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An integrated task management system to reduce semantic conflicts in multi-user computer-aided design

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Abstract
Simultaneous multi-user computer-aided design enables teams of designers to contribute simultaneously to the same model. As multiple users make contributions to the model, all users see additions from all other collaborators in real-time. However, without careful coordination, conflicts that violate the design intent of the model may occur. These are referred to as semantic conflicts and lead to redundant work by users. This article presents a method to reduce semantic conflicts through a task management system integrated directly into multi-user computer-aided design. Experiments were run that compare multi-user teams' design modeling times with and without the integrated task management system. The results of these experiments show that the integrated task management system significantly reduces the time to complete design models by reducing semantic conflicts through enhanced organization and communication.

Keywords
Collaborative engineering, concurrent design, multi-user computer-aided design, conflict management, semantic conflict avoidance

Introduction

Existing commercial computer-aided design (CAD) systems are single-user modeling environments that severely limit design collaboration. The National Science Foundation (NSF) Center for e-Design at Brigham Young University (BYU) is developing multi-user plug-ins for commercial CAD systems which enable two or more users to simultaneously contribute to a shared model (Hepworth et al., 2014a, 2014b; Red et al., 2011, 2012, 2013; Xu et al., 2011). As users contribute to the shared model, the various contributions appear in real-time for all users. This provides a collaborative environment where operations by all users are displayed to the users as they occur, enabling a parallel design workflow for commercial CAD models.

Conflicts that occur between users in the same environment are a central issue in a simultaneous multi-user environment. There are two main types of conflicts that may occur: syntactic conflicts and semantic conflicts. A syntactic conflict occurs when conflicting operations from multiple users lead to inconsistencies between models on separate clients. We have done previous research into avoiding and resolving syntactic conflicts in multi-user CAD systems (Hepworth et al., 2014a, 2014b).

Semantic conflicts occur when multiple users perform syntactically valid operations that result in violations to other users' design intent. Since there is a misunderstanding between the various contributing users of how the geometry should be modeled, the resulting geometry does not satisfy any of the users' vision of the model. Conflicts of this nature result in redundant work by designers, thus adding extra time to the overall design process.

One common semantic conflict is the creation of multiple, duplicate, or redundant geometric features. An example of this is where two users create holes at slightly different locations along an angle extrusion.

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The design intent is not to have two overlapping holes, but rather to have a single hole at a specific location. In order to conform to the appropriate design intent of the model, one of the holes will need to be deleted. This wastes time because the users perform redundant work creating a second hole and deleting it.

This article presents a method to allow designers to quickly communicate and organize their efforts within the multi-user CAD system through an integrated task management system. A system of this nature provides an improved organizational framework to coordinate users' efforts. It also allows for multi-user agility (the ability of the user to respond to change) by enabling users to contribute when and where they are needed. Using the integrated task management system results in a reduced number of semantic conflicts and thus decreases the overall time to complete models in a simultaneous, multi-user CAD system.

In this article, we will discuss the background related to multi-user synchronous design and conflict management in section "Background." The theory of reducing semantic conflicts by enhancing communication and organization while still preserving multi-user agility in a multi-user CAD environment is discussed in section "Methodology." We present the details of a task management system, integrated in a multi-user CAD system which provides a vehicle to improve multi-user communication and organization in section "NXConnect collaborative suite." In sections "Experiment" and "Results," we discuss the experimental process and results of the experiment to show that the integrated task management system has a significant effect on reducing semantic conflicts in a multi-user CAD modeling session. Finally, conclusions from the results are discussed in section "Conclusion."

Background

The time it takes a team of users to collectively model a part depends on how well a model can be partitioned and the communication overhead involved. Di Penta et al. (2007), Putnam (n.d.), and Rodriguez et al. (2011) discuss how these factors affect completion time of software development projects. Design tasks can be classified as one of the four different types, with regard to whether or not the task can be divided for more than one user to work on. From most to least desirable, they are as follows: perfectly partitionable, communication overheads, complex communication overheads, and not partitionable. A task that is perfectly partitionable can be subdivided infinitely and shared among an infinite number of co-workers, decreasing the effort per person to complete the task each time a new co-worker is added. This type of task, according to Di Penta et al., has the following relationship

$$t = \frac{e}{n} \tag{1}$$

where t is the total time to accomplish the task, e is the total effort required, and n represents the number of modelers. A communication overhead task still allows the effort required per person (proportional to t in the equation) for a project to decrease, but introduces a cost factor that accounts for the need for team members (and computers) to communicate. The effort required to communicate detracts from the effort available to apply to the task at hand. If the communication becomes more complex, the shape of the curve changes to become more parabolic and a "sweet-spot" develops. This is the point at which the effort has been minimized, and adding additional team members would actually increase the per-person effort and thus also the time to complete the task. Others have found that too much communication in general hampers a project (Kratzer, 2004). A non-partitionable task is one that cannot be distributed among team members and requires the same amount of time regardless of team size.

