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AN AGENT-BASED APPROACH TO COLLABORATIVE PRODUCT DESIGN

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ABSTRACT

The growth of computer science and technology has brought new opportunities for multidisciplinary designers and engineers to collaborate with each other in a concurrent and coordinated manner. The development of computational agents with unified data structures and software protocols can contribute to the establishment of a new way of working in collaborative design, which is increasingly becoming an international practice. In this paper, we first propose a computational model of collaborative product design management aiming to improve the efficiency and effectiveness of the cooperation and coordination among participating disciplines. Then, we present a new framework of collaborative design which adopts an agent-based approach and relocates designers, managers, systems, and supporting agents in a unified knowledge representation scheme for product design. An agent-based system is now being implemented and the design of a set of dinning table and chairs is chosen to demonstrate how the system can help designers in the management and coordination of the collaborative product design process.

Key Words: Agent-based Approach, Collaborative Design, Product Design Management, Product Data Modeling, Collaborative Product Design Process Modeling

INTORDUCTION

Increasing product complexity, explosive global competition, and rapidly changing customer's demands are forcing product manufacturers to improve the efficiency of design decision-making and shrink design cycle times. Advances in the computer science and technology have opened new opportunities for multidisciplinary designers and engineers to collaborative with each other more efficiently and effectively.

Collaborative design can create added value in the design and production process by bringing the benefit of team work and cooperation in a concurrent and coordinated manner. Also, it help reduce the loss of efficiency resulted from potential conflicts and misunderstandings among team members. However, the difficulties arising from the requirements for design coordination mixed with differences among heterogeneous system architectures and information structures tend to undermine the effectiveness and the success of collaborative design among multidisciplinary designers.

Recently, agent technology has been recognized by more and more researchers as a promising approach to analyzing, designing, and implementing industrial distributed systems. An intelligent agent consists of self-contained knowledge-based systems capable of perceiving, reasoning, adapting, learning, cooperating, and delegating in a dynamic environment to tackle specialist problems. The way in which intelligent software agents residing in a multi-agent system interact and cooperate with one another to achieve a common goal is similar to the way that human designers collaborate with each other to carry out a product design project. Thus, we believe that a collaborative product design environment implemented by taking an agent-based approach will be capable of assisting human designers or design teams effectively and efficiently in collaborative product design.

In this paper, based on the analysis of the characteristics of a collaborative design process, we first propose a computational model of collaborative product design management to improve the efficiency and effectiveness of the cooperation and coordination among participating disciplines situated in distributed design environments. Then, we present a new framework of collaborative design which adopts an agent-based approach and relocates designers, managers, systems, and supporting agents in a unified knowledge representation scheme for product design and describes an agent-based system capable of assisting designers in the management and coordination of collaborative design process via the cooperation of a network of agents including mainly management agents, communication agents, and design agents etc. The design knowledge representation and the architecture of the agent-based system are discussed in a general product design process. In such a process, the formation of a type of design agent facilitating collaborative product design as well as integrating external CAD software is described in details. At last, the implementation strategy of the agent-based system is introduced and the design of a set of dinning table and chairs is chosen to demonstrate how the system can help designers in the management and coordination of the collaborative product design process.

RELATED WORK

The development of computational agents with unified data structures and software protocols can contribute to the establishment of a new way of working in collaborative design, which is increasingly becoming an international practice. Parunak (1998) examined the areas related to design activities where agent technology can be best employed and argued that agents were uniquely suited to addressing the problems characterized by modularity, decentralization, changeability, poor structure, and high complexity. Shen et al (2003) stated that the appropriate use of agents could result in desired modularity, allowing flexible simulations, and in better response and improved software reusability which an ideal collaborative design environment should exhibits.

As an emergent approach to developing distributed systems, agent technology has been employed to develop collaborative product design systems by a number of researchers. Their researches were generally concerned with three aspects: product modeling, consistency maintenance, and system architecture (Rosenman and Wang 2001). Agents have mostly been used for supporting cooperation among designers, providing a semantic glue between traditional tools, or for allowing better simulations (Shen and Wang 2003). One of the earliest projects in this area is PACT which demonstrates the use of agents to combine pre-existing engineering systems to constitute a common framework, using facilitators and wrappers, by adopting a federated architecture (Cutkosky and Engelmore 1993). DIDE is developed to achieve collaboration and openness in an engineering design environment through the integration of CAD/CAM tools, databases, knowledge base systems, and etc (Shen and Barthes 1997). SHARE project conducted at Stanford University, USA, including First-Link (Park and Cutkosky 1994), Next-Link (Petrie and Cutkosky 1994), and Process-Link (Goldmann 1996), aimed at using agents to help multidisciplinary design engineers track and coordinate their design decisions with each other in the concurrent design of aircraft cable harnesses with the support of a Redux agent. Liu and Tang (2002) presented a multi-agent design environment that supported cooperative and evolutionary design by cooperation of a group of agents. Rosenman and Wang (2001) presented a component agent based open system architecture for a collaborative CAD system supporting virtual product design.

