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A Collaborative Design Environment to Support Multidisciplinary Conceptual Systems Design

Jan Osburg, Dimitri Mavris
Aerospace Systems Design Laboratory, Georgia Institute of Technology, Atlanta, GA 30332-0150

ABSTRACT

The Aerospace Systems Design Laboratory at the Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, has recently created the "Collaborative Design Environment" (CoDE), a next-generation design facility supporting efficient, rapid-turnaround conceptual design. The CoDE combines cost-effective, off-the-shelf information technology with advanced design methodologies and tools in a customized, user-centered physical layout that harnesses the power of creative design teams. The CoDE will enable researchers to develop, test and apply new approaches to conceptual design, and to improve modeling and simulation fidelity. It will also support sponsored design projects as well as student teams participating in national design competitions.

INTRODUCTION

The need for a better conceptual design process for aerospace systems has led to the creation of several dedicated design facilities in the US and abroad, such as the Jet Propulsion Laboratory's "Project Design Center" (PDC, [8]), the Aerospace Corporation's "Concept Design Center" (CDC; [1, 15]), and the European Space Agency's "Concurrent Design Facility" (CDF, [2, 4]). By physically collocating systems and discipline experts, along with their software tools, in a design "war room", communication within the design team is enhanced and the speed and quality of design iterations is increased.

Some of these facilities have been in operation for almost a decade. Their success, and the decreasing cost of equipping such centers, will make their more widespread adaptation in the near- to mid-term future likely. This, in turn, necessitates today's engineering graduates having to be experienced in working in such highly interactive, intense environments.

As an applied research institution training students in the art and science of multidisciplinary conceptual design of complex systems, the Aerospace Systems Design Laboratory (ASDL) at Georgia Tech has therefore launched its own such facility, the "Collaborative Design Environment" (CoDE).

The CoDE will enable researchers to develop, test and apply new approaches to conceptual design by utilizing high-fidelity modeling, simulation and analysis tools in a collaborative, team-centered environment. It will also support student teams participating in national graduate-level design competitions.

This paper outlines the design and features of the CoDE. To provide context, a brief overview of ASDL and the design facilities mentioned above is given first.

ORGANIZATIONAL ENVIRONMENT

The CoDE is operated by the Aerospace Systems Design Laboratory at Georgia Tech, which was founded in 1992 and is today one of a small number of academic/educational research laboratories in the country that focuses on the design of complex systems such as aerospace and naval vehicles. ASDL is led by one of the authors, Dr. Dimitri Mavris, who is supported by a professional research staff consisting of nearly 20 research engineers and post-doctoral fellows. The director and the research staff together direct and mentor over 140 graduate students who also serve as research assistants, along with about 30 undergraduate students.

Because ASDL focuses on systems-level design, all relevant disciplines, such as fluid mechanics, structures, propulsion, stability and controls, electrical and mechanical systems, etc., are represented through the research staff and student researchers. Most importantly, they are all collocated in one facility. Due to the proximity of the disciplinary expertise, ASDL provides a unique environment for research and education in design engineering and analysis methods. Since design is inherently a multidisciplinary activity, it is essential for a successful program that students and faculty have the opportunity to work closely together in teams, and that critical mass in all disciplines as well as at the systems level is achieved.

Recent research projects at ASDL that illustrate the type of research that will benefit from the availability of the CoDE include [13]:

- Development of a collaborative capability-based tradeoff environment for complex military system architectures
- Integrated Engineering Plant for future naval surface combatants
- Probabilistic conceptual design analysis of multi-stage launch vehicles
- Probabilistic design space exploration and Robust Design for torpedo systems
- Design methodology for revolutionary aerospace concepts
- Enhancing the design process for complex space systems through early integration of risk and variable-fidelity modeling
- Analysis methods for revolutionary aeropropulsion concepts
- Development of concepts for the supersonic aircraft sector
- Personal air vehicle sector analysis and tool development
- Development of a strategic business decision-making environment for commercial jet engine selection
- Implementation of a physics-based decision-making framework for evaluation of the multidisciplinary aircraft uncertainty