In today's commercial CAD systems, the atomic unit of simultaneous contribution is the part. This means that multiple users cannot simultaneously contribute to a part because it cannot be divided into smaller units of simultaneous contribution. Since some parts can take a significant amount of time to model, having a single user model these parts can slow down the overall design process. In a previous article, we suggest that in a simultaneous multi-user system, the atomic unit be the feature (Hepworth et al., 2014a). This means that no two users may simultaneously contribute to the same feature, but may simultaneously contribute to the same part. Since parts can contain many features, allowing multiple users to simultaneously model a part can reduce the time it takes to complete the part model.

Allowing multiple users to simultaneously contribute to the same part introduces the potential for semantic conflicts. Several collaborative CAD environments are reported in the literature (Bidarra et al., 2002; Dietrich et al., 1997; Jing et al., 2009; Kao and Grier, 1998; Mishra et al., 1997; Nam and Wright, 1998; Qiang et al., 2001; Ramani et al., 2003; Stork et al., 1998; Stork and Jasnoch, 1997; Tang et al., 2007; Zhou and Li, 2003). Some articles have discussed methods to avoid semantic and syntactic conflicts through blocking access to some or all the multi-user models. One approach to avoid semantic conflicts is to force or suggest that users take turns in the part so that conflicts do not occur (Bidarra et al., 2002; Chan et al., 1999; Li et al., 2004). A major downside to this approach is that these turn-based solutions do not allow for simultaneous contributions from multiple users because it keeps the part as the atomic unit of simultaneous contribution. In addition, research by Nijstad and Stroebe (2006) shows that taking turns interferes with knowledge activation and idea production.

Another approach is spatial decomposition that involves subdividing the part into spatial regions in which only certain users are allowed to visualize or contribute (Bu et al., 2006; Cera et al., 2003; Li et al., 2004; Red et al., 2012). This allows multiple users to simultaneously work in parallel on a part through providing a smaller atomic unit of simultaneous contribution. This approach increases the number of partitions in a part to enable more parallelization. However, since the atomic unit encompasses more than one feature, the number of partitions is less than when the feature is the atomic unit. Therefore, the level of parallelization will never be as high as it would be if the feature were the atomic unit. This method also requires spatial boundaries to be adjusted to allow that user to continue to contribute, adding overhead to the process and reducing users' agility to contribute where and when they are needed (Hepworth et al., 2014a).

Another approach to avoid conflicts is to allow users to lock geometric objects or features on demand so that other users cannot modify them (Bu et al., 2006; Li et al., 2004; Moncur et al., 2013). This avoids semantic conflicts on edits to geometry already created but does not prevent conflicts between users on geometry creation. The number of partitions for this method is also less than when the feature is the atomic unit. This method limits multi-user agility in a similar manner as spatial decomposition. Other approaches coordinate collaborative efforts based on rules or grant model access to users based on roles and authorization levels (Chen et al., 2004; Shen et al., 2007). These methods may improve multi-user coordination, but still limit modeling agility by blocking access to portions of the part at a level which includes multiple features.

Previous methods of reducing semantic conflicts focus on blocking simultaneous access to all or portions of a model. These approaches divide the atomic unit of simultaneous contribution into sections of the part, made up of sets of features. However, we propose that the feature be the atomic unit of simultaneous contribution in a multi-user CAD system, allowing a higher level of partitioning compared to previous methods. Thus, models have the potential to be completed in less time. When the feature is the atomic unit, users are not blocked from accessing any portion of the model except features that others are currently editing. All users are given full model access to contribute to any portion of the model at any time. This allows users to more quickly respond to the needs of the group. Engineering resources can more quickly be applied at the moment they are needed. Ultimately, this makes it possible for a model to be partitioned and distributed among a modeling team in the most effective way possible, more closely approximating a fully partitionable task.

Methodology

Setting the feature as the atomic unit in a multi-user CAD system facilitates the best possible multi-user distribution and thus the potential for the most efficient multi-user modeling. However, modeling in this type of environment can result in many semantic conflicts without a method for users to effectively communicate and organize their various tasks. Semantic conflicts are a type of communication overhead and are caused by miscommunications between designers or a lack of organization to coordinate multi-user efforts. Di Penta et al. discuss the notion that the number of communication channels, and thus communication complexity, increases as more members are added to a team. This relationship is described by the following equation where C is the number of communication channels

$$C = \frac{n(n-1)}{2} \tag{2}$$

A centralized communication system has the potential to significantly reduce the number of communication channels, regardless of the number of team members. Since users only have one effective channel of communication, communication complexity is significantly reduced (see Figure 1). Chat rooms and conference calls are two examples of centralized communication systems. The main benefit of these types of systems is that they allow for the dissemination of information to the entire group at once. Since communicating with all members of the group only requires a team member to communicate via one channel (to the central hub), the number of pathways required for communicating is essentially reduced to one. This can result in a significant decrease in communication overhead.