Although agent technology has been considered very promising for developing collaborative design systems, and most of the systems that have been implemented so far are domain dependent, and were intended for integrating legacy design tools. Such systems are still at a proof-of-the-concept prototype development stage. Furthermore, only a few literatures mentioned design process model for supporting dynamic design project management in a multi-agent collaborative design system. A detailed discussion on the issues and challenges in developing multi-agent design systems can be found in literature (Lander 1997).

In this paper, we present a computational model of design project management and which forms the core of an agent-based system supporting collaborative activities in the domain of product design.

A COMPUTATIONAL MODEL OF PRODUCT DESIGN MANAGEMENT

A product design project often requires the cooperation among multidisciplinary designers or design teams who are usually working on different locations and at different times. Usually, such a project can often last for a long period of time, during which the product requirements may have to be changed. Any change in product requirement, specification caused by various reasons including misunderstanding among team members can cause delays and setbacks for the project. Therefore, a novel product design management model is of vital interest to the success of complex product design projects and impacts greatly on the global competitiveness of designers and manufacturers.

There are several main issues arising from the collaborative product design process:

- At the beginning stage of a product design project, the design information about the product is usually imprecise, incomplete, uncertain, and is likely to be refined or modified at later stages. Therefore, it is hard to predict how the project progresses.
- The dynamic nature of product exploration and problem specification requires that the product plan and schedule be flexible and have rooms for changes. This is particularly true when the product involves close collaborations with geographically dispersed partners.
- During the design process, various decisions are made by each individual participating in the design project. These decisions have consequences and impose additional

constraints to others involved in the design process. In a collaborative product design system, the impact of individual decision making while exploring on others must be minimized without undermining the overall progress of the project and without bringing negative influences to the others working on the same project.

To address these management problems mentioned above, a novel computational model for product design management should be featured by the following characteristics:

- Supporting collaborative product design project planning, coordination, and schedule execution.
- Helping participants to understand the rationales behind design decisions.
- Helping with the re-planning and re-scheduling of the design process as the needs arise.
- Maintaining the consistency of the product data whenever changes take place.

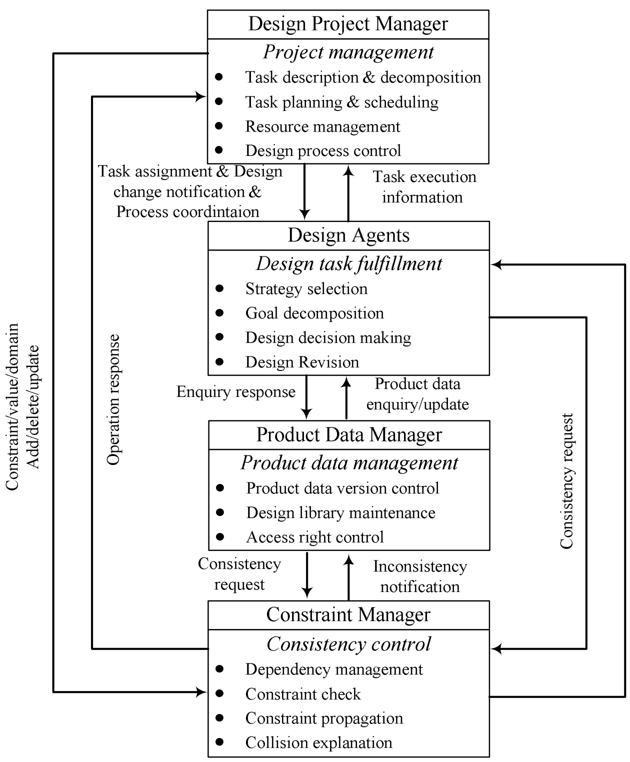


Figure 1. A computational model of product design management

Based on the above analysis, a computational model of product design management is proposed, as shown in Figure 1. Four main components including Design Project Manager, Design Agent, Product Data Manager, and Constraint Manager, are identified in this proposed product design management model.

The **Design Project Manager** component is responsible for task description and decomposition, task planning/re-planning and scheduling/re-scheduling, resource management, and design process control.

The **Design Agents** serve to adopt the appropriate design strategies to fulfill assigned design tasks by the Design Project Manager.

The **Product Data Manager** component is responsible of maintaining design output produced by the design agents, maintaining the design library, product data version control, and access right control.