In addition, ASDL students are participating in numerous design competitions each year that focus on complex systems design [3]:

- AIAA Graduate Missile Design Competition
- RASC-AL Access-to-Space Vehicle Architecture Development Competition
- AIAA Undergraduate Engine Design Competition
- American Helicopter Society Graduate Student Design Competition
- AIAA Graduate Team Aircraft Design Competition
- Navy Tactical Surface-to-Surface Missile Design Competition
- AIAA Graduate Hypersonic Vehicle Design Competition

Many of these and other projects underway at ASDL share a common need to use a collaborative, interactive, rapid-turnaround environment to explore and assess the requirements, engineering design factors, and technologies which comprise the decision space, as well as model and simulate the systems under design. This demands new and innovative computational, visualization, and communication environments, in which designers and decision-makers can interact with each other and shape the design solutions towards the optimum.

STATE OF THE ART

Throughout the past decade, several organizations have developed dedicated design team facilities. These "war rooms" have been met with great success, reducing design iteration time and improving design results. Even though they differ in their individual implementations, the basic concept of each facility is to have all design team members located in the same room in order to facilitate communication among them, and to provide them with spreadsheet-based modeling and simulation tools that allow each discipline to be represented at a comparable level of fidelity.

JPL PDC

The Jet Propulsion Laboratory's "Project Design Center" played a pioneering role in the development of such facilities. Founded in 1994, it is among the best-known, and it has facilitated the conceptual design and review of over 500 future space exploration missions so far. Examples include [8]:

- Mars Sample Return
- Mars Science Laboratory
- Advanced Mars rovers and aircraft
- Jupiter and Neptune orbiters with probes
- Terrestrial Planet Finder

Figure 1 (top left) shows the floor plan of the PDC. Its characteristic layout feature is several parallel rows of computer desks oriented at a right angle to the projection/presentation area.

Aerospace Corporation CDC

The Aerospace Corporation assisted JPL in developing the PDC and subsequently, based on that experience, in 1997 created their own in-house design team center, dubbed "Concept Design Center" [1]. Its floor plan emphasizes face-to-face communication, with a meeting table in the center of the room and the experts' computer desks located around the periphery (cf. Figure 1, top right). This layout facilitates communication since it avoids experts having to talk across rows of computer monitors.

Examples for systems designed or analyzed at CDC include [9]:

- Space Based Infrared System Low
- Space Based Radar
- Global Multi-Mission Space Platform
- Air Force Satellite Control Network

ESTEC CDF

In 1998, the European Space Agency created a prototype of a dedicated design room, which over the course of a few years evolved into the full-fledged "Concurrent Design Facility". Similar in intent and concept to the PDC, its floor plan is centered on a customer table, with multiple projectors along one wall and desks for the design experts arranged in a U-shape (Figure 1, bottom).

It has hosted multiple successful design studies and workshops; among them [4]:

- Atmospheric Space Interactions Monitor
- Mars DemoLander 1
- International Microgravity Plasma Facility
- Soyuz crew transportation vehicle design enhacement
- Space Station Design Workshop [16]
- Eddington stellar physics and planet finder telescope

<u>Others</u>

The success of these initial design facilities has encouraged other organizations to follow suit. Published efforts include NASA Goddard's "Integrated Mission Design Center" [5] and the "Satellite Design Office" established by EADS-Astrium in Germany [9], as well as MIT's "Design Studio".

KEY FEATURES OF A NEXT-GENERATION DESIGN FACILITY

Before construction of the CoDE was begun, its key features were developed based on lessons learned from the operation of the design facilities outlined above, and on the authors' extensive experience with facilitating team-centered multidisciplinary design efforts like graduate aircraft design competitions [3] and international "Space Station Design Workshops" [10, 16].

