International Journal of Engineering Education Vol. 29, No. 1, pp. 33–44, 2013
Printed in Great Britain
0949-149X/91 $3.00+0.00

Creative Collaboration: A Case Study of the Role of Computers in Supporting Representational and Relational Interaction in Student Engineering Design Teams*

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In this paper, the authors present a framework for examining the role of computers in supporting creative collaborative engineering design. It is argued that the affordance of computational technology for supporting both representational and relational aspects of design is essential for creative collaboration. Representational aspects refer to the creation of verbal descriptions or visual sketches necessary for the generation and sharing of ideas. Relational aspects refer to support for communicative and collaborative aspects that are the cornerstones of teamwork. To illustrate the usefulness of the proposed framework, the authors present empirical findings from a case study of a collaborative engineering design project. In this study, a team of engineering design students successfully appropriate available technologies to create collaborative practices. The design practices of this team are compared with another team working on the same project but that met face-to-face. Through this comparison it is shown that computation technology can be used creatively by design teams.

Keywords: engineering design; design and technology; student design teams; collaboration; teamwork; creativity; representations; affordances

1. Introduction

The use of computing has increased steadily in engineering professional practice and engineering education over the last several decades and has become an integral part of present day workplaces and educational settings. From a realm of limited use, computing has become omnipresent at all levels of engineering practice and teaching. Engineers increasingly work collaboratively around the globe; technology is a primary driver of such arrangements [1]. Virtual teams, teams where members communicate primarily using technology [2], are becoming a norm in most engineering work settings [3, 4]. Virtual teams often come together as needed in order to complete deliverables outlined by the customer [2, 4] and have been seen to increase the productivity of the team members and promote participation [5].Therefore, not only has computing changed engineering representational practices, it has also significantly reshaped relational practices among engineers.

In addition to the effect of computing in the workplace, the advent of online learning technologies is significantly shaping engineering teaching and learning with virtual teams consisting of students and teachers gaining increased acceptance [6]. Within engineering, design, which is often considered a defining characteristic of the engineering profession [7], has changed substantially with the advent of computing. For example, their use has led to new modalities for designing, such as the replacement of physical experimentation with modeling and simulation. Design has been a focus of research in engineering education, and research on engineering design thinking and learning has established that design is hard to learn and still harder to teach [8]. Therefore, it is important to examine the changes brought about by computing and information technology in how designers interact and collaborate and accomplish engineering design.

In this paper our purpose is two-fold, both theoretical and empirical. First, we present a framework for examining the role of computers in supporting creative collaborative engineering design (Section 2). We argue that the affordance of computational technology for supporting both representational and relational aspects of design is essential for creative collaboration. Second, to illustrate the usefulness of our framework, we pre-

* Accepted 28 August 2012.

sent empirical findings from a case study of a collaborative engineering design project (Section 4). We show how a team of engineering design students successfully appropriated available technologies to create collaborative practices. We demonstrate the intertwined role of computing in supporting representational and relational practices (see Fig. 1) thereby allowing the students to be inventive and innovative both in the manner in which they approach and work on the problem and also in the way they design the final solution. Our overall goal is to provide a new way of thinking about the role of computers in enhancing creativity by supporting design collaboration and to demonstrate this new perspective through a field study. The research question guiding this study is: *How do computational affordances for representational and relational support lead to creative collaborative design practices?*

2. Literature review and guiding framework

Although most prior research on creativity has focused on the lone genius working alone, the reality of creativity is much more complex, with multiple, different ideas coming from groups of people and their collaborative efforts [9, 10]. The influence of group dynamics on creativity is critical to engineering design projects, as group collaboration is necessary to handle a problem's large scope and interdisciplinary nature. Past research has shown that groups have the tendency to inhibit creativity because of premature consensus leading to stale solutions [9]. However, recent research contradicts these findings, and instead argues that groups can be creative depending on how they collaborate; i.e., the output of groups can be creative if the conditions under which they function support creative collaboration [10].

Using this research as a foundation, scholars have examined intensively the role of technology in creating conditions for creative collaboration. For instance, Nunamaker *et al.* [11] looked at the role of a group decision support system in facilitating group creativity and found that the use of technology helped in the generation of ideas, specifically by inhibiting social disapproval among team members. Research [12] also shows that, particularly in the early stages such as brainstorming, an electronic system can assist teams to overcome the constraints of time and space, which allows for a more diverse participation and, as a result, more and better ideas. The ability of technology to allow for anonymous interaction has also garnered much attention; studies show that anonymous groups are more flexible [13]. Most prior work examining the impact of technology on group creativity is based on experimental studies [11–13], which raised concern about the ecological viability of the findings. True collaboration does not occur in an experiment. There is reason to assume that a field study of technology-infused collaboration will lead to a discovery of new findings. But how do we approach the research of creative collaboration in engineering design?

The role of representations in the design process is a critical element that can provide a window into creativity in general and creative collaboration in particular. Engineering problem solving and engineering design have been shown to rely significantly on a designer's use of representations [8] and their transformations across symbol systems [14]. This element of engineering design has been significantly impacted by the increased use of computational techniques for representing and manipulating representations [15]. When representations are used collaboratively, relational aspects of interaction also become important. One of the critical needs is to create common ground and joint activity space among team members [16]. We can thus argue that creativity in collaboration arises from affordances for the creation, sharing, and manipulation of representations, provided by a computational technology. These representations can range from verbal descriptions, freehand sketches, all the way to CAD drawings and creative ideas emerging from the sharing of these representations. Although representations can be both internal and external within engineering design teams, the output or product of many assignments is an external representation.

