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Review

Approaches to design collaboration research

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Abstract

This survey of architectural design collaboration identifies and categorizes strong research from the past 10 years. It starts by describing how the research ranges in focus, scale, and structure, then clarifies how different projects fit in a continuum from conceptual theory to pragmatic application. It explains how conceptual frameworks and standards enable interdisciplinary exchange by envisioning and structuring interaction. It then highlights specific interaction studies and compares methods for analyzing how media affects teamwork. The paper continues by explaining the promise of innovations, such as tangible interfaces and interactive artwork, and concludes by identifying areas for further development.

Keywords: Design collaboration; Human–computer interaction; Groupwork; Computer-supported cooperative design

1. Introduction

Facilitating group design is a complicated operation. Defining the tasks involved, clarifying the social processes and encoding the processes are critical to developing effective tools. Collaboration tools facilitate teamwork by promoting communication and by consolidating project information and making it accessible. By helping teams organize and clarify roles, tasks, and scheduling, they can increase efficiency. They can enable interdisciplinary work by illustrating specialized terminology or by mediating between different building models.

How collaboration researchers approach these tasks depends on how they envision the design process and how they see the computer's role. As a result, research projects vary in focus, scope, and structure. With these different outlooks, the projects fall within different parts of the research and development pipeline. This survey of recent conference papers in architectural design collaboration highlights achievements and reveals deficiencies.

2. Ways to approach collaboration

What do collaboration researchers see as the *focus* of their investigation? Many focus on how software can produce more useful artifacts for an interdisciplinary design team. This means looking carefully at how data can convey information between group members and considering issues such as file formats, data organization, and information flow. For example, the commercial software developers' International Alliance for Interoperability (IAI) has set up Industry Foundation Classes (IFC) so that all building project

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information is vendor-independent [1]. By contrast, other researchers start from the human side, looking at how people think, how groups work together, or how they can work with computers. The social science view assumes that individual motivations or social hierarchies and interactions should drive the data structures or programs that support them. For example, from observing teams, Sonnenwald [2] has defined key positions of intragroup stars, mentors, sponsors, etc. who play complementary roles in successful groupwork. Identifying role types and interaction is a necessary step towards tailored tools. For digitally mediated interaction, computer interfaces play a major part in how people relate to each other. When researchers choose to work on immersive environments or mobile tools, they focus on how the equipment changes interaction.

In refining how software is applied to specific activities, the *scope* of the project shapes findings. The complexity of the experiment, as in number of data types, phases of design, and number of collaborators, determines the kind of information that is discovered. Case studies of professional or educational situations allow unexpected factors to emerge, but do not provide definitive findings. Controlled experiments let us understand critical factors by artificially limiting variables to create rigorous data. In the latter case, the work is created to be measured, whereas in the former case, measurement or observation is secondary to the work.

The scope of the project is related to how much *structure* is imposed. Smaller teams and simpler projects require less-structured communication. For example, an e-mail listserv that broadcasts messages to all can work for a small group or a less-active medium-size group. For a larger team, project communication needs to be sorted, tagged, and filtered by information type, topic, ownership, and viewing permissions. In a similar manner, more complex graphical data requires hierarchical or object-oriented building models.

3. Types of projects

Compared to other fields, architectural research methods vary quite widely in procedures and execution. Projects fall along a development spectrum from abstract concept through schematic implementation to detailed application and testing. Academic projects tend to remain at a proof of concept stage, while the commercial efforts often refine an interface for the market, relying on established technical concepts. The latter is illustrated by commercial collaboration services, or Architectural/Engineering/Construction (AEC) project extranets, that have chosen to focus on the technically simple electronic paper trail: online document organization and access supplemented by communication and scheduling tools. By tailoring document markup and tracking systems to particular AEC interactions [CAD drawings, requests for information (RFIs), submittals, punchlists, and logs], companies such as E-builder's TeamBuilder, Bricsnet Project Center, and Autodesk's Buzzsaw.com have sought to increase efficiency and reduce administrative costs. The failure of many extranet firms is due more to the conservative nature of the building industry than to the technical problems with the software. AEC firms were reluctant to entrust project data to systems with untested reliability, security, and sustainability [3].

Examining three categories of projects can highlight progress and further possibilities: conceptual frameworks, interaction studies, and new interfaces.