The overall objective of dedicated design environments like the CoDE is to combine the creativity and experience of design team members with rapid-turnaround modeling, simulation and analysis tools, in an environment that fosters enhanced communication, reduced modeling errors, and shortened iteration and decision loops.

Additional requirements for the design environment in support of this objective are:

- Enhancing communication among the design team members
- Being intuitive/easy to use for novice participants, to reduce the learning curve in a high-turnover academic environment
- Enabling customization when needed to adapt to the requirements of specific design projects or tasks
- Keeping acquisition and maintenance cost within limits, both to enable the initial implementation in a cost-conscious academic environment and to encourage adoption by small/medium business

The following sections list the key features of a next generation design facility that were derived from these requirements.

OFF-THE-SHELF EQUIPMENT

Using as much off-the-shelf equipment as possible yields significant advantages: it reduces acquisition and maintenance cost, provides for more flexible and more economical operation, is easier to upgrade, and many users will already have a basic familiarity with it, which significantly reduces the learning curve.

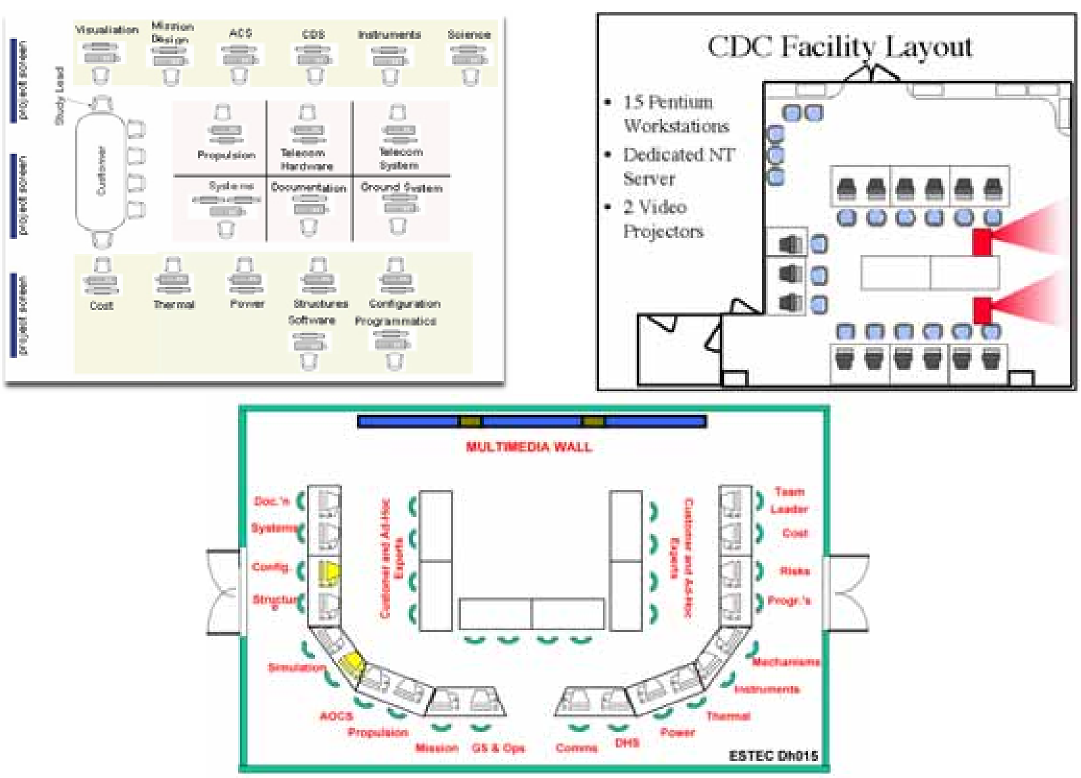


Figure 1: Floor plans of PDC (top left, [8]), CDC (top right, [1]) and CDF (bottom, [2])

FLEXIBLE MODULAR FLOORPLAN

Due to the varying size and organization of the design teams expected to use the design environment, the location of power and data connectors is designed to enable the rearrangement of desks and work areas. By making it easy to customize the floor plan, the design team is put in control of its environment. A standard configuration will be provided as a baseline.