It is these external representations that are the focus of our work. Yamamoto and Nakakoji [17] propose four ways in which representations play a critical role in the design process:

1. the means by which external representations are produced influence designers in deciding which course of actions to take,
2. designers generate and interact with multiple representations that include partial representations of the final artifact as well as various other external representations,
3. the external representations are produced to express a solution and also to interpret the situation, and
4. the design process is a 'hermeneutic cycle' where the representations have project meanings that are gradually revised and confirmed.

Our central argument, thus, is that the use of representations is essential for collaborative team work in design projects *and* collaboration can be understood and improved by examining the use of representations within a team. Specifically, we can

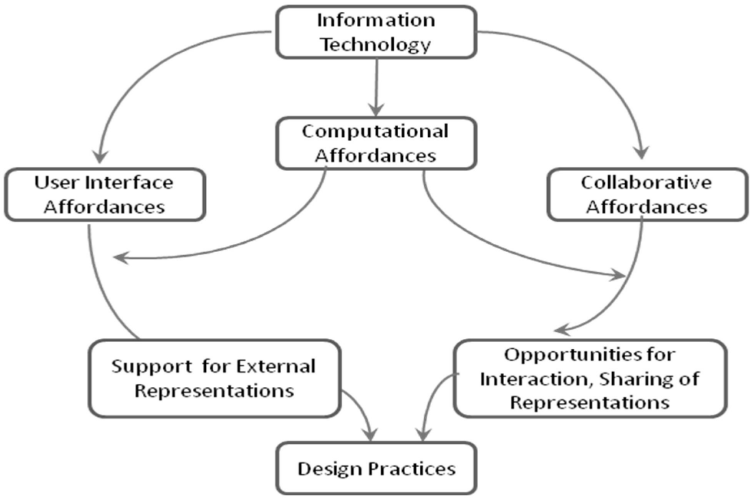

Fig. 1. Role of computational affordances on design practices.

delineate two aspects of design practices as they related to the use of computational technology: (1) the affordances of a computational device or system for supporting the creation of external representations, and (2) the affordances of the device or system for supporting interaction around external representations, particularly their sharing across team members. Figure 1 depicts the central framework that we use in this study to analyze and interpret the data.

3. Research study

3.1 Setting

The context for the field study was a second year mechanical engineering course on engineering design at a large land-grant institution in southeastern United States. Extensive use of technology was made in the class, including the use of Tablet PCs. Students used the devices in class as well as out of class. In particular, Microsoft OneNote™ was used extensively by students for collaboration. Through this software, students could connect directly with each other through their Tablet PCs. They could concurrently share notes they wrote or figures they drew while working in a common environment. Each class featured a similar schedule: students took a short quiz on a previously assigned reading, the instructor led a 10–15 minute discussion about the topic, and finally, the students used the remainder of the class time (roughly 30–40 minutes) to perform a structured hands-on design activity.

In addition to quizzes, in-class activities, assignments, and exams, a semester-long design project was used to assess student understanding of course content. The design project provided students with an opportunity to apply and synthesize design methodology concepts to an open-ended, unstructured problem. In addition to the organized class meetings, the successful completion of the design project required students to meet outside of class. The project featured multiple deliverables that accounted for 50% of the students' final course grade. Deliverables commonly took the form of written reports structured around the primary phases of the design process: problem definition, conceptual design, preliminary design, and detail design. These deliverables, and their associated design content, are presented in Table 1.

3.2 Methods and data collection

This study utilized a naturally occurring quasi-experimental design [18] where data were collected using qualitative methods [19]. Video data and audio data were collected as students worked in their teams. Students were interviewed at the end of the project cycle. Another source of data was online collaboration data, which included logs of chat as well as logs of OneNote™ sessions. Student deliverables and design documentation were also collected. Data were analyzed using document analysis, open coding, and observation protocols. The design project provided students with an opportunity to apply and synthesize design methodology concepts to an open-ended, unstructured problem. The project featured multiple deliverables (accounting for 50% of their final course grade), focused primarily in written reports that were organized around the primary phases of the design process: problem definition, conceptual design, preliminary design, and detail design.

The 36 students enrolled in the class were randomly assigned to three-person teams at the start of

Table 1. Design phase deliverables

Design phase (DP)	Included design content
Design Phase 1 (DP1) Problem definition and project management	Mission statement Gantt chart Design structure matrix Customer needs analysis Needs-metrics matrix Competitive benchmarking Identification of target specifications
Design Phase 2 (DP2): Conceptual design	Functional decomposition Prior art search Concept generation Morphological matrix Concept scoring matrix Concept testing
Design Phase 3 (DP3): Preliminary design	3D CAD model Product architecture Industrial design
Final Project Submission (FPS): Detail design	Failure modes effects analysis DfM: Assembly time estimation DfM: Cost estimation

the term. Teams were given the opportunity to choose project topics from a pre-defined list provided by the instructor. This paper focuses on two teams that chose the same design project: to design a desk that was compatible for laptop use. As there was insufficient in-class time allotted for student teams to work on their design projects, they were required to work outside of normal class meeting times to complete their projects. The two teams that selected the desk design project chose different collaborative approaches for their outside-of-class meetings.