3.1. Conceptual frameworks

Visioning papers explain the mechanisms and future of the AEC collaboration process. They consolidate, analyze, and extrapolate from existing information, putting it into conceptual and societal frameworks. They are most effective when they support visionary speculations with evidence in innovative pilot projects. In the early 1990s, Mitchell [4] projected how urban life and design practice would be changed by computer networks. By seeding the idea at a fortuitous moment, he influenced designers' adoption of networked teamwork. Tzonis [5] reviews the history of design collaboration and explains the challenge of interdisciplinary communication as the need to overcome different mindsets and vocabularies. He proposes "bridgeheads" that clarify meanings and values in disagreements through translations or new languages, noting how his students' projects are attempting to create them.

Researchers addressing the big picture can choose to create a comprehensive AEC model that recognizes inherent complexity, work on the whole process in abstracted simplicity, or select part of the process for examination.

The comprehensive systems recognize the specific identity of building systems and components and define data categories so that their roles and relationships can be facilitated. For example, in the work for collaborative design learning, Tuncer et al. [6] define categories of building information for the Web so that searches for information can be more intelligent. Placing information about a window mullion in the context of glazing systems and wall apertures allows gathering of related information. Khemlani and Kelay address how walls represented as split edges of cells can accommodate both readings of spaces and edges. This allows the same building data to be evaluated in terms of performance measures from many disciplines (space adjacency, circulation efficiency, amount of wall, etc.) While the many categories in these projects (and the IAI's IFC, ConDocs, AIA Layer standards, and architectural CAD systems[1]) recognize the function and relationships of elements, they constrain the definition of a building. They can offer more comprehensive views of a building project than more generic geometric descriptions. Consequently, the systems can be burdensome to learn and overly detailed for simple projects.

A different tactic is to abstract the complex mechanisms of the AEC collaboration process and distill them into succinct diagrams and descriptions. Huang [8] examines information workflow in architectural offices and then proposes how industrial design optimization could be applied to them. His papers describe clear paradigms by generalizing and simplifying many cases. In them, he clarifies the design process mechanism and provides an approach for improvement rather than development specifics.

Modeling data constructs, standards, or software specifications can facilitate interdisciplinary projects. Cohen explains that standards can help temporary alliances become productive quickly, in the way that medical emergency teams do. Because they can rely on established procedures, doctors, nurses, and technicians who are total strangers can work together effectively [9]. Kiviniemi explains that standards are particularly relevant when considering the whole life cycle of a building, rather than just its design and construction phase. Including facilities management and maintenance considerations in building collaboration tools provides a much longer period for amortizing expenses and increases the potential for efficiencies [10]. Junge et al.'s [11] VEGA project addresses the need for standards by establishing how different disciplines' data can be interchanged through communicating layers. VEGA's domain-specific applications depend on an interactive translator that gives and takes information from a database. This type of ambitious project requires a large development team and a long implementation time to generate usable results, making it risky in a time of quickly changing technology.

3.2. Interaction studies: how media works with social organization

3.2.1. Comparing media: text and audio and video

In contrast to large-scale conceptual models, studies of social interaction are selective in scope and content. They often set up scenarios for testing how prototype equipment affects social relationships. The projects relate to other Computer Supported Cooperative Work (CSCW) research and benefit from interdisciplinary thinking.

Maher has led a number of research projects exploring the possibilities of shaping online communities from early studies of text-based Multi-User Dungeons (MUDs) and Multi-User Dungeons Object-Oriented (MOOs) [12] with Cicognani. Her book on Virtual Design Studios explains the technology required for remote joint projects and the kinds of interaction enabled. She used the International Journal of Design Computing's DCNet'98 conference to involve participants testing the robustness of 3D browser plug-ins for accessing live presentations [13].

Maher and Kvan have compared how specific media fosters or constrains design tasks, trying to understand how an individual responds to a mediated interaction scenario. Maher's group has set up controlled tests to compare, for example, how individuals rely on audio, video, and text channels for conveying information [14]. Wong and Kvan have found that responsive audio and interactive text are more important than videos on the faces of the partners [15].

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[1] For a discussion of using functional categories for architectural models, see Ref. [7].

Switching in between application sharing and picture-in-picture face video can take focus away from the task at hand.

