly more guidance and more information, and are able to better meet the customer's needs quickly, while avoiding unnecessary effort on work outside the scope of the customer's requirements.

3.4.3 Project Manager

While the Customer Representative is able to advise a design team on project requirements and goals, it is important that design teams also have access to a Project Manager, in order that important technical decisions affecting the design and implementation of the project can be made quickly and decisively. For example, an electronics engineer may have identified a COTS product whose specifications meet many of the technical requirements of one component of the design, but is not capable of meeting some other requirements. At that point, the engineer may determine that he or she has a number of options: purchase the part and modify the design to compensate for the lower performance, purchase the part and design a method of augmenting its capabilities, or build a custom component. While the engineer can recommend one of these choices, the final decision needs to be made by the Project Manager. As with the Customer Representative, the Project Manager participates in the IDC study in an advisory position, giving guidance and responding to technical design questions, rather than as an active project engineer.

3.4.4 Design Team Facilitator

Finally, to maximize efficiency in IDC sessions, the activity should be monitored and, to some extent, controlled by a facilitator whose primary responsibility is to keep information flowing smoothly during the session. The role of facilitator in a CE environment is a unique one, requiring an individual who has experience in project design, a basic understanding of a large number of technical disciplines, good

leadership qualities, and very strong interpersonal skills. Typically, the facilitator for a given study is someone outside the project, in order that they can maintain an objective focus on making certain that the design team collaborates well, rather than on the design itself.

It is important to note that the facilitator is not responsible for making technical decisions for the project or leading engineers toward a particular approach or choice. The facilitator is responsible for ensuring that each design team member has quick access to the information that he or she needs in order to perform his or her duties, and that everyone is aware of any major issues that occur. The facilitator may need to direct a particular engineer to perform one analysis before another, so that another station can use the data generated, or instruct two disciplines to work together on a particular issue which affects them both. Or, he or she might alert the entire team to pause their current work so that important information can be shared with everyone, or persuade a team member to release preliminary information to the design team before that person is ready, so that other team members can begin working with the best currently-available data. In short, the facilitator serves as a “traffic cop” of sorts, making certain that information continues to flow effectively within the IDC and preventing “bottlenecks” in that information flow.

3.5 Training for Design Sessions

Training has proven to be a key element in achieving the greatest possible benefit from a concurrent design session. In the LaRC IDC, several types of training are used to ensure that everyone is at the same level of understanding. First, users are given a basic introduction to the concept of concurrent engineering, and the idea that design sessions are intended to be real-time working meetings. The benefits of this concept are enumerated, and the potential uses listed, so that participants can extrapolate potential benefits this approach could add to their other work. Next, the basics of sharing knowledge in the IDC are described. As each technique is described, each participant is encouraged to try them out in real-time at their own station. Participants are trained in how to map to the shared network drive, and the best way to name files, so that all work can be shared and archived most easily. The DICE projection control Web site is demonstrated, so that each person can turn the projectors on and off, and control which computer is displayed on what screen. Security and back-up procedures in the use of the computers are described. For participants that need to access files on their desktop PC in their office, procedures for file access and running a program remotely are explained. The software tool for sharing Excel spreadsheets, IceMaker, is described and demonstrated. To get participants comfortable with its use, dummy or real data is input and shared as a real-time exercise.

If one of the final products of the design session is documentation, participants are trained in the best ways to use Microsoft Word so that the writeup will go together smoothly at the end of the session. Training everyone in the use of styles, captions, auto-captioning figures, automatically cross-referencing figures and tables, and proper ways to format figures, not only save time in putting together the sections for the final combined writeup, but make each participant more efficient in their jobs for the future.

4.0 The Mission Simulation Lab

MiSL [11] is a VR-based lab focused on improving the efficiency of the payload design process by allowing project engineers to inspect and interact their designs in a full-scale 3D Virtual Environment (VE). This capability grants engineers a “real-world” understanding of issues that are not easily understood using CAD programs alone. One such example is the issue of spacing and clearance between payload components. While a CAD model can be easily measured to learn the distance between two components, it is not always clear whether that numerical distance will be sufficient to allow technicians the access they require.