- *Team F2F*—Team F2F (F2F stands for 'face-to-face') chose to meet in-person at a time that was mutually acceptable to all team members. The research team defined the meeting location so that the appropriate data could be properly collected. Their interactions were primarily face-to-face using a mixture of Tablet PCs and whiteboards as a means of graphic display. Team F2F was made up of two male students and one female student. All of the students were in their 2nd year of college and were 19 years old.
- *Team Virtual*—Team Virtual chose to meet virtually through electronic means, using programs like AIM chat rooms and Microsoft Office OneNote shared sessions to complete class assignments and design tasks outside of class. The team chose to conduct their team meetings through mediated practices since all of the students lived off-campus and felt that issues related to transportation and identifying a common meeting place made the time investment unworthy. Team Virtual consisted of three male students. Two members of this team were in their second year; the third member was in his 4th year, and was a transfer student from a different university.

Focus group interviews were conducted at the end of the academic term, days prior to the beginning of the final exams. Owing to time constraints surrounding final exams and leaving campus, Team F2F was not able to participate in the interviews. Team Virtual was the only team to participate in the interviews—the data provided valuable insight into their approaches to collaboration and use of representations since the technological mediation limited the understanding of their approaches.

3.3 Data analysis

As the deliverables were major milestones within the design process, data was analyzed in phases. The majority of recorded team meetings occurred during the development of the Design Phase 2 deliverable (DP2). This phase of the project involved a large amount of teamwork, as it required teams to determine project management strategies, review relevant intellectual property, and generate, evaluate, and select concepts. For this reason data analysis was primarily centered on the development of DP2. The other three design project phases (Table 1) provided support for the findings from DP2 observations.

Analysis was conducted in two stages. A side-by-side comparison of the teams' end products was used to identify differences in design process and outcomes. This was followed by open coding [19] of all video, audio, and other miscellaneous data collected in the time period immediately preceding the submission of the DP2. Open coding was used to identify themes and patterns within classroom work and team meetings. These themes were then used to create an observation protocol that would provide details regarding the interactions during class and team meetings. The observation coding protocol, seen in Table 2, was adapted from the VaNTH Observation System [20]. The protocol was broken into four segments: (1) who is initiating the interaction, (2) whom are they interacting with, (3) about what topic, and (4) using what tools for communication. Communication tools were limited to the use of Tablet PCs, paper, and verbal communication. Tablet PCs could be used in one of two formats: primary and secondary means. The primary use of a Tablet PC for communication involved the use of OneNote, so that the user can directly interact with others with their own tablet. The secondary approach involves the examination of work done on a tablet by examining a computer other than that of the operator in question.

While Team Virtual was the only known team in the course to primarily work at a distance using technological affordances, the data provides a unique insight into the workings of a single team with a unique set of circumstances in a given design task. The team's use of virtual means for meeting was not imposed by the instructor or the research team but was negotiated by the team members themselves. The analysis and findings provide insight into how technology may impact on the use of representations and team dynamics in virtual environments. Although the limitation of this study to a single case reduces its generalizability, the novelty and depth of the study can contribute to the creation of new theory and knowledge.

4. Findings

In this section we discuss the findings from the study under five different categories. The first four areas are comparative across Team Virtual and Team F2F. We first discuss the class meeting for both Team Virtual and Team F2F (one area in which the teams were the most similar). We then explore team dynamics in general, and then their team meetings in specific. We found the most differences between the two teams' meetings, which fundamentally altered the design process across the teams. We then briefly discuss their design outcomes. In the last section, we present results from a focus group with Team Virtual. This focus group puts their team dynamics and collaboration in perspective and also highlights the creative aspects of their technology-based interaction.

4.1 Class meetings

The classroom interactions between the teams were similar. The majority of the classroom interactions consisted of a team member addressing the other team members about instructions and solutions to the class assignment. The primary medium used by the teams was their Tablet PCs. Peer feedback and discussions were facilitated by either rotating the tablets' screens or passing around tablets to allow other members of the team to collaborate and critique the work. The tasks assigned during the class were designed with teamwork in mind but the students often divided the task with an eye towards division of labor, often based on their expertise. This allowed the team members to work concurrently without being dependent on each other and thereby complete the task in the least amount of time. This way of dividing a task is common in engineering design projects [21]. The drawback of this approach was that there were little opportunities for in-depth discussion regarding design tools and team collaboration on concept generation.