3.2.2. Protocol analysis

Understanding group interaction requires protocol analysis, that is, tracking, examining, and summarizing the activity. Protocol analysis projects define categories of verbal or graphic acts, create mapping schemes, apply them to small group design scenarios, and explain what the mapping reveals. The Design Studies journal regularly publishes collaboration papers from environmental and industrial design that show how to map speech acts or graphic gestures to operative categories (see work by Cross, Goldschmidt, and Gero for example). The projects address one or more of the following: devising ways for individuals to interact, trying a new tracking scheme (categorizing and graphing the operations), and understanding the mechanism of the tracked design interaction. Looking at the journal's annual best papers gives an overview of this specialization.[2]

Several projects provide insight into group dynamics by tracking interaction using video or 3D graphics. The visuals summarize interaction to date for both participants and observers.

3.2.3. Tracking interaction with graphics: ETH

The book *Bits and Spaces* edited by Engeli covers a spectrum of the ETH CAAD group's experiments in digital media as a vehicle for interaction. The group, led first by Schmitt and then Engeli, has experimented in how group dynamics can be orchestrated and automatically graphed. For example, in the influential PhaseX project, a teaching team talented in programming and aesthetics provided interactive Web pages so their students could build off each other's projects. Using different themes that exercise specific software applications, the assignments ask the students to design geometric models that are uploaded and shared on through the Web. The Web interface helped students to view each other's projects and download them as a basis for the next transformation. The stronger teaching exercises shown in *Bits and Spaces* imbue spaces with meaning either through strong themes such as identity or by integrating text into graphic compositions.

Alternative views through the database of design schemes provide different entry points for understanding. The PhaseX Website showed each project's progeny and parents as individual images (inworld) and as a color-coded genetic tree (outworld). The data mapping builds on the Muriel Cooper's Visible Language Workshop at MIT's Media Lab, looking at how information can be mapped onto 3D space. By locating related graphical submissions close together, the authors develop a context of adjacencies and juxtapositions.

3.2.4. Tracking interaction with graphics: Kyoto VDS

Similar innovation is seen in Yamaguchi's alternate mappings of Virtual Design Studio interactions. They condensed the VDS interaction into a partnership-based "Tug of War" chart or time-based charts. In the Tug of War chart, each of three participants was assigned an X-, Y-, or Z-axis, and then each project was located according to the partners involved and the degree of collaboration. Two kinds of time-based charts show the amount of participation on any given day by organizing design submittal icons, thumbnails, and feedback markers. Graphs of team interaction provide insight at a glance into the kind of participation and the rhythm of the project contributions.

3.2.5. Tracking interaction with video awareness

An alternative to projects facilitating and tracking design data exchange is the presence awareness projects. Their goal is to provide possibilities of casual interaction by letting people share peripheral aspects of each other's working life. Following work with video walls done at Xerox PARC [17], experiments have looked at using transferred ambient sound or desktop glimpses [18] to increase peripheral consciousness and perhaps stimulate more intentional interaction. To convey personal behavior while providing privacy, some projects allow participants to choose the visibility of their activities or signal openness to social interaction.

3.2.6. Video for physical/virtual hybrids

Intentional versus background video collaboration projects are based on the belief that human expression and nonverbal skills are more important than the format, artifacts, or medium of design. By capturing

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[2] For a range of approaches, see Ref. [16].

spontaneous expressions and gestures, audio and video can reveal motivations for and responses to design proposals. Environmentally sized video walls for educational design collaborations allow for simultaneous videoconference, data presentation, and data markup. Guillermo Vasquez de Velasco of Texas A&M and Renate Fruchter of Stanford are both involved with setting up and testing these facilities. The Stanford Center for Integrated Facility Engineering (CIFE) lab has set up a wall of three rear-projection screens with sensors to allow gestural mouse control that has been used conducting interdisciplinary AEC classes and demonstration projects. Artistic video experiments play with the boundary between virtual and physical space. For example, Lonsway and Anders are exploring the theoretical implications of having a projected virtual person imposing onto their real space, in a method akin to event media walls.

3.2.7. Tracking interaction

Some projects preserve a degree of privacy through abstraction. For example, Gavin's Theatre of Work system creates a 3D environment according to how a shareware system is used by a team [19]. To reveal invisible work relationships, the project maps interaction between individuals onto a 3D world. Through the use of Hillier's Space Syntax analysis, it then suggests how adjacencies could be optimized. Another project that uses a video camera for awareness abstracts the output to preserve privacy. To track the activity of elder residents, video is blurred or down-sampled into a very coarse array of pixels to allow monitoring of health problems and accidents while minimizing intrusion [20].