However, many existing centralized communication tools provide no intrinsic support for organizing the tasks needed to accomplish a design project. Other disciplines, such as software development, have attempted to reduce their teams' communication overheads by implementing centralized task creation and management systems for their teams. For example, Maurer and Martel (2002) describe a system called Minimally Invasive Long-Term Organizational Support (MILOS) which was used to enable teams of programmers working together from various locations to collaborate more effectively. MacMillan et al. (2004) also describe a multi-user, electronic planning tool which they show helps military teams collaborate more effectively.

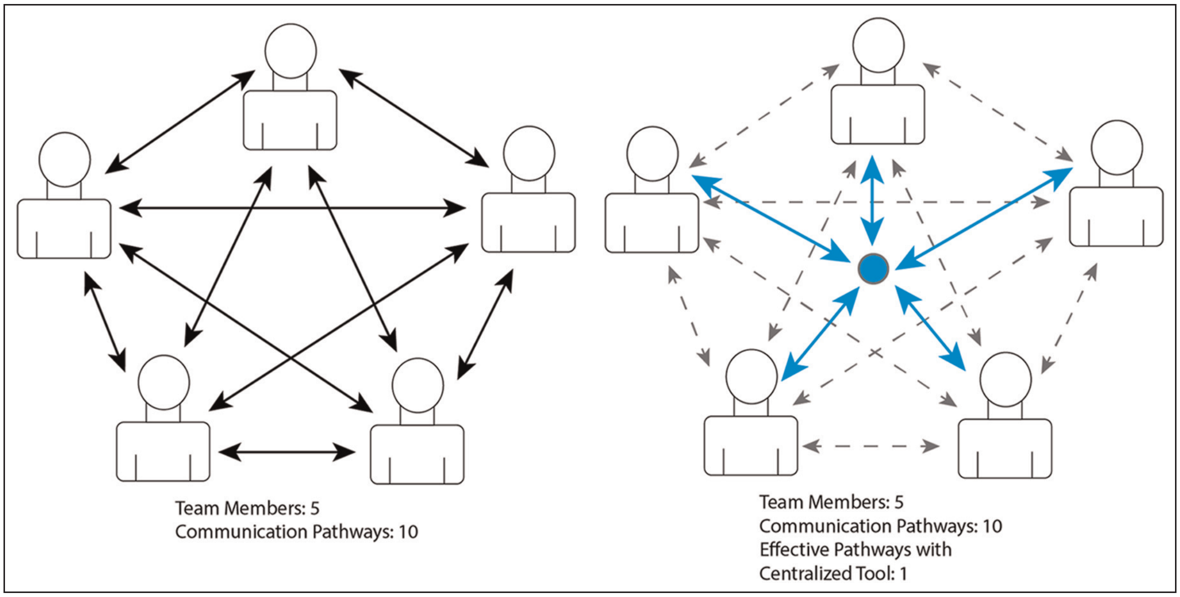

Figure 1. A centralized communication system reduces the number of communication channels to one.

We propose a centralized and integrated task management system to minimize semantic conflicts and preserve agility for modeling in multi-user CAD. This system provides a list of all active users in the model and provides methods for users to add, remove, modify, assign, and mark completion of design tasks. Using this simple tool, the organization of the design project is managed by the group as the model is built. Beyond enabling team members to communicate through a central hub, an integrated task-list tool allows all users to simultaneously manage design tasks inside the multi-user CAD system—answering the questions, "What needs to be done?" and "Who is supposed to be doing it?" This integrated and centralized tool reduces the number of communication channels and provides an effective framework for users to coordinate and organize their efforts. Since this system operates with the notion that the feature is the atomic unit, it enables multi-user modeling agility by allowing users to contribute wherever and whenever they are needed.

NXConnect collaborative suite

Overview of NXConnect

NXConnect is a simultaneous, multi-user plug-in to Siemens NX, developed at the NSF Center for e-Design, BYU site. NXConnect enables users to simultaneously contribute to the same NX model, while contributions from users appear in real-time. This is accomplished through the use of the NX Open application programming interface (API) to extract the data to perform operations as they occur in distributed clients. Each client has a replicated version of the same NX model which stays in sync by exchanging operation data between clients through a central server. A central database persistently stores the most up-to-date version of the NX model as a set of operation data (Hepworth et al., 2014a, 2014b; Red et al., 2011, 2012, 2013; Xu et al., 2011).

To assist users in simultaneous collaboration in NXConnect, two integrated collaboration tools have been developed. One is a chat system designed to allow instant communication between users in the same model. The other is an integrated task management system to organize the tasks needed to complete the model by the multi-user team. Both systems automatically group users which are in the same part model and allow users to create unique groups to communicate. These collaboration tools are designed to assist simultaneous users in organizing a design workflow to complete the model in the most efficient way possible and match the description given by Prasad for "groupware" tools that improve electronic proximity (MacMillan et al., 2004).