4.2 Team dynamics

During the course of the semester the entire class, including Team Virtual and Team F2F, were required to complete two peer evaluations. The evaluations occurred at Week 6, the midpoint of the course, and Week 16, the end of the course. Both teams expressed that they had a good working

Table 2. Observation protocol

Who	To whom	What	Media
Team member A	Team member A	Design tool	White/black board
Team member B	Team member B	Divide tasks	Primary tablet
Team member C	Team member C	Technology problems	Secondary tablet
Whole team	Whole team	Personal discussions	Alternate
Other team	Other team	Assignment instructions	Paper
Professor	Professor	Task details	Verbal
		Academic issues	Text
		Design: alternatives	Aim
		Design: constraints	
		Design: limitations	
		Design: selection	
		Design: reporting	
		Encouragement	

relationship within the team, rating all their peers between 3 and 5 points out of 5. By the end of the semester, both teams gave ratings of 5 for all members. The lowest grade of 3 out of 5 occurred only once during the first peer evaluation in Team F2F. This grade was due to one team member's perception that another team member was not contributing as much as the others were.

Team F2F and Team Virtual both expressed difficulties related to maintaining their focus during meetings and a prioritization of tasks. Two of the three members of Team F2F noted that there needed to be more focus on the tasks at hand rather than moving to off-topic subjects of discussion. A review of the video and transcripts indicates that approximately half of the teams' communications during out-of-class meetings were related to topics other than the design task. These topics frequently included social interactions, current class assignments, and informal evaluations of professors.

Team Virtual experienced a similar lack of focus. Team members reported in the peer evaluations that team members seemed to multi-task during the meetings. The lack of face-to-face interactions allowed the members to casually remove themselves from the meeting in order to accomplish other tasks.

Team Virtual also experienced a scheduling problem that was not seen by Team F2F. The versatility of meeting time and locations provided by a virtual collaboration permitted the opportunity for team members to arrive late, leave early, and forget meeting times altogether. Team F2F did not have these problems, as their meetings were scheduled at the same time each week. This was further facilitated by the necessity of a researcher to be present during their meetings for data collection.

4.3 Team meetings: virtual vs. face-to-face

Several patterns related to the use of technology, design tools, and peer collaboration emerged during the team meetings. From Team Virtual's choice to use technology as their primary means of communication for meetings, it can be assumed that they were fairly comfortable and confident with the use of OneNote and AIM to conduct meetings (Fig. 2). Team Virtual experienced fewer technological problems than Team F2F. The primary problem they encountered was the occasional loss of connection to OneNote^{TM}. In these instances, they were quick to modify meeting tools and resorted to e-mail and AIM document sharing to relay information.

In contrast, Team F2F frequently experienced difficulties with the OneNote share feature. This difficulty disturbed the flow of meetings, requiring the team to halt work for an extended period of time while the whole team regained connection. In order to mitigate these difficulties, the team worked off personal documents, physically rotating their screens so that team members could observe what was being done. After several meetings with technological difficulties, the team resorted to the use of a white board. The Tablet PCs were used only as a means to record what was done during the meeting as required by the course.

Throughout the course, several design tools were introduced to the class. The teams practiced these tools in class and were required to use and document them in their design projects (the design of the desks). During their meetings, Team F2F occasionally discussed the purpose, proper use, and future applications of several design tools. These discussions were frequently initiated by one team member explaining or correcting a fellow team member's misconception or inquiry. Team Virtual, on the other hand, rarely experienced these discussions during team meetings. Team Virtual used the tools as a means to move the design along and meet the requirements of the assignment. When assessing the use of a tool, one member of Team Virtual questioned whether the use was 'enough to cover the bases', which was simply replied to affirmatively by another team member. A similar question was asked by a member of Team F2F and led to a brief discussion of the tool, looking at its purpose and execution. This behavior of students is similar to student behavior in other engineering design courses (see [21]).

The level of peer collaboration varied for each team, depending on the task at hand. Overall, Team F2F worked together more frequently than Team Virtual. This was most evident during fact-finding, concept generation, and concept selection. When referencing the text or online sources, Team F2F frequently passed around texts and computers, allowing all team members to examine and evaluate the findings. When approached with a similar situation, members of Team Virtual took the word of their team-mate and continued with the process.

The concept generation phase of the design required teams to conceptualize two different designs. The process provided six individual designs for the selection process. While each member of Team F2F created his or her own design, peer feedback was involved throughout the process. During concept generation, one member of Team F2F mentioned that they were 'just throwing out ideas', inviting the rest of the team to expand on their ideas for accomplishing the design. Team Virtual took an independent approach to the design, only consulting with team-mates during the selection process. The teams' selection processes followed a similar trend. Team Virtual chose to divide the rating tasks after one team member suggested 'each person do a selection criteria,'