For instance, the assembly procedure for an experiment may require mounting two boxes near each other on a structure, and then mating cables to one of them on a connector which faces the other. Certainly, the

CAD file can inform the engineer of the exact distance between the two boxes, but does that distance allow enough space for a technician to fit his or her hand and the cable in the gap? Will there be enough room to move his or her hand properly to securely mate the connector? Is there sufficient clearance for the cable to bend without causing stress on it (or the boxes)? These are questions that are not easily answered simply by knowing the dimensions of the space in question. In a 3D VE displaying a full-scale model of the assembly, the entire model appears to be sitting in the room for the engineers to examine. Users can lean closer to view spacing, just as they would if the model were a solid, completely constructed object available for examination, without concern over colliding with instrument components. They can walk around the model or kneel down to gain another viewpoint, and when their hands are modeled and tracked, can reach between the virtual components to gain greater understanding. Having this simulated real-world view of the project gives engineers the opportunity to assess issues like those listed above in an intuitive, easily-understood research environment. Figure 3 compares the same payload design viewed within Pro/E and after being imported into a MiSL VE. As evidenced in Figure 3(b), the presence of true-to-scale real-world items in the VE (i.e., tables, cabinets, etc.) provides the user considerable reference information— even in two dimensions – that a CAD representation cannot.

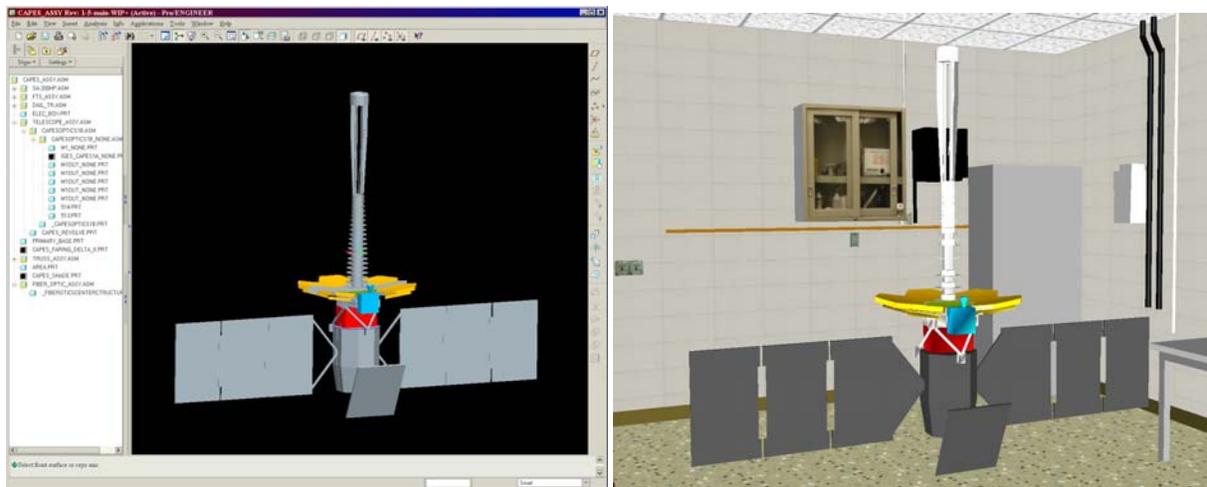


Figure 3: (a) CAD program view, and (b) full-scale VR view of a payload design.

4.1 MiSL Tools

MiSL utilizes a wide variety of integrated COTS tools in order to create realistic simulations. A high level of fidelity is necessary to ensure that MiSL input into design decisions is accurate and that training is as close to the actual environment as possible.