Integrated chat system

The integrated chat system provides users with the ability to communicate via text-based messages with any user currently logged into NXConnect. Each user is automatically added to a part-based chat group where modelers working within the same part are able to communicate. If different groups are desired, users can create additional custom groups with a custom set of contributors. All chat groups in which the user is

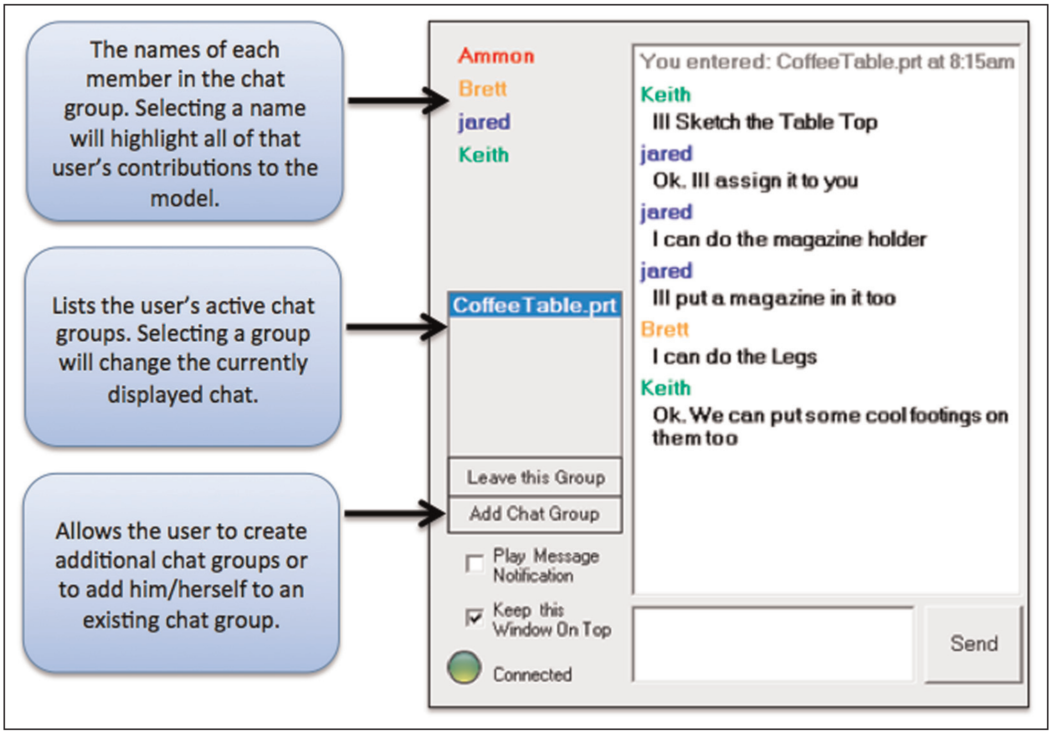

Figure 2. Image of the integrated chat system.

currently a member are displayed to the left of the chat box. The names of each collaborator in the active chat group are displayed on the upper left of the chat box. The user can click on a group name to change the active chat group, updating the chat messages and the list of collaborators (see Figure 2). This functionality is housed within the collaboration tools window.

Integrated task management system

The integrated task management system is designed to be simple, lightweight, and user friendly. The simple layout allows users to quickly ascertain task assignments without being overwhelmed with information. Ethnographic and business-oriented work by Bellotti et al. (2004) suggests that an optimal task management tool should be as simple as possible and not require large amounts of screen space or extremely detailed descriptions. This simplicity allows for the information to be understood at a glance. As Prasad explains in his work on Cooperative Concurrent Teams, designers must be able to communicate effectively across, up, and down the organization. A tool such as the integrated task management system also enhances a team's ability to better manage the complex interplay among Prasad's (1996) 7Ts, especially "tasks."

The task management system is nested within the collaboration tools window directly to the right of the chat box. The tool is shared between all collaborators in the active chat group and is updated for all collaborators in real-time. When a user changes the active chat group, the tasks corresponding to that group are automatically displayed. All tasks are stored in the central database and associated with the model to which they apply. This allows the task management system to be persistent between NXConnect modeling sessions.

The task management system displays a table of tasks with an add task button at the bottom. Each row in the table is a task that corresponds to the following columns: a checkbox for task completion, a description of the task to be performed, an assignee, and a delete button. The task complete checkbox allows any user to mark when a task has been completed. A visual indication of completion is given by adding a check to the box and a green background to the task description. This can be checked and unchecked on demand, by any member of the multi-user team. The task description column provides an area for users to describe the details to complete the task. This section can be edited by any users after its initial creation. The assignee drop-down box contains a list of all members of the group whether or not they are actively in the part. Any member of the group can assign a task to himself, another user, or the group as a whole. When a task is assigned to the group, it means that no single user is responsible for completing the task. The final column simply contains a button to delete a task from the list (Figure 3).