CENTRAL MEETING TABLE

The main purpose of the design facility is to foster design team creativity and the pooling of expert knowledge by facilitating face-to-face communication, both verbal and non-verbal, among design team members. A clutter-free meeting table is therefore at the center of each work area. Computers are positioned around the periphery, within easy reach by design team members – who just need to swivel around in their chairs – but without blocking the view.

SMARTBOARD AND PROJECTORS

Exchange of knowledge and ideas is further facilitated by making several projectors and SmartBoards [14] available. This provides ample space for the simultaneous display of multiple items, from brainstorming lists, schedules and agendas, to simulation tools, spreadsheets and geometry displays. Sharing and rapidly iterating ideas, models, and analysis results facilitates joint work on tools and processes, for a truly collaborative design effort.

BREAKOUT AREAS

The overall design room can be divided into several autonomous work areas, primarily to allow for breakout activities by subteams. However, this also allows the design facility to be used by multiple independent design teams, or to accommodate several regular meetings. Breakout areas are fully equipped with computers, meeting tables, projectors and smartboards. They can quickly be joined together or separated as needed by means of curtains.

STANDARD MEETING SUPPORT EQUIPMENT

A variety of standard office equipment is provided to facilitate further efficient collaboration:

- A wireless teleconferencing phone (with remote microphones for use in the breakout areas), which also supports remote collaboration via WebEx
- A digital camera to capture analog media, and to document design process
- A printer/fax/scanner/copier multifunction unit
- A regular laserprinter
- A large-format plotter
- Flipcharts and regular whiteboards as backup

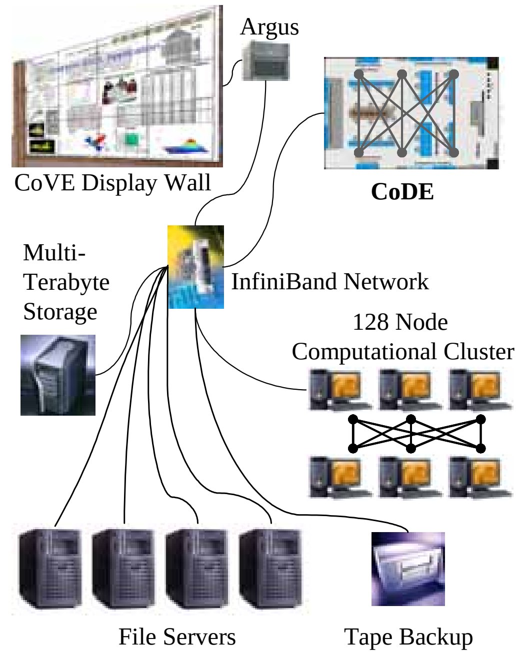


Figure 2: High-speed computational infrastructure

VOIP AND WEB VIDEOCONFERENCING

Every computer is equipped with a Voice-over-IP (VoIP) telephone connection and a webcam. Drivers for participation in WebEx sessions are installed as well. This avoids the cost for hardwired phones or videoconferencing equipment, while still enabling each designer to get in touch with remote experts, customers or reviewers.

LCD TOUCHPADS FOR SKETCHING

Communication among design teams usually includes hand sketches which can quickly help visualize concepts and communicate geometry-related or other non-verbal ideas. LCD touchpads enable a modern-day version of the “napkin sketch”. Particularly when combined with computer projection, they allow for the instantaneous sharing and electronic recording of this form of visual communication that is crucial to the design process.

COLLOCATED VISUALIZATION/REVIEW FACILITY

Exploring multi-dimensional design spaces is facilitated by the ability to display the relationships between multiple design variables and metrics simultaneously. This requires much higher resolution and size than what is usually available on a desktop screen or standard computer projector, and thus benefits from the availability of a high-resolution visualization screen.