4.1.1 Pose Estimation and Immersion

In order to provide an immersive, simulated 3D virtual environment, six-dimensional (6D) information about the position and orientation (or pose) of the user's head, hands, feet, etc must be available. To this end, MiSL employs two tracking systems. The first is a HiBall™ optical tracker [12, 13] used for head tracking (i.e. six degrees-of-freedom (6 DOF) pose estimation of the user). It is attached atop a V8™ [14] head-mounted display (HMD) for full stereo immersion. Pose estimates for extremities (hands, feet, etc.) are estimated with a FASTRAK™ magnetic tracking system [15]. A Cyberglove™ [16] provides joint-angle measurements for both hands allowing for accurate display of hand and finger configuration, as shown in Figure 5. For applications where high-fidelity finger pose estimates are not required, we use a Pinch Glove™ [17] to detect contact between two or more fingers for gesture recognition and control of the VE.

4.1.2 Sensory Feedback

MiSL provides environmental sensory information to the user in several ways. The first is through the use of haptic feedback. When a user reaches out to touch a virtual object, the sense of presence [18] achieved is far greater when the actual object or some simulation device can be felt or provides resistance where expected (i.e., when the VE obeys the laws of physics). Currently, we do not employ force feedback (mechanism to provide resistance to fingers when grasping a virtual object, for ex.), having found that passive haptics [19] have thus far been sufficient in our applications. For an example of passive haptics in MiSL, see section 4.2.

Positional (aka 3D) sound is another feedback mechanism that people expect in the real world (i.e., we turn our heads in the direction of a sudden noise). AuSIM's GoldMiner™ [20] provides positional sound in MiSL allowing for a collaborator's voice to source from the location of the collaborator and motors to hum in proper position.

Research has shown that task performance and collaboration in virtual environments improves when users have a sense of self (i.e., can see their hands, feet, etc.) and when they can see other VE participants [21]. MiSL employs general avatars (representations of people in a VE), but is working to improve the fidelity of these models by using People Putty™ [22]. The goal is to scan in users' faces for rendering so that the avatar looks like the person it represents. When coupled with positional sound, the personalized avatar will mouth the words being spoken by the VE participant.

4.2 The CALIPSO Atmospheric Test Chamber (ATC)

One of the first projects supported in MiSL was the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) [23]. The project needed a suitable chamber to transport their instrument from its assembly site in Colorado to Vandenberg Air Force Base, in California. The chamber needed to maintain an airtight, clean environment to avoid payload contamination and damage. However, project engineers required a means to enter the clean environment to access payload launch locks, which had to be manually set for ground testing and launch.

The project had acquired a transportation chamber previously used by another project. In order to house the assembled CALIPSO instrument, project engineers designed an adapter (in Pro/E) which raised the height of this chamber and included access panels so that project personnel could enter and manipulate the launch locks. However, some team members were concerned that technicians would have insufficient clearance to enter through the access panels and reach the locks without bumping the payload. While the team could estimate the space available around the access panels, there was no way to definitively declare that this space was enough to ensure the safety of the payload. The CALIPSO Integration and Test Manager asked MiSL for assistance in determining whether the project should proceed with building this adapter.

The MiSL team began by acquiring the CAD models of both the CALIPSO instrument and the ATC adapter. Since these were the first CAD files used by MiSL, lab engineers developed a process for translating Pro/E models into OpenGL using NuGraf®, a COTS 3D rendering package. No CAD models were available of the existing transportation chamber, however. Instead, the MiSL team visited its storage location and took numerous physical measurements and photographs. Using this information, the MiSL team was able to create OpenGL code to draw the ATC in a VE, and combine it with the imported models of the CALIPSO payload and the adapter to create an environment in which the entire system could be experienced using VR. This environment was enhanced with the addition of passive haptic objects to simulate the sensation of being inside the enclosure. Figure 4(a) shows the passive haptic objects used for this simulation: a wooden frame on the floor to simulate the frame around the edge of the container, office partition panels to simulate the chamber walls, and a floor-mounted dowel to indicate to

the user when they made contact with the payload. Figure 4(b) shows a screen capture of the MiSL VE, with the CALIPSO payload surrounded by the adapter (the top of the transportation chamber is not yet visible in this scene).