The **Constraint Manager** component is responsible for design dependency management, constraint check, constraint propagation, and collision explanation.

For a new product design project, the first step is to identify the specification of the design task, i.e. the design goal, which the final design output will be evaluated against. A design task is associated with a set of attributes including inputs, expected outputs, duration, start time, end time, and assigned agents. Inputs and outputs are passed in the form of product part/assembly, parameters, which can represent data as well as documents or physical objects. A task can be further decomposed into several subtasks. In this way, the decomposition of the overall design project can be viewed as a design task tree. During the design process, tasks are executed by design agents through making design decisions which finally result in the design outputs.

To carry out a design project, design tasks must be planned first. Design task planning differentiates from scheduling in that planning is considered to be the definition of the logical links between inter-related tasks while scheduling focuses on specifying the resources as well as start and end times of the tasks to achieve the design plan. The planning and scheduling of all design tasks must make sure that the project progresses in a timely controlled manner, in the meantime, ensuring the identification of successful design solutions, given the resources and time available. As such, it cannot be formulated as a quantitative search or optimization problem. Rather, it is a dynamic process with both quantitative and qualitative constraints that can be best resolved by human design managers supported by intelligent design collaboration supporting systems. In formulating a computational model for design management, it is assumed that a causal dependency exists between the available inputs and the produced outputs of a design task. Agents and other resources need to be scheduled by the design project manager component to do the various tasks of the design plan, by assigning them to tasks for a specified time interval. By assigning an agent and the needed resources to each of the tasks of the plan, the timing of each task is identified and the design schedule is made. The design schedule needs to state the critical path, and for each task its earliest and latest start and end time. Again, a qualitative approach to task scheduling is needed because of uncertainty at the beginning of a design project. As more information becomes available, the schedule may need to be constantly adjusted.

By determining which of the tasks' input has to be in place before the work on it can be started, and by finding out which tasks produce the required input, the dependency relationship between two tasks can be identified, and then a plan can be created. This plan describes an ordered sequence of tasks and the order is imposed by the tasks' input and out relationships. However, in a concurrent engineering context, shared tasks or Overlapping tasks are more difficult to coordinate than isolated tasks. Therefore computational mechanisms need to be identified in order to support a process of concurrent activities and non-monotonic reasoning underlining the nature of these tasks.

The design project manager component is also responsible for supervising the execution of the scheduled tasks. When a new task occurs, or the input for one of a design agent's tasks becomes available or changed, or a task or task assignment is invalidated, or the timing for a task has been changed, notifications will be sent to the concerned design agents with the support of constraint manager.

OVERVIEW OF THE AGENT-BASED SYSTEM

Based on the computational model of product design management described in previous section, we propose an agent-based system to facilitate, rather than automate, teamwork in a collaborative product design project where multidisciplinary designers or design teams involved are geographically and temporally dispersed.

Knowledge Representation

Due to lack of information about design management and coordination, the feature-based parametric product data model which is employed by popular CAX (CAD/CAE/CAM) systems is not rich enough to ensure effective and efficient collaborative design. To address this problem, we have developed a Collaborative Product Data Model (CPDM) to be used in our agent-based system. It is established by extending a parametric feature-based model to comprise three data modules: Collaborative Design Management Data, Design Coordination Data, and Product Data.

Collaborative Design Management Data contains the information for managing and maintaining product data in a collaborative product design process. Such information includes information about product designer, information about the organization, product data version, accessing and modifying permission, and information about the alternative strategies or processes.

Design Coordination Data contains the information to coordinate the collaborative product design process. Such information includes user-specified design constrains, rules to perform constraint propagation, and recording design history.

Product Data contains the product structural and physical information through the encapsulation of the parametric feature-based product data model.

Based on the CPDM, our system employs a constraint-based Collaborative Design Process Model (CDPM) which views a collaborative design process as a sequence of state transitions from one design state to another resulting from the design decisions made by designers and the precondition of design state transition is the consistency of all design constraints being preserved. Design constraint propagation and conflict notification are realized through a complex, dynamic, and hierarchical design constraint network.

A more detailed description of CPDM and CDPM can be found in authors' another paper (Wang and Tang 2005).

A Multi-Agent System Architecture

An agent-based system supporting collaborative product design is being developed based on the computation model of product design management and the data structures discussed above. It is organized as a network of intelligent agents which interact with each other and participating team members to facilitate collaborative design work. These agents include Project Management Agent, Design Agents, Product Data Management Agent, Design Coordination Agent, Design Communication Agent, Computational Support Agent, and Agent Manager. Among these agents, Project Management Agent fulfills the job of the Design Project Manager component of the proposed computational model of product design management, and Product Data Management Agent serves as the Product Data Manager component while Design Coordination Agent takes the responsibility of the Constraint Manager component. Design Communication Agent provides communication service for human designers or coordination message transporting service among other agents and human designers. Computational Support Agent provides engineering computation or analysis service and Agent Manager serves as the runtime environment for all other agents.