COLLOCATED HIGH-PERFORMANCE COMPUTING

Physics-based, higher-fidelity modeling enables higher-fidelity design and better, earlier feasibility analysis. However, this comes at substantially higher computational cost, pushing computing times per iteration from fractions of seconds in case of spreadsheet-based approximative models to minutes or hours for high-fidelity codes. Furthermore, modern approaches to design require a larger number of such design iterations and tool executions.

Even though Moore's Law [12] has put unprecedented computing power on the desktops of designers, the availability of dedicated high-performance computing power, as represented by a multiprocessor cluster or supercomputer, will provide the design team with even more capability for high-fidelity and rapid-turnaround modeling, simulation and analysis.

DEDICATED DOCUMENTATION SPECIALIST

In addition to the hardware-related features described above, a key procedural element is also part of the concept: Design teams are encouraged to assign the role of documentation specialist, in addition to filling the usual slots for discipline experts, systems designers and project managers. This position is key to capturing design ideas and documenting the design process, thus acting as group memory for the design team. The documentation specialist is tasked with taking notes, capturing key screenshots, compiling design reports and presentations. This task is kept separate from the roles of design team leader/manager and chief engineer, and this team member can therefore concentrate on documentation.

In addition to the prerequisite writing and organizational skills, the design team member filling this position must also have a solid engineering background in order to be able to capture the essence of the highly dynamic design process.

DESIGN PROCESSES

As important as the physical environment and the computational infrastructure is the design process which the design team executes in that environment. ASDL has developed a cutting-edge set of methodologies and tools that enable rapid-turnaround, model-based design and analysis, as well as robust design, technology portfolio selection, and system-of-systems research [13].

Automation environments such as ModelCenter [11] and I-SIGHT [6] are used to tie together disciplinary tools, while statistical and graphics software like JMP [7] is used to visualize the design space. Such tools will allow design teams to go beyond the linked spreadsheet system models used in the first-generation design environments, and instead use physics-based codes and capability-based design tools.

These processes and tools will be available to users of the design facility, and will be adapted and expanded based on the capabilities provided by the facility and the needs of the design teams.

IMPLEMENTATION: ASDL'S COLLABORATIVE DESIGN ENVIRONMENT

The CoDE implements the features and concepts outlined in the previous chapter. It combines cost-effective, off-the-shelf information technology like high-speed desktop computers, meeting and visualization equipment with ASDL's unique design methodologies and tools in a customized, user-centered physical layout that harnesses the power of creative design teams. The goals driving this effort are to reduce design cycle time,