Experiment

To verify that the integrated task management system reduces the number of semantic conflicts in a multi-user modeling session, several timed tests were performed by modelers using NXConnect with and without the task management system. A total of 12 users experienced in NXConnect participated in performing the tests. Figure 4 shows the order of events in the overall experiment. In order to account for varying skill levels between modelers, we began the experiment by measuring a baseline speed for each modeler. This was done by giving each tester an identical model specification and timing each of them as they completed the model. This baseline speed test was repeated with a different model at the end of the testing to account for each modeler's improvement in modeling through the tests.

After the preliminary individual test, the users were divided into two groups of six. One group was given access to the integrated task management system and one was not. These groups were then both divided into two teams, thereby forming four teams with three members (two teams from each group). For the first two rounds of testing, teams 1 and 2 were given access to the integrated task management system, while teams 3 and 4 were only given access to the chat tool. A practice round was conducted that allowed users to become familiar using the tools available to them. Following the practice round, two rounds of testing were conducted. Between rounds, the two teams of each group were randomly reshuffled, creating four more teams. In rounds 3 and 4, the teams were the same as in rounds 1 and 2. However, in these rounds of testing, access to the integrated task management system was switched. When access to the tool was switched, teams were given another chance to practice using their assigned collaboration tools before the next two rounds of testing. Figure 5 shows an image of each of the models created by the teams.

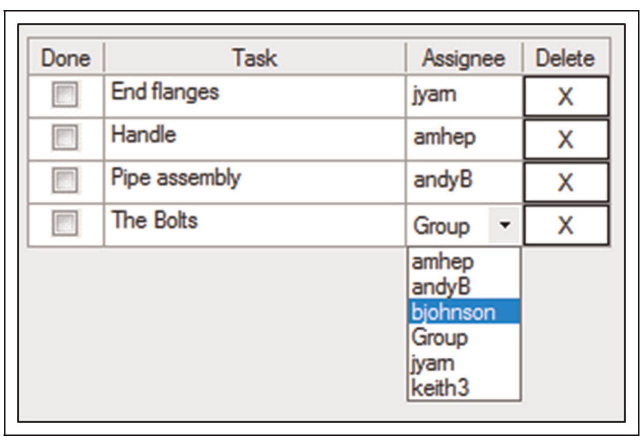

Figure 3. The integrated task management system is separated into four columns: task complete checkbox, task description, assignee combo box, and delete button.

For each test, the teams were assigned a single part file. Every modeler was given a unique username for every trial to prevent modelers from knowing the identity of their teammates. Before the tests, both groups received training on how to use the chat tool. Teams with the integrated task management system received additional training on how to use the task management system. All teams were restricted from all forms of voice communication. No restrictions were placed on what external non-voice communication software the groups decided to use.

Once the training had finished, the modelers each returned to their workstations and received an instruction packet which included the following:

1. A unique login and password;
2. Name of the part file to open;
3. Design specifications for the model;
4. Image of completed model for reference;
5. A recap of instructions they received during the briefing.

This process was repeated with each of the four parts. The time for each team to complete each model

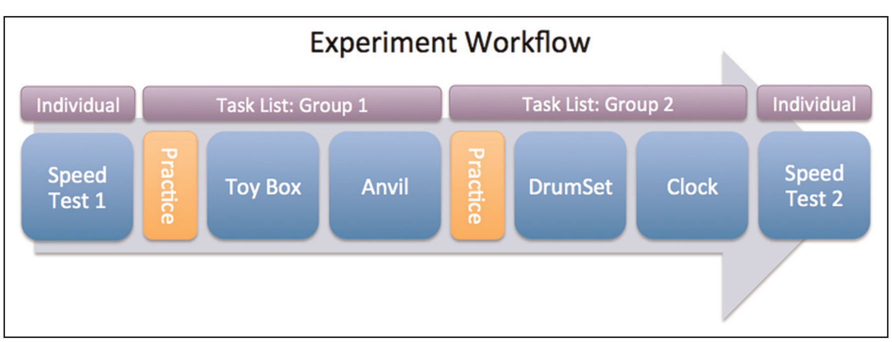

Figure 4. The order of tests starting and ending with a speed test evaluation.