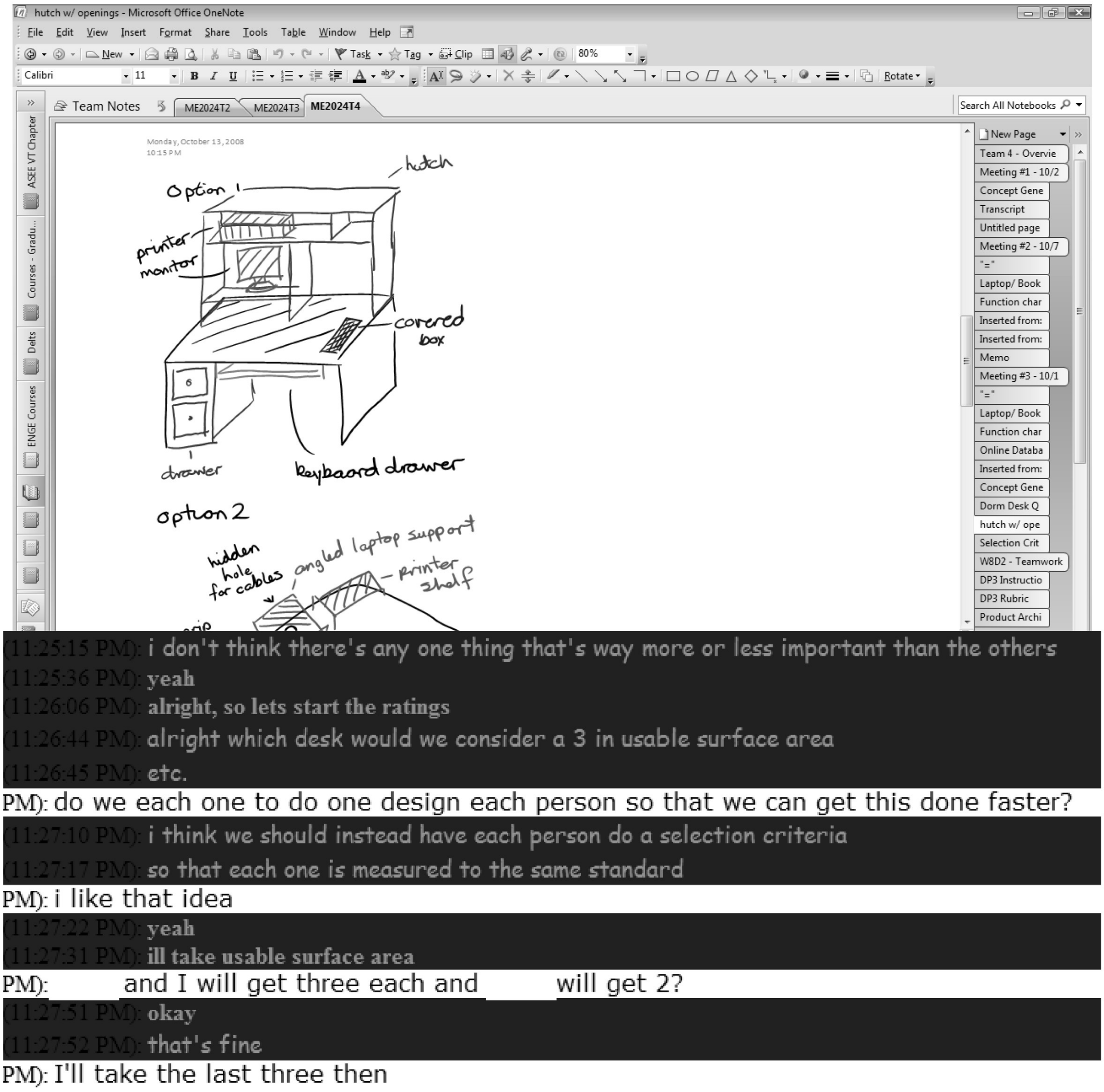

Fig. 2. Team Virtual—Concurrent OneNote^{TM} shared session and Instant Messaging.

which received the prompt response of 'I like that idea' by another team member. This divide-and-conquer approach was seen during the weighting of the selection criteria. One team member took it upon themselves to weight each selection criteria, which was promptly agreed to by the rest of the team. At the conclusion of the selection, process, there was no discussion of the ratings. However, Team F2F's concept selection was more collaborative. Each weighting of the selection criteria was discussed and agreed upon by the team. This was followed by point-by-point discussion of each selection criteria and with respect to the six generated designs.

4.4 Design outcomes

As part of the requirements for DP2, teams were required to determine the functions of the design and to brainstorm several solutions. Both teams approached these design tasks from similar perspectives (Table 3) despite differences in team interactions. Both teams included functions that dealt with the storage of books and office supplies, power management, cable management, and workspace. Team F2F expanded on the storage of books and office supplies and incorporated paper organization and protection as well. Team Virtual added several functions that were not considered by Team F2F. These functions included a specific laptop, monitor, printer, miscellaneous electronics location, and lighting.

From this analysis, it can be surmised that both teams approached the design from different perspectives. Team Virtual was focused on the breadth of design capabilities, while Team F2F was concerned with the depth.

Table 3. Comparison of face-to-face and virtual team interactions and use of technology

	Team F2F observations	**Team Virtual observations**	**Team Virtual (focus group)**
Class meetings			
Primary medium & interaction	Rotation of personal Tablet PC screen	Rotation of personal Tablet PC screen	
Task designation	Division of labor	Division of labor	
Out-of-class meetings			
Efficiency (average length of meeting)	Straight to the point (1 hour)	Socialization (2.5 hours)	
Use of technology	Comfortable & adaptive	Limited & traditional	
Source of disruption	Multi-tasking	Socialization	
Team approach	Modular	Iterative	• Team members can work at own pace • Critique and discuss when problems identified

4.5 Focus group with Team Virtual

At the closure of the design project, a focus group, with a protocol designed using guidelines in [22], was conducted with Team Virtual in order to better understand their design practices. The team members expressed their appreciation for the availability of information technology, particularly for the ability to use shared sessions through OneNote.