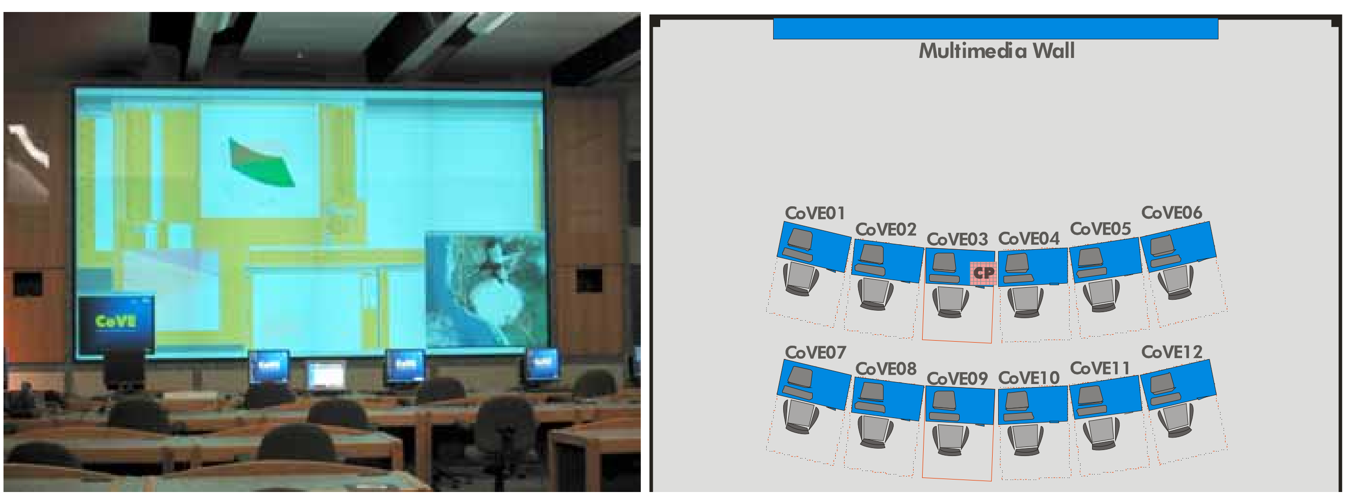


Figure 3: Collaborative Visualization Environment (CoVE) with display wall (left); CoVE floor plan (right)

facilitate reaching consensus among key players on a design team, and reduce or eliminate modeling discrepancies. CoDE floorplan and equipment are designed for reconfigurability to meet evolving requirements.

Even though the new facility was planned to accommodate the specific requirements of ASDL's researchers and students, its design was kept sufficiently generic in order to facilitate more widespread adoption.

COLLOCATED FACILITIES

The CoDE constitutes the third and final element in a trinity of dedicated design support facilities at ASDL. The other two facilities, CoVE and CoRe, are described here.

<u>CoVE</u>

The CoDE is located contiguous to Georgia Tech's unique "Collaborative Visualization Environment for Complex Systems Design" (CoVE).

The CoVE features a high-resolution display wall of approximately 9.4 Megapixels. The environment, shown in Figure 3, provides seating for up to 12 design team members, each with their own computers and local displays, and dozens of reviewers and observers. The CoVE includes IP-based video conferencing capabilities to connect with off-site participants.

The CoVE provides designers of complex systems with the capability to explore design spaces with hundreds of design parameters and incorporating multiple analyses. This collaborative environment allows the decision-makers to interact with the multiple domain experts and analysts, who may be located at different sites.

Past research and experience at ASDL have shown the importance of incorporating the use of physics-based analyses, probabilistic methods and simulation early into the design process. In order to fully utilize such tools in the CoVE, extensive computational resources (see below) as well as a facility supporting design and modeling activities are needed. The CoDE therefore significantly enhances the utility of the CoVE by providing the necessary resources to do near real-time collaborative design, and the CoVE adds significant design space exploration and visualization capabilities to the CoDE.

<u>CoRe</u>

CoDE users are also able to draw upon ASDL's high-performance computational infrastructure for real-time physics-based collaborative design and strategic decision-making. This massive-parallel "Computational Resource" (CoRe) consists of three major subsystems (Figure 2):

A computational cluster with 128 processors
A 7 Terabyte storage subsystem
An Infiniband high-speed network

This collocation makes the CoDE/CoVE/CoRe complex the only facility where a conceptual design "war room" is located right next door to a review center equipped with a high-resolution megascreen, and supported by a massive-parallel computing cluster, resulting in a unique national asset. This combination provides design teams with the ultimate in efficiency and support for every step of the conceptual design process, from the generation of initial ideas to high-fidelity modeling and simulation to critical review of capability-based designs by decision-makers.

FLOORPLAN

The CoDE floor plan (Figure 4) fosters design team interaction and integrates COTS process support tools like projectors and Smartboards. As outlined in the preceding chapter, a driving consideration was to give each design team member immediate access both to a computer and a work area shared with other team members where impromptu meetings and discussions as well as other non-computer-based elements of the design process can be accommodated. This resulted in the decision to place the meeting table in the center of each design area, and to position the computer desks around the periphery (but still within easy reach by the designers seated around the meeting table). This approach assures the efficient integration of design team creativity and computational support.

Another design driver was to provide each work area with both a standard computer projector and a Smartboard for easy exchange of ideas and communication among the design team.