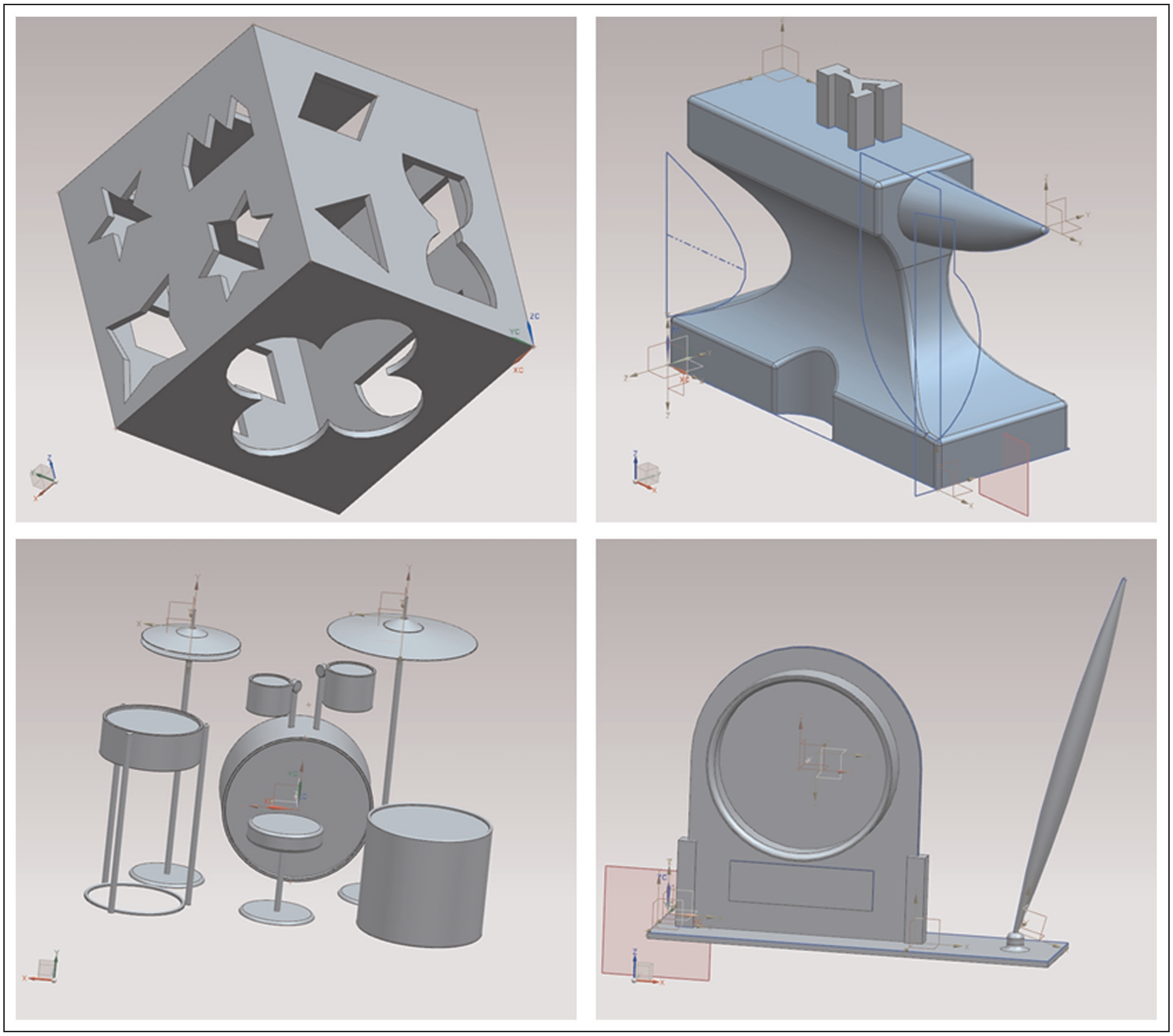

Figure 5. Images of the various models modeled by each group.

was measured and their chats were recorded in a log. In each round, the first model (such as the toy box in round 1) was measured and inspected by the researchers to determine whether the exact specifications of the model had been met before accepting the model as completed. The second model in each round (such as the anvil in round 1) was left more open-ended. Modelers determined when they had completed the model, and the researchers confirmed their decision to ensure all necessary features were present.

Results

The results of our experiment are presented in three distinct ways:

1. *Model time comparison*. It compares the time to complete different models, based on whether or not the teams had the task management system (model held constant, team members varied).
2. *Team time comparison*. It compares each unique team's performance with and without the integrated task management system for the various models they completed (team members held constant, models varied).
3. *Chat message comparison*. It compares the number of messages (coordination and confusion) sent by teams with and without the task management system for each model

Model time comparison results

Figure 6 shows the average raw time taken to complete each model with and without the integrated task management system. The blue (striped) columns display the

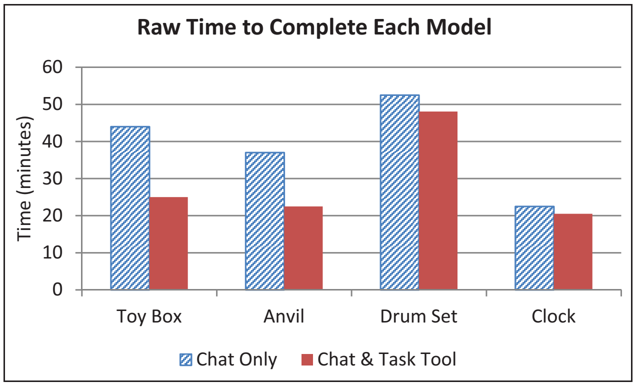

Figure 6. Raw time to complete each model.