> It's a cool thing especially with those shared sessions because the three of us couldn't always be [physically] together when needed. But through One Note you know we can set-up a shared session so that we can all see the same thing. And then we could talk about the same thing at the same time before on instant messenger. And that's—I said OneNote it's been like the biggest—the program it's made the most impact; most useful piece of technology that we've had (*Member 1*).

Not only did shared sessions allow the team to collaborate from different physical locations, it also changed the way in which the students collaborated. The shared sessions allowed the team members to dynamically view each others' work and to review it, making their final product more cohesive.

> It makes it more of a team like collaboration as well, instead of—because if we've split it up like hard copy everybody would do their piece. And submit it without approval really knowing what everything looked at until or maybe if Member 1 sent out the final copy so we can see it. But this way we can see what everybody else is doing and check it all; so that each piece is more of a

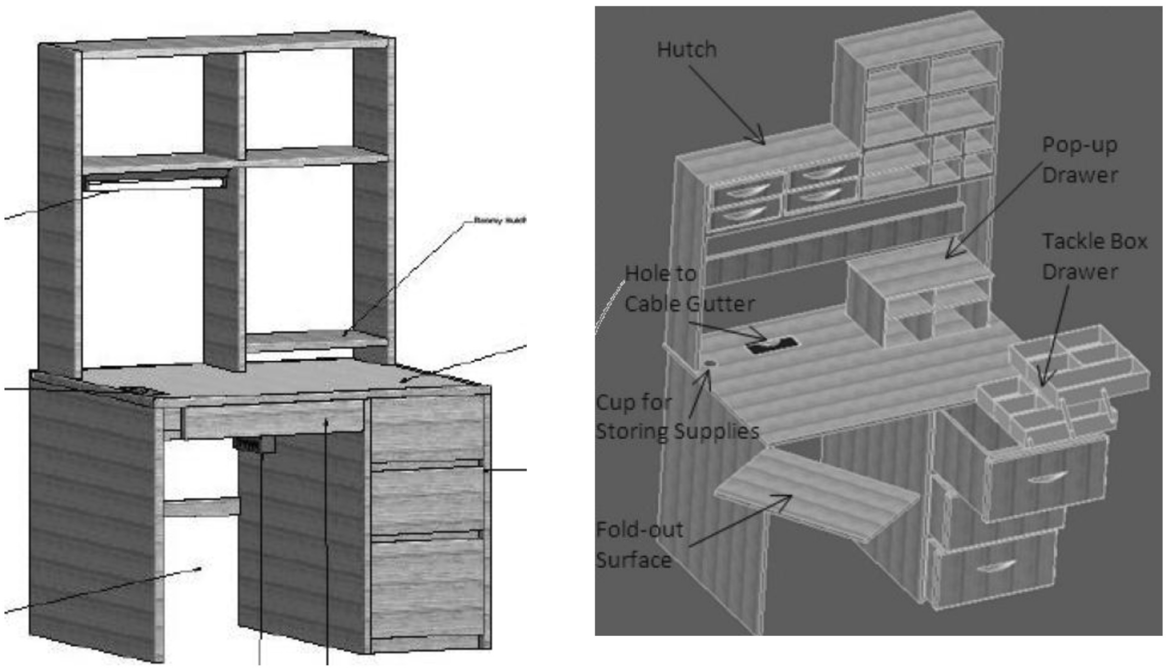

Fig. 3. Final design by Team Virtual (left) and Team F2F (right).

Table 4. Functions and solutions for final design

Team Virtual		**Team F2F**	
Function	**Solution**	**Function**	**Solution**
Laptop/Docking Station	**NSS***	**—****	**—**
Books	Drawer & hutch	Store books Organize books Protect books	Pop-up drawer
Office supplies	Covered box	Store paper Protect paper Store supplies Organize supplies Protect supplies	Basket Shallow drawer Built-in cup Fold out drawer Trays
Monitor	Hutch	—	—
Printer	Hutch	—	—
Peripherals	Nss	—	—
Writing space	Keyboard drawer	Provide workspace	Side folds out
Cord management	Organizing straps	Store cables Manage cables	Cable gutter Cable ties
Lighting	Built-in	—	—
Power management	Power strip	Store/accept external energy	A/C electric power

* NSS was designated by Team Virtual to stand for No Specific Solution.
** — notes that the design function was not addressed by Team F2F.

> collection of the three of us instead of just one person doing each individual thing and then just thrown in all together just like a collage or something (*Member 2*).

Member 1 agreed with Member 2, and added, 'It blends us and creates 'our' report instead of 'my turn of report, his turn of report'.'

The team's use of technology and their overall experience with design and collaboration was closely tied to the problem context and the different steps that were a part of the design project. As Member 3 remarked, 'Well I think the design projects are a good way for us to [work together] as a group and actually go over and understand things. I think we're more focused as we have three people who actually, you know, want to understand it, want to work it out.' Member 1 added that through the project they were able to 'see the depth of the design process.' Member 1 described how soon after the assignment of the design project the team came up with, rather fixated, on a specific design and how by being asked to follow the design process their ideas developed over time:

> I mean as soon as we got assigned our desk idea—instantly we all came up with an idea that—and we just started shooting our ideas. And we're all like, 'Yeah that sounds good, that sounds good.' And we evaluating it in 5 minutes came with a desk that we're ready to send it. I mean we had no idea because I didn't, I had no idea you know 1½ month and 2 months later we'd still be working on this. And just getting us to the point where we felt we were 5 minutes into the project. And then looking back on it, you see you know, 'I did this, this and this.' At that time it was like, 'Why am I doing this? I don't really need it.' But when you're at the end you look back on it and it makes everything so much easier. It gets all compiled in nice charts and tables. And it's a good log of everything you've done and where—what you were thinking and what you were doing and where you're going and overall perception of the process.