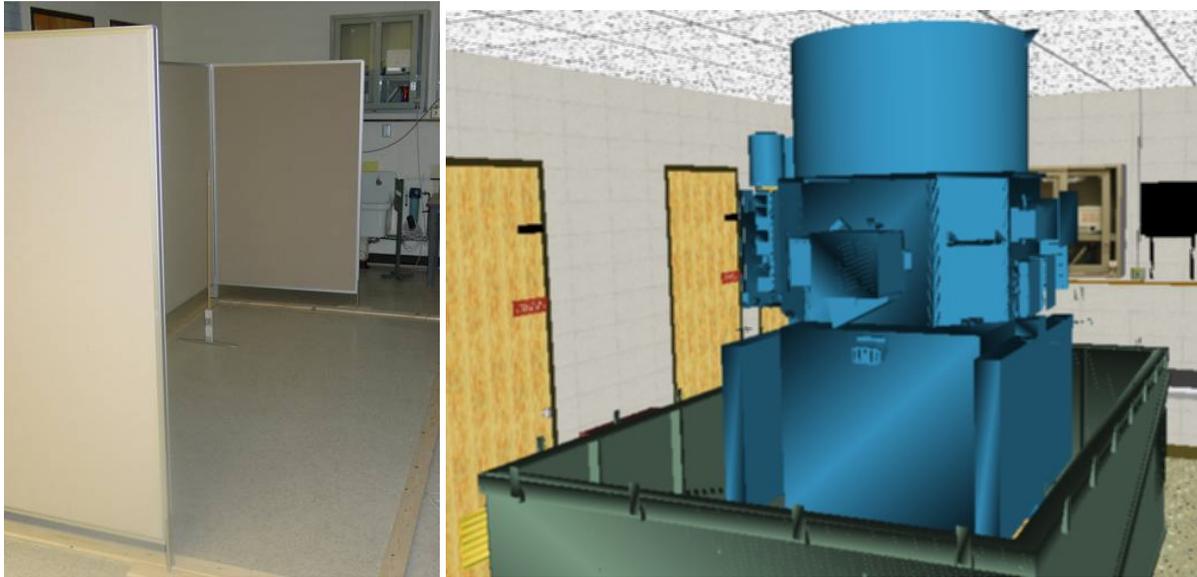


Figure 4: (a) Passive haptic objects in MiSL, and (b) the CALIPSO VE (including adapter).

Several CALIPSO engineers visited MiSL to examine this simulation and determine if with the adapter that had been designed would enable the team to have safe access to the transportation chamber, and therefore whether the chamber could be used to transport the payload. Figure 5 shows a MiSL technician standing within the simulated adapted enclosure and trying to reach the launch locks. After weeks of internal project debate, the decision was made within minutes of examining the VE that the proposed enclosure did not allow enough clearance. The CALIPSO team immediately began investigating other transportation options, saving them several weeks of work that would have been required to create and test the adapter, and also saving several thousand dollars that would have been spent on materials.



Figure 5: (a) A MiSL engineer attempts to reach the CALIPSO launch locks, and (b) the user's view.

The main goal of inserting MiSL into the design process is an overall reduction in total project design time. In order to minimize the short-term impact on project schedules, the MiSL team has spent considerable effort toward offering a short turnaround time by documenting procedures for importing CAD files and making those procedures as repeatable as possible. The time required to import CAD files for the CALIPSO task was considerable, since this was the first such import performed in MiSL. However, this process has now become common, and can be performed much quicker: in most circumstances, MiSL can now create a basic VE from most CAD files within one to four hours.