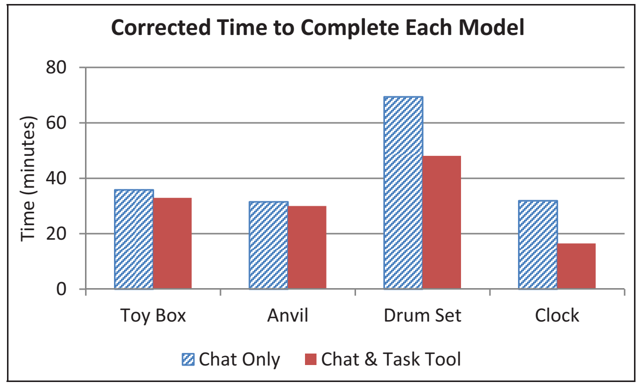

Figure 7. Corrected time to complete each model.

average time of the two teams without the integrated task management system. The red (solid) columns display the average time of the two teams with the integrated task management system. These data do not take into account the varying skill levels of the groups' members.

The raw time to complete each model was the first telling sign of improvement from the integrated task management system. In all four models, the two groups with the task management system averaged a faster time than the two groups without the integrated task management system. The average time improvement for all models using the integrated task management system was 25%.

In addition to the raw data, the results were corrected to account for the varying skill level among teams and to more accurately compare teams with more highly skilled modelers to teams with fewer highly skilled modelers. This adjustment was performed by giving each participant a modeling score, m, based on their individual speed test times. This is calculated by

$$m = t_1 + t_2 \tag{3}$$

where t_1 represents the participant's time from the first individual speed test and t_2 represents the participant's time from the second individual speed test.

Each of the eight teams was then given a collective modeling score, C, calculated by

$$C = m_1 + m_2 + m_3 \tag{4}$$

where $m_1, m_2,$ and m_3 represent the respective scores of each modeler on the team.

An average score across all teams, C_A, was calculated for each model

$$\frac{C_A = C_1 + C_2 + C_3 + C_4}{4} \tag{5}$$

where $C_1, C_2, C_3,$ and C_4 represent the respective scores of each team participating in the test. The corrected time for a specific model, A_i, for each team, i, is then calculated by

$$A_i = \frac{C_A}{C_i} \times T_i \tag{6}$$

where C_i represents the team score C for team i and T_i represents the time it took for team i to complete the model.

Figure 7 shows the average corrected time taken to complete each model with and without the integrated task management system. The times are corrected using equation (6) to take into account the varying skill level of the modelers in each team based on their performance in the pre- and post-speed tests. The blue dashed columns display average corrected times without the integrated task management system. This is compared to the red, solid columns displaying the average corrected times with the integrated task management system.

After correcting the data to account for the skill level of different modelers, the result trends were consistent with the raw times. In every model, the teams with the integrated task management system still averaged a faster time than the teams who only used chat. The average time reduction for the corrected test data was 23%. These results indicate that the time to complete a model or task will be improved when using an integrated task management system for multi-user modeling activities in industry by a similar time percentage.

Team time comparison results

In addition to comparing the time to complete each model, the times for teams to complete models with and without the integrated task management system were compared. Each of the eight unique teams participated in one model with the integrated task

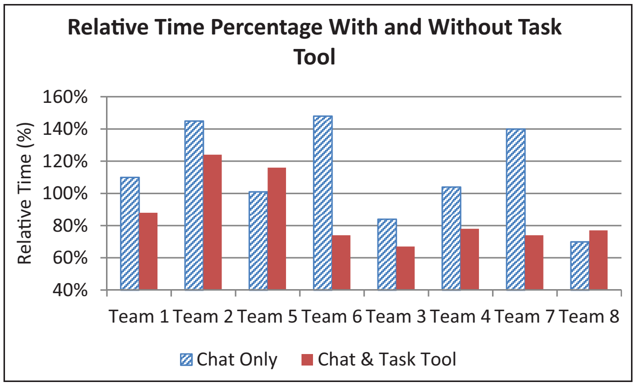

Figure 8. Relative time percentage required for completion by teams with and without the task management system.

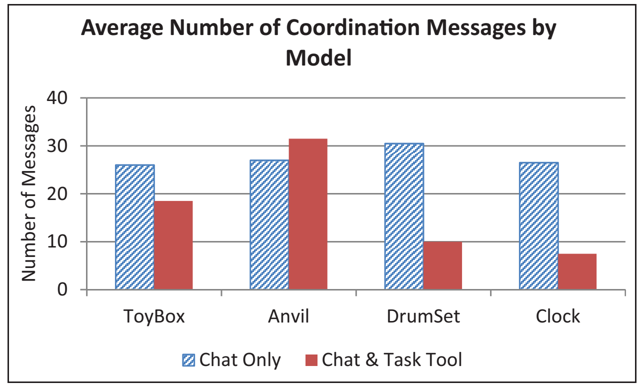

Figure 9. Comparison of coordination chat messages sent for each model.

management system and one without (see Figure 8). Since the times for each team to complete the two different models with and without the list are not comparable, the times for model completion are compared against the average for all teams. This is done by finding a relative time percentage, R_i, for each team, i, calculated by

$$R_i = \frac{T_i}{T_a} \tag{7}$$

where T_i is the raw time it took team i to complete the model and T_a is the average time it took each team to complete the model. Figure 8 shows each team's relative performance with and without the integrated task management system.