One half of the CoDE room contains the main design team work area. It is dominated by a meeting table large enough to seat all design team members, with an outlying row of tables on each side equipped with computers. This work area is supported by a Smartboard, a projector and a regular whiteboard. This area was the first to be implemented, providing an initial operational capability as of May 2005.

Two "Breakout Areas" in the other half of the room provide additional interaction space for subteams tasked to tackle specific elements of a design. These areas can quickly be isolated if necessary by means of sound-attenuating curtain dividers.

Like the main work area, each breakout area has a layout that facilitates rapid transition from computer-based work to direct interaction among the team members, and is also equipped with its own projector and Smartboard. To enable comparing the effect of different spatial arrangements on design team collaboration, the main axes of each breakout area are

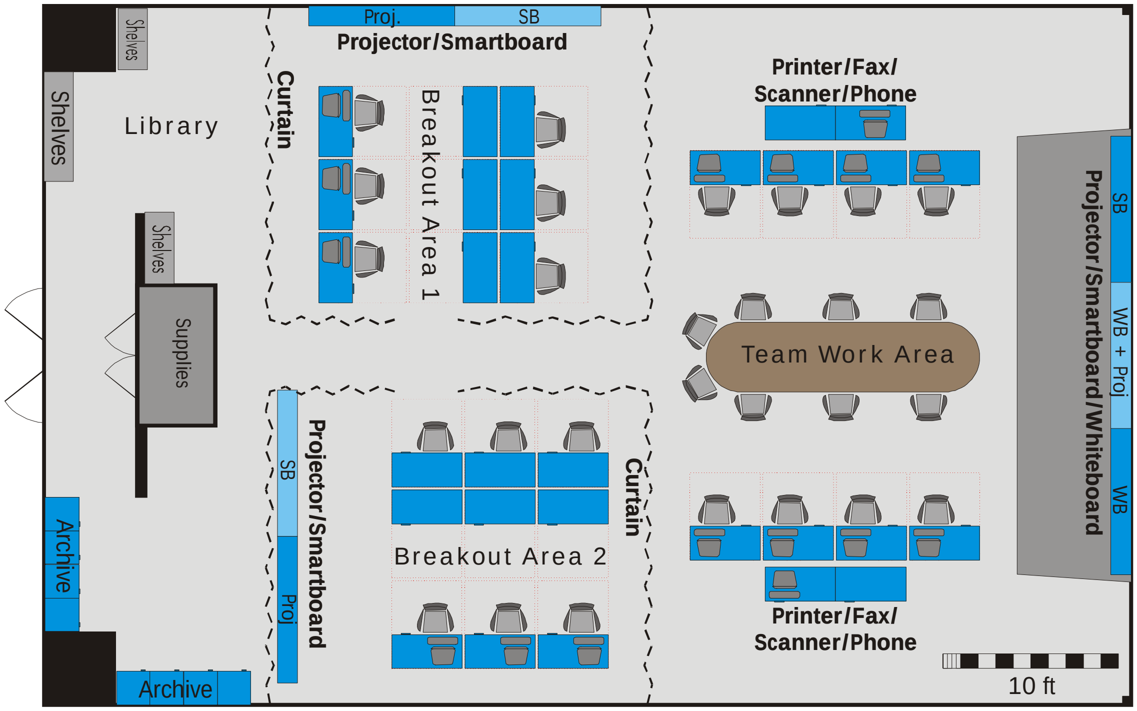


Figure 4: CoDE Floor Plan

oriented in different directions with respect to the main work area

A corner of the room is furnished as a library, where reference material, manuals, and other paper-based information supporting design teams using the CoDE can be kept close at hand. Another corner contains filing cabinets to archive documentation for each design project. Two side areas contain printers, multifunction fax/scanners, cordless and teleconferencing phones and a large-format plotter.

Network and power connections to the individual work areas are provided via a grid of floor-mounted receptacles and LAN jacks.

The flexibility designed into the floor plan elements allows for reconfiguration to model other design centers (Figure 5) or to explore alternative layouts.