5.0 The IDSC

Since both the IDC and MiSL were created to improve the LaRC project design process, potential synergistic interaction between the two was obvious. One issue to be addressed in creating a simple interface between the two was simply distance: they were housed in separate buildings, making it inconvenient for users of either resource to transfer easily to the other. In addition, the original IDC site was too small to adequately support the necessary amount of equipment and personnel for large design studies. When the IDC was moved to a larger location, which was better suited to support the required infrastructure, this relocation offered the opportunity to make better use of the IDC-MiSL relationship as well by transferring MiSL to an adjacent setting. The combination of these two collocated advanced resources is the IDSC, LaRC's "meta-center" whose purpose is to systematically apply the latest design techniques and technologies in a concentrated effort to produce well-considered designs and high-quality work products using the collective experience of a powerful multidisciplinary team of experts.

In the IDSC, IDC-created CAD files can now be quickly imported into MiSL so that MiSL engineers can insert them into a new VE for the design team to examine. The close proximity of the two facilities allows IDC personnel to simply walk next door to view these simulations, and then return to their station without effort. This allows the IDC engineers to promptly modify their designs in response to items noted during the MiSL simulation. These modified CAD files can then be re-submitted to the MiSL team for the generation of new VEs, which the IDC engineers can revisit, and so on. Also, other IDC engineers can simultaneously update their own data and records to reflect the MiSL-inspired changes made by their colleagues.

5.1 Case Study: CAPES

The pilot study performed in the IDSC was the Combined Active and Passive Environmental Sounder (CAPES), a proposed instrument which combined a high-vertical-resolution lidar with a Fourier Transform Spectrometer (FTS) into a single instrument which can analyze several atmospheric components and climate change variables from an Earth-orbiting satellite. The project scientist began by explaining the goals and high-level requirements to the design team in the IDC. The design team then performed a one-week CE study, during which numerous project elements were proposed, discussed, and selected. The resulting work products from the CAPES study included: a mid-level payload design; a selected launch vehicle, launch site, and orbit plan; thermal, optical, and structural analyses of the instrument; ground station selections for data downlink; a detailed cost model; power, mass, and data rate requirements; basic operation modes and mission plans; and many other vital project planning elements. Each project team member also documented the procedures they followed during the session, the issues raised and solutions selected, and the methods used to perform their portion of the project design. These individual discipline reports were then combined into one IDC CAPES design report.

The payload shown in Figure 3 is the CAPES instrument design created during this IDC session, showing many key design elements created during the IDC session (including the gray solar panels, used to provide power, and the gray radiator which dissipates excess heat). The blue box shown is the FTS instrument, which needed to be stationed as close as possible to the focal point of the lidar's primary mirror. The yellow objects are moveable mirrored "petals", shown in their deployed position to form the

primary mirror. This mirror design was achieved after numerous discussions and trades in the IDC which would most likely have taken several months using the traditional design approach. The mirror was initially envisioned to be a single large mirror. However, after a launch vehicle was selected, the solid mirror was too large to fit within the launch vehicle's enclosure. The affected design team members immediately held trades with the customer to discuss, among other ideas, reducing mirror diameter, selecting a different launch vehicle, or sectioning the mirror into movable pieces which could fold back for launch and then deploy on orbit. The entire project team finally determined that the sectioned mirror would be the best compromise, and IDC engineers then performed a number of analyses in response to this decision:

- optical analysis to match the mirror petal shape to the optical requirements
- thermal analysis to discover mirror fluctuations during orbit
- structural analysis to determine how to minimize these fluctuations
- additional mass of the structural changes
- power and propellant requirements driven by the additional mass
- overall cost changes due to the changing structural and propellant numbers
- thermal requirements driven by the new power requirements

Obviously, this amount of design work and team interaction could take months in a “work-and-meet” environment. Instead, all of these items (and several others) were fully developed within the one-week IDC study.

Once the overall instrument design was determined, the IDC structural engineer delivered the CAD model to MiSL. The MiSL team then created a new VE, imported this model into it, and also incorporated models of a deployable sun shield the team had designed for the mirror assembly and a basic model of the launch vehicle's faring. Using these models, MiSL created a simulation which allowed CAPES team members to closely examine the instrument in 3D. The simulation also includes animation of the mirror petals moving from the stowed (launch) position to the open (deployed) position, so that users can view the on-orbit movement of these components. By adding the launch vehicle faring into the VE, users can also view the clearance between the faring and the stowed payload, as well as the difference between the faring diameter and the deployed mirror.