When asked whether they perceived their design to be creative, the team talked about how their perception of what is creative changed over time:

> At the beginning we thought we're being creative by putting all this crazy things in but really I think we're different kind of creative now. It's not creative like, 'Hey, that's really cool. That's something I've never seen.' It's creative like, well this is a way that we can do this that isn't being done by anything we know of right now. It's not a flashy thing it's not a cool thing. It's just a little different a little different way of looking at it or whatever. I liked one of the things our desk has is the light built-in the hatch. It's not crazy but it's cool its right there you can flip it on. It's something that you know not everybody would expect to find it on a desk so. What are some of the other things we got? Like an office supplies' a little –We got holds for pencils and whatever, whatever it needs to be there. So it's right there and it's handy. And that's another thing that we just haven't seen before. It wasn't cool and fun but it was still creative (*Member 2*).

Following on Member 2's comments, Member 1 described how they came up with the idea of including a built-in surge protector in the desk when they realized that all the effort they had put into building the desk was of no avail if there was a lightning storm and the desk lacked a surge protector. He added that these seemingly inconsequential elements linked their design directly to customer satisfaction and thus made it creative: "It's creative to combine customer's needs into one product (*Member 1*).

Overall, by looking at their design process we can recognize the use of representations and their relation with design and collaboration. They were able to share representations, store them as part of their design process log, and later reflect on what they had done. Reflecting on the overall process helped them in coming up with new ideas.

We also asked the team about the specifics of their design collaboration. Member 2 remarked,

> Usually we'll have a chat, a chat room on IM on instant messenger. Three of us are on the same room so we could see everything we all say. And we'll literally say, 'Alright I'll do this, you do this and you do this.' And we'll go and get this particular whatever our own job has been able to get our job done. And then if it's—it depends. If you know this specific table we could probably explain what exactly we were doing with that specific table. There might have been some exceptions like when we were doing the design so just the tables were just—everybody throw an idea in. Because we were just randomly brainstorming whatever we happen to be . . . it all really depend on you know what table had to be done, what all we had to do I guess (*Member 2*).

The team further explained how they collaborated effectively by utilizing division of labor among the team members as seen through the observations (Fig. 4). Team Member 1 stated that either a team member stepped up and said, "Oh I want to do this, I want to do this now," otherwise they would just list the tasks and ask other team members to pick one. After completing their individual tasks they would look over each other's work and one person, usually Member 1, would compile it. While this differs from Team F2F iterative approach, the virtual team paused for discussion when problems or opportunities were identified in the design, as in the case of the surge protector and office supplies described by the team members. While the observations indicated a strict divide-and-conquer approach, the interviews revealed a stronger collaboration based on individual pace and focus areas commonly seen in industry. Often times during the semester they would e-mail or IM each other saying, 'What else can I do? What else can I do?' Member 3 said, 'I don't think any of the three of us want to leave the other two guys hanging. So I think we do manage to get everything done with everybody doing just about equal amount of work. Or equal amount of time spent or whatever happens to be. Just however the pieces fall—everybody gets a piece done that works together for it.' Furthermore, while working on the project they were also able to assist each other, 'And it's nice because someone can keep on working on their own stuff but as soon as understands something and say, 'Hey I don't think I'm getting the right number for this. What am I doing wrong?'

Overall, the focus group with Team Virtual confirmed the pattern of interaction and collaboration we had observed. Since we had copies of all their electronic meeting sessions, we were able to triangulate findings across the different data sources. Consistent with the framework we had outlined, Team Virtual leveraged the affordances of their computing technology—Tablet PC—for both representational and relational support and thereby creativity collaborated on the design project.

5. Discussion

Building on our prior work [23], in this paper we present results from a case study of engineering design to highlight the critical integration of collaborative and cognitive aspects of design practice for creative work. This integration is achieved in face-to-face communication through talk and gestures, such as pointing to an external representation, and through the creation of different forms of representations to move the design process forward through the examination of the details of each of the design functions. We found that in the virtual communicative practice created and adopted by the student engineering team, face-to-face interaction was not substituted by technology such as videoconferencing (which was easily available), but novel combi-

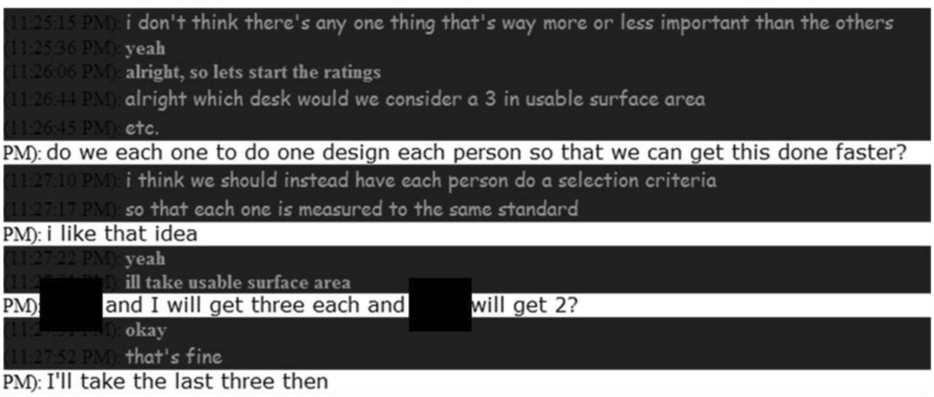

Fig. 4. Team virtual discussing assignment of tasks.