Many awareness projects, like other CSCW or virtual community projects, do not deal specifically with the design process, but have findings that are important for AEC collaborations. For example, Kim's [21] explanation of how structured roles, events, and subniches are critical for a thriving community holds true for all platforms, even though they were derived from studying low-tech MUDs and MOOs.

3.2.8. Case studies of groupwork in action

Studying collaboration behavior in architectural education and practice complements technological development. Studies analyzing design communication need reliable, robust software to examine subtle aspects of design interaction. Some projects make an argument for accessible tools, explaining that tools like telephone and e-mail facilitate even the most sophisticated discussions, while visionary prototypes often show more future potential rather than immediate pragmatic solutions.

Since the first Virtual Design Studio experiments, schools have used the Internet for testing technology and observing pedagogical interaction.[3] Many schools have facilitated remote interaction with peer institutions and expert professionals using such devices such as remote critics on a videoconferencing cart and remote rapid prototyping. For overviews of academic collaboration projects, see Dave and Danahy's [23] and Craig and Zimring's [24] reviews of precedents as a context for their own efforts. Educational projects provide the opportunity to manipulate the tasks, team structure, and technology in ways that are impossible in practice. Noteworthy international projects have been run by Kvan, Morozumi, Wojtowicz, Andia, and Vasquez.

Architectural collaboration would benefit from detailed ethnographic studies that have been done more frequently of professional engineering offices [25]. Results of these fly-on-the wall observations can provide illuminating results. For example, Espinosa et al. [26] found the increased delegation (more specialization) among team members that collaboration systems may lead to poorer decision making because fewer team members have overlapping views of relevant information.

Partnerships between schools and firms give practicing professionals conceptual ideas while involving students and faculty as participants and observers in real projects. For example, Fischer has developed his "4D" animations of the building process partly through these partnerships. The 4D system facilitates construction sequencing and helps identify scheduling bottlenecks by linking frames of an animated 3D building model to a construction schedule. Design and construction professionals join students in interactively examining stages of real projects, turning on and off layers to see conflicts between specific disciplines and site access availability. They use a triple

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[3] For initial ideas, see Ref. [22].

wide computer projection screen for videoconferencing while sharing project visualizations.

3.3. New interfaces for interaction

3.3.1. 3D collaborative virtual environments (desktop)

New user interfaces are important for collaboration because they increase the ways that people can relate to each other. Rather than accept conventions for communication, the best research projects explore new metaphors through new modes or artifacts of communication. For example, the first online building projects made a new kind of urban design possible. Fuchs and Martinico [27] created procedures and standards so that designers from any location could add 3D CAD buildings to shape a new urban landscape. This was echoed by Websites such as 3D AlphaWorld that encouraged users to build territories as part of online communities. Soon afterwards, Caneparo's labs [28] each developed 3D systems with avatars and text-based chat to support interaction between multiple users. Each created robust environments and characters, one with an Italian classical flavor and the other with charming Japanese characters.

More recent innovations in VRML quality have come from Japan. Lee and Iki [29] demonstrate a customized interface to allow for the interactive viewing and editing of animated windmills. The project allows contributors to simulate different styles of windmills and different kinds of wind in evaluating urban design possibilities. Fukuda et al.'s [30] project integrates lighting simulation into VRML modeling. By streamlining how radiosity renderings are brought into VRML, and by developing special night-lighting effects, they bring up the quality of VRML simulations so that they are useful for sophisticated aesthetic judgments. Both groups show how their own proprietary software and seemingly basic tools like Quicktime VR and VRML can be crafted into visually stunning graphics to support public participation in urban design.

Rather than mimicking the built environment or following literal metaphors, Gu and Maher are exploring how virtual worlds can dynamically adapt to participants' interest. The proposed environment would reflect behaviors negotiated between user-centered agents and place-centered agents. This would allow visitors to their virtual museum to collaborative with the artists shaping the exhibition [31].

3.3.2. Sketch and gestural input

University of Washington's Design Machine Group (DMG) has looked at how to make the input, annotation, and editing of 3D models be more natural. By parsing down a designer's basic actions, they can map a slim set of sketch strokes or hand shapes to essential form-making operations. At CAAD Futures 2001, the group presented Space Pen [32] for 2D markup of VRML models and VR Sketchpad for sketched-based VRML model generation [33]. The latter uses the Electronic Cocktail Napkin's recognition of hand-drawn symbols to trigger wall generation and symbol insertion.