<u>Equipment</u>

To rapidly provide an initial operational capability, the following major equipment has been installed as of June 2005 (cf. Figure 6):

8 high-performance PCs running Windows XP
1 multifunction laser printer/scanner/fax
1 high-speed laser printer
2 SmartBoards
4 computer projectors
1 high-resolution digital SLR camera
1 teleconferencing phone

Additional computers, projectors and SmartBoards, as well as the large-format printer and LCD touchpads, will be added in the near future as funding becomes available.

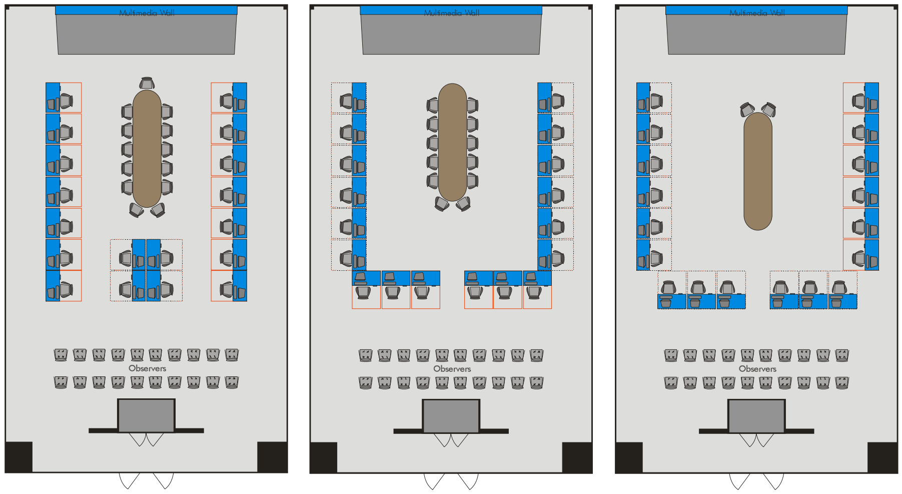
<u>Initial Applications</u>

The first use of the CoDE will be by a team designing an unmanned, morphing, hypersonic combat air vehicle as part of ASDL's sponsored research. This challenging project will put the design team as well as the design facility to its initial test. The default processes and tools to be used in the CoDE will be determined in close collaboration with this initial design team.

In the fall, the CoDE will also begin to support the multiple graduate student teams that Georgia Tech fields in national design competitions each year. This will provide students with first-hand experience in a cutting-edge design environment as an integral part of their academic training, and at the same time enable them to improve the quality and hence increase the already significant competitive success of their designs. Concurrently, the frequent design competitions will also provide ASDL researchers with a large pool of potential volunteers to test and develop new design approaches and tools.

CONCLUSIONS

The Aerospace Systems Design Laboratory at Georgia Tech has launched a next-generation collaborative



cf. JPL "Project Design Center"

cf. ESA "Concurrent Design Facility

cf. Aerospace Corporation "Concept Design Center"

Figure 5: Modeling floor plan schemes of other design facilities

design facility, the "Collaborative Design Environment" (CoDE). The CoDE will enable researchers to develop, test and apply new approaches to conceptual design by utilizing high-fidelity modeling, simulation and analysis tools in a collaborative, team-centered environment. It will also support student teams participating in national graduate design competitions.

This paper outlined the features and initial implementation of the CoDE. Future reports will document the process used by its design teams and the lessons learned by solving real-world problems in this unique environment.

ACKNOWLEDGMENTS

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Figure 6: CoDE Initial Operational Capability as of July 2005

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ASDL: Aerospace Systems Design Laboratory

CDF: Conceptual Design Facility

CoDE: Collaborative Design Environment

CoRe: Computational Resource

COTS: Commercial-off-the-shelf

CoVE: Collaborative Visualization Environment

ESA: European Space Agency

IP: Internet Protocol

JPL: Jet Propulsion Laboratory

PDC: Project Design Center