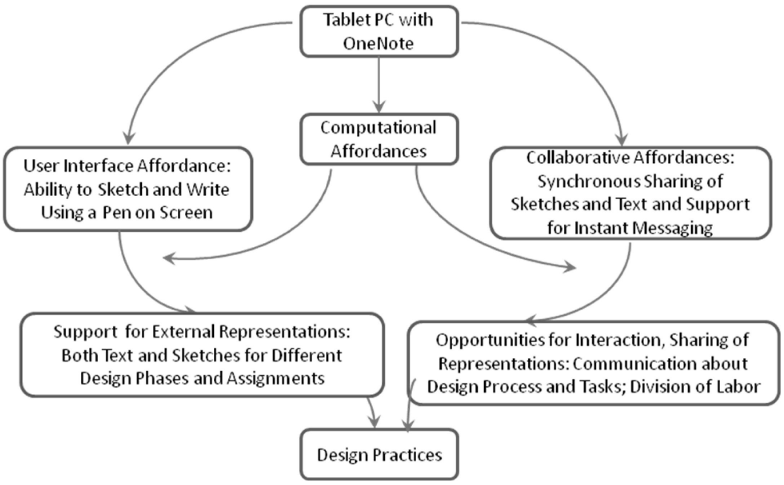

Fig. 5. Framework applied to Team Virtual.

nations of technology use were established. The student team had a synchronously running chat stream using an Instant Messaging service, and a simultaneously running OneNote™ session. In addition, they would occasionally use audio conferencing. The IM chat allowed them to communicate and assign tasks, while the OneNote session™ allowed them to use design tools (such as drawing) to accomplish their tasks. Fundamentally, this mediated practice was established since the students lived off-campus and felt that tackling issues related to transportation and identifying a common meeting place made the time investment unworthy. On closer analysis of the data, we found that the process of interaction among face-to-face teams and virtual teams differed qualitatively. When students met face-to-face their dialogue focuses significantly on off-task issues; when students worked online, they stayed on more on task. The off-task conversation often resulted in new ideas being introduced into the design process and this aspect—the distinction in dialogue when working online versus face-to-face—needs to be investigated further.

Overall, we found that technology was able to support the design process among students in the virtual team in an extremely capable fashion. Figure 5 depicts the framework first proposed in Fig. 1 as applied to Team Virtual. One critical aspect of the design practice that is not captured by the figure is the emergent nature of the design practices. As stated earlier, the use of technology as practiced by Team Virtual was not mandated as part of the course requirement or even suggested as a way to accomplish the design project. The student team decided on its own to rely on technology for their design meetings and developed practices that allowed them to complete their design on time and as specified. They displayed creative thinking that allowed them to work on their design and, relative to the team that met face-to-face, their design output was similar, if not more creative by addressing additional design functions that were not recognized by Team F2F. Overall, design representations formed part of a distributed cognitive system and influenced teamwork as well as actual design practice. This afforded both a creative product and creative learning. The students developed skills that are essential for lifelong learning. They learned how to appropriate technology to help them meet their goals and harness the design capabilities of digital technology to be inventive, a process reflected in professional settings [24]. The design of a single product is a onetime endeavor, but learning how to design creatively in a distance team is a skill that can be applied again and again. As the educational ecosystem integrates information technology even more centrally, a significant change in the way in which learning occurs can be expected. Similar to the transformation of professional engineering work by 'open' models of collaboration and innovation, a change in the educational and learning environment is occurring whereby more 'open' resources and ways of collaborating are evident [25, 26]. The emergence of massive open online courses or MOOCs [27] indicates the popularity of the trend towards 'open content' and 'open organizing' [26].

6. Conclusion

In this paper we present a case study that showcases how creative collaboration in engineering design teams can be supported and fostered through the use of computation technology. For successful collaboration, the technology should support both representational and relational aspects of collaborative design. Furthermore, the collaboration pattern should be allowed to emerge within the team, thereby ensuring adoption and usefulness of the technology in an appropriate manner. More research is needed to compare and contrast the design practices of our case study with other teams. Other studies can also test the viability of the theoretical model that we outline and use to interpret the findings.

Acknowledgements—This work was supported by NSF Award#0757540. We would like to thank the informants in our study for agreeing to participate and for their support in data collection. A prior version of this work, see reference [23], was presented at *Frontiers in Education Conference*, San Antonio, TX, 2009. This is a substantially revised version of that paper including new theoretical arguments, data, analysis, and discussion.

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