From the chart above, six of the eight teams performed significantly better when using the integrated task management system tool. The average difference between team performances with the task management system versus without (on different models) was 25%. These results indicate that teams using an integrated task management system in a multi-user design environment will experience a significant improvement in their team's performance.

Chat message comparison results

To determine the effect of the integrated task management system on communication, coordination and confusion messages were counted from a chat log that was recorded for each team while creating the model. These messages were compared between the teams who had the integrated task management system and those who only had access to the chat. Coordination messages were defined as all messages having to do with coordination of work effort, including confirmation. Examples of actual coordination messages include the following: "I'm doing the negative extrude through the middle of the block," "i'm working on the six-sided star now," and "k i'll do the throwing star." Figure 9 shows the average coordination messages sent for each model comparing the teams using only chat to those that used chat and the task management system. One caveat of these data is that two chat logs were lost: one chat log for the toy box with chat only and one chat log for the anvil with chat only were lost. Unfortunately, this means that the average of the chat only for toy box and anvil is only one team each.

The results of the coordination message comparison suggest that the number of coordination messages sent is reduced by teams who are able to utilize the integrated task management system. The overall average reduction in coordination messages for teams using the task management system in these models is 38%. We attribute the reduction in coordination messages to the task management system which allowed users to coordinate their work in an organized manner. Using the task management system gave teams a systematic means by which to communicate user activities. Since coordination information was communicated through the task management system, there was less need to coordinate through chat, thus removing communication overhead.

Confusion messages were also counted and compared between teams using the integrated task management system and those who did not. Confusion messages were defined as messages that show evidence of a user expecting one thing to happen, but experiencing something else happening and not knowing why. These messages contain elements of surprise, frustration, and/or misunderstanding. Confusion messages are a prime example of "communication overhead" for engineering design teams (Di Penta et al., 2007). Examples of confusion messages are as follows: "i said i was doing the base," "[Jon] was supposed to be doing that," and "someone did my cuts." Figure 10 is a graph

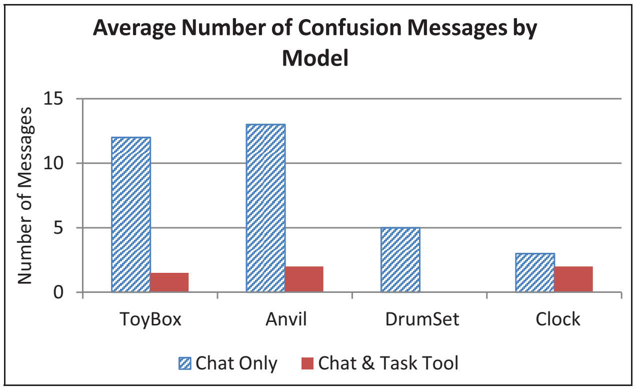

Figure 10. Comparison of confusion chat messages sent for each model.

of the average number of confusion messages sent for each of the models, comparing teams using the task management system and those who did not.

The results of the confusion message comparison suggest that confusion messages are drastically reduced when using the integrated task management system. The average reduction in confusion messages in these tests for teams using the task management system while creating these models is 76%. This large reduction in the number of confusion messages sent strongly suggests that teams utilizing the task management system had significantly fewer semantic conflicts than those who did not. The ability to identify tasks, assign team members, and mark completion of those tasks is a simple and effective way to organize users' assignments. The improved organization and coordination that the task management system provides reduces communication overhead and thus the overall time to complete design models.

Limitations of the experiments

We recognize that there are a few limitations to these experiments. Each of the models used in the experiment is fairly simple compared to industrial grade models. In addition, the number of users simultaneously modeling is limited to three simultaneous modelers. The experiments described herein are the first of many. The purpose of these experiments is to test whether the integrated task management system will improve synchronous modeling in any case, which it does. Although these experiments do not directly show that the integrated task management system provides benefits on an industrial scale, they do show benefits on smaller scales. It is likely that the results will scale to larger models and number of modelers, but further studies should be performed to verify this.

Conclusion

Semantic conflicts are an issue which negatively affect the modeling speed of teams working in a simultaneous multi-user CAD environment. An integrated task management system was implemented in multi-user CAD to prevent semantic conflicts by reducing the number of communication channels required and providing a simple organization framework to coordinate user efforts. This method preserves multi-user agility by giving all users full access to the entire part, except for features which are being edited by another user. The task management system integrated in NXConnect was found to improve modeling speeds by helping users to coordinate responsibilities, thus avoiding semantic conflicts. The integrated task management system was also found to reduce the number of coordination and confusion messages sent by multi-user CAD modeling teams. These results suggest that multi-user teams utilizing an integrated task management system will improve coordination and reduce semantic conflicts while simultaneously contributing to a collaborative design model.

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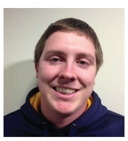

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