6.0 Future Work

While the IDSC facilities are versatile environments with numerous advanced capabilities, we have identified a number of extensions to the current capabilities that would offer users a still wider range of design functions and abilities.

6.1 Interacting with and Manipulating virtual objects

In order to provide effective training in MiSL, avatars and feedback are essential – but, in some cases, insufficient. In a lab or clean room, technicians and engineers use tools to accomplish the tasks of cable mating/demating, crimping, cable routing, etc. The types of tools used vary from task to task and are not limited to any specific subset of devices. This levies two requirements on MiSL. First, we must be able to track and accurately render tools, and second, the user should not be limited to a small selection of tools, but should be able to bring in any tools that he or she works with. This kind of capability is under development in a collaborative effort between LaRC's MiSL team and colleagues at the University of Florida's (UF) Virtual Experiences Research Group (VERG). Mixed environments [24, 25] allow for the incorporation of real objects with virtual ones so that users believe that they are actually performing, for example, an assembly verification task.

To extemporaneously incorporate real objects (e.g., tools), we create virtual representations of the required objects(s) or tool(s); track the real objects such that the corresponding virtual representations mimic the real object's motion and articulation; and then insert the virtual representations into the hybrid environment, such that they are active participant in simulations. Figure 6 shows the process for incorporating a tool into a virtual/hybrid environment and the resulting interaction. Figure panels represent the following:

1. A tool is scanned with the laser scanner.
2. The model resulting from one scan.
3. The final model after merging, hole filling, and smoothing algorithms.
4. Colored markers are affixed to the physical tool.
5. Control points and rotation axes are defined in software.
6. Vertices are assigned to control points and are shown rotating about the axis.
7. The user handles real objects while interacting with virtual models.
8. The user's view through the head mounted display.

Once this technique has been improved to the level of production quality, hybrid environments will provide a necessary link between the virtual environment and the real world.