Recent DMG work has looked at gestures and physical interfaces. A video camera captures the shape of a gloved hand against a contrasting background and derives depth from the hand size [34]. These computer interface innovations facilitate person-to-person interaction around server-based geometric models.

3.3.3. Physical interfaces

Ishii has been working on collaboration since his early Clearboard video projects that allowed drawing partners to face each other, look into each other's eyes, and yet see the drawing information right-reading. His Tangible Media at the MIT Media Lab works on how electronically enhanced physical objects can be repositories for shared information and tools for communication. In an urban design project, wooden building block shapes could be moved around a table with sensors so that sun shadows and reflections could be shown for different times of daylighting conditions and different surface materials. A more recent project allows a landscape designer to sculpt a tactile clay model whose shape is captured and then modified with projected transformations [35].

3.3.4. Immersive collaborative VR and interactive environments

Whereas videoconferencing has always been about bringing people together, more typically, immersive VR has been centered on an individual. Davidson and Campbell brought critics together to tour and critique virtual worlds. The viewers of their spaces could use miniature models to select viewing options [36]. More recently, Schnabel and Kvan [37] compared how pairs of students could perform simple 3D design tasks with an immersive versus a standard desktop interface. Tracking the content of the partners' conversations, they found that design comments dominated over navigation and interface comments. In reviewing the results, they felt that 3D interactivity aided design, providing better control of the elements.

Artworks shown at SIGGRAPH 2001 showed off some of the spatial potentials of collaborative VR. In Murakami's Contact Water project [38], face-to-face participants wearing view-through head-mounted displays could see each other and toss interactive animated figures to each other. The location and orientation of the players' helmets and specially marked paddles were picked up by sensors so that views could dynamically adjusted. Each player would see the animated dolphin composited into the video feed of the scene. While the appearance of the project is very light-hearted, its ramifications for 3D design are deep. The processes enabling a local group to play together with sea creatures would also allow remote or local groups to interact with a 3D design.

In the future, ubiquitous computing, in terms of both environmentally embedded devices and mobile wireless devices, will shape many team design projects. Streitz et al. [39] have created schematic concept environments with integrated information panels and physical prototypes for digitally enhanced workplace furnishings. Inexpensive motion and heat sensors are allowing artists and designers to shape new kinds of interactive environments [40]. Wireless handheld computers allow visitors to Cornell University to access location-specific data and add their own corrections [41].

4. Conclusion: remaining challenges

While the amount of energy going towards digital design collaboration has been great, efforts could be more carefully aimed. Research shortcomings reinforce the need to develop standards, interdisciplinary dialogue, and new interfaces. The most common problem is redundant or insular work. Many efforts to tailor Web technology for designers make small improvements over existing examples. They show how difficult it is to take advantage of past projects and make significant advances, especially in a competitive atmosphere. Even with careful study of other strategies and approaches, developers may need to recreate previously developed features as a base for further work. In a sense, the research world is challenged by the same interoperability that plagues CAAD practice.

Many of the research efforts would profit greatly from collaboration with other disciplines. The CAAD field is full of tool builders and visionary designers who could use social scientists to help them tune technology to fit design activities[4] and evaluate efforts. Related developments in CSCW, Virtual Environments, 3D Web formats, and interface design provide important results for team design work. Using communication tools for interdisciplinary research effort could help bridge academic, professional, and commercial developer communities. Currently, papers on industrial and engineering design processes are rarely mentioned in architectural research conferences. Because design is such a wide-ranging pursuit, ideas from related traditions could bring out new discoveries.

Perhaps there is a lesson in the failure of the project extranets. Even if a tool is easy to use and facilitates routine tasks well, some people just do not want a new tool. The risk of handing over all project information to an untested system was too great: they could not see the kind of security and reliability. To win new users, technology must be both functional and appealing. In that sense, the Contact Water project gives a clue: we enjoy a sense of delight in everyday tasks.

What is going to make a difference? Better interfaces for communicating design information and standardized file information and procedures could streamline team interaction. We need to optimize the emerging systems by closely observing and evaluating them in both controlled and open-ended professional situations. For communication tools to be most useful, they must integrate visualization with building performance and provide useful functionality throughout the building life cycle. To work well from pre-design to facilities management, the tools need to be both flexible and robust. They need to facilitate large modifications to early organizational decisions while

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[4] For an example of a social guide to technical interaction, see Ref. [42].

supporting later development of complex databases. Rather than simulating what is possible in face-to-face interaction, we need to use opportunities to find inherent aspects of the media.

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