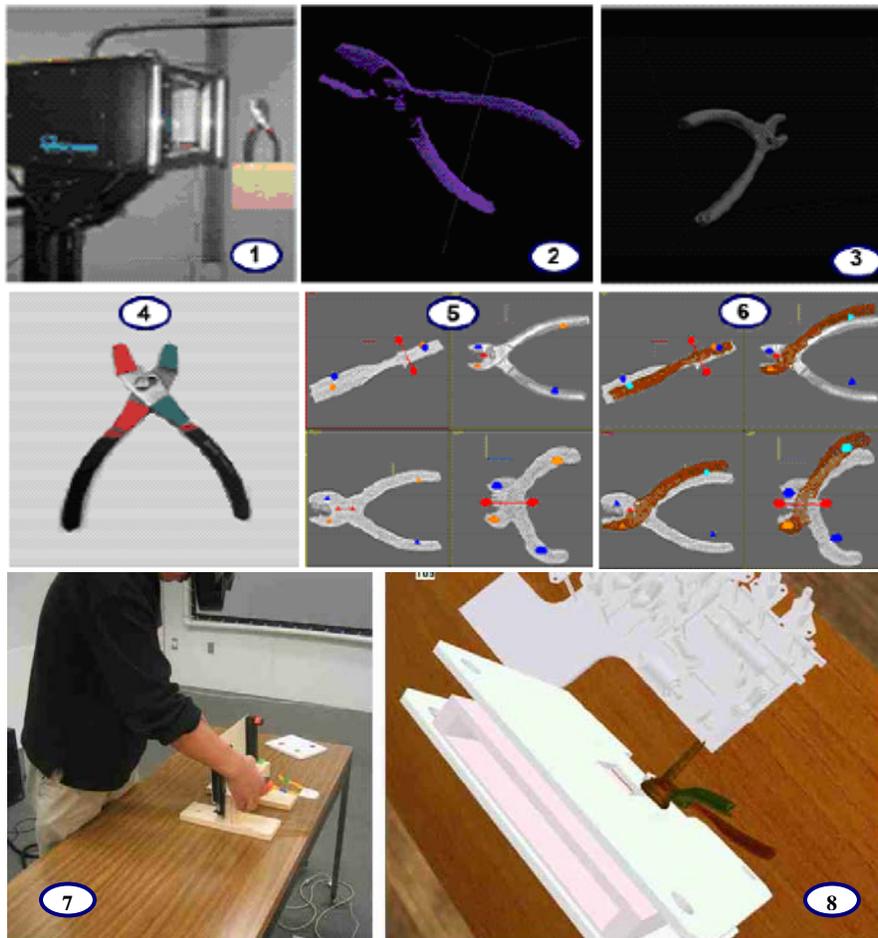


Figure 6. Integrating a tool into the hybrid environment (1-6). The user manipulates the pliers and picks up a connector in the physical space (7) and views the corresponding motion and articulation in the corresponding virtual models (8).

6.2 Collaboration between Multiple CE Centers

Since nearly all of the NASA centers (and several of our industry partners) now have CE facilities, a recent effort has been focused on combining the abilities of each to collaborate at the center level, pooling the combined resources of the facilities while allowing each center to focus on the areas that they are best qualified to develop. NASA's Jet Propulsion Laboratory (JPL) led the recent NASA Engineering Design Team (NEDT) study, in which a fictional large-scale mission was designed by personnel at eight separate geographic locations working simultaneously. Obviously, coordination of this effort was extremely challenging and required several team members. However, a larger issue was verifying that all of the centers could communicate with each other using voice, data, and video. The LaRC IDC was successfully able to collaborate with other centers using a variety of tools simultaneously:

- IceMaker to share spreadsheet data with other centers
- multiple online chat sessions in internet "conference rooms" on several topics
- multiple simultaneous voice conferences using JPL's Voice-over-IP (VOIP) systems
- viewing of remote presentations with web conferencing tools
- continuous audio and video teleconferences with all other sites

This multi-center study was a very good initial step toward making inter-center CE a routine part of the way that projects are designed when several sites work together.

7.0 Results

The IDSC facilities are changing the way that project designs are developed at LaRC. Several design teams have now employed the IDC for their projects, reporting vast improvements over more traditional design methods in many areas. IDC customers are frequently astounded at the level of detail of their project designs, and the amount of trade-offs performed and decision-making reflected in those designs, after spending a short amount of time in the IDC. Large amounts of important information can be generated in these studies in addition to instrument designs, including orbital analysis, launch vehicle selection, project cost analysis, data flow diagrams, and more. This wealth of important information can greatly reduce the time required for project design and, therefore, the cost.

MiSL has also played an important role in design analysis and visualization for LaRC projects. By employing the VR technology available in MiSL, project teams are able to closely examine their designs in a way that was never available to them before, allowing them to more easily recognize and correct potential design problems much earlier. The necessary modifications can then be quickly added to project designs, reducing overruns in both project cost and schedule.

One of the great challenges for any large team comes in identifying a way to optimize communication and project awareness. This aspect of the project is greatly improved in the IDSC, as all team members are encouraged to think like a system engineer, rather than focusing solely on one aspect of a project. Every IDSC user is welcome to offer input into project design decisions, and rationale for the final decisions is communicated to all. One product of this improved communication is higher overall team morale: by ensuring that no one is left "out of the loop" or uninformed, every team member is an important contributor to the end result, and everyone's contribution is highly valued.

By employing current technology in a collaborative environment, the IDSC has enabled LaRC teams to drastically reduce the time required to develop project designs, while ensuring that those designs are of the highest possible quality. Perhaps even more important, the experts who are responsible for creating them are able to work in an environment which enables them to do their best work and encourages them to reach beyond the boundaries that may have affected them in previous project design environments. The result is not only better designs, but also more productive and satisfied engineers.

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