The system architecture and hardware configuration are illustrated in Figure 2. The architecture integrates all the agents with design and engineering tools/services including product database, design knowledge base, share/private workspace, and video conference system, to interact with human designers in an open environment. Next, the main agents being developed are described briefly.

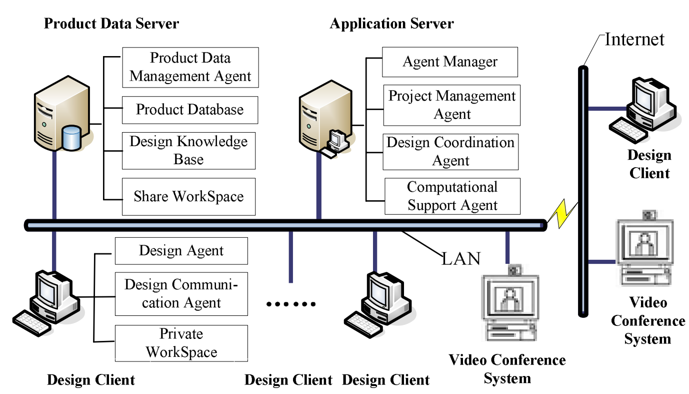


Figure 2. The general system architecture and the hardware configuration

Project Management Agent is responsible of helping project manager to describe the design project, specify the initial parameters and design constraints, decompose a complex design project into sub tasks, assign them to designers, schedule them and track the whole design process. It has a user interface for assisting project manager in managing the project plan and schedule, keeping track of progress of the project, and more importantly, making necessary changes while the plan gets more detailed and the higher levels of the plan have to be updated. Also, it serves to remind the project manager and involved designers of the outstanding issues related to schedule execution.

Design Agents encapsulate some traditional popular CAD systems and are used by designers to fulfill design tasks through cooperation with other agents. They will be described in details later.

Product Data Management Agent is responsible for managing the product database and ensuring the consistency of the product data in the product design process, and informing concerned design agents of the product data change event (such as submission, modification and so on) made by other design agents.

Design Coordination Agent serves to coordinate the design process through design constraint propagation, notifying involved designers of constraint conflicts and their respective reason, and helping designers address the conflicts.

Design Communication Agent provides support for interaction among designers by services, such as email, video/audio conferencing, file transfer service, application sharing, whiteboard, and etc or coordination message transporting service among other agents and human designers..

Computational Support Agent accounts for engineering calculations or analysis upon request. It may be a Finite Element Analysis tool, Optimizer of some other engineering computation tools.

Agent Manager is responsible for controlling the utilization and availability of all agents by maintaining an accurate, complete and timely list of all active agents through which agents residing in the system are capable of cooperating and communicating with each other.

All the agents are connected by a local network (LAN) via which they communicate with each other. Also, the external design agents residing on the internet carrying out specific design tasks can communicate with agents located in the local network via the Internet.

Design Agent

Although various agent-based systems have been developed in the domain of design, design agent as a generic component of an intelligent collaborative design environment has yet to be formally specified, implemented, integrated and tested.

In our system, a design agent is a kind of semi-autonomous and domain-dependent agent. It should be noted that these design agents are not intended to automate the design process, but provide support to human designers in terms of design knowledge, constraint propagation, conflict resolution, and design process coordination through cooperating with other agents. Components of a design agent are shown in Figure 3.

Traditional CAD software is encapsulated into the design agent using a wrapper. There have been some standards, such as CORBA, DOM, allowing for legacy applications to be encapsulated using wrapper classes and to behave as distributed components. There are three advantages of including CAD software in a design agent. First, traditional CAD software has been developed maturely and can provide very powerful solid modeling capabilities. Secondly, extra burden imposed on designers to get familiar with the collaborative design environment can be kept as less as possible. Thirdly, by integrating such systems, time and money will be saved.

Collaborative design tools assist designers in examining project information, exploring product data library, providing multiple design constraint view, checking consistency of design constraints, synchronizing product data, and etc, with the cooperation of other agents.

Design knowledge base is responsible of maintaining design knowledge and context knowledge. Design knowledge includes problem solving strategies, design rules, functions, methods, mathematical models whilst context knowledge includes the information relevant to the background and context in terms of antecedents and consequences to which the design knowledge is applied.

Communication layer provides a communication mechanism to facilitate the interaction with other agents through agent runtime environment. As KQML (Query and Manipulation Language) has been widely used in various agent-based systems to support communication processes among agents, and has been accepted as one of the standard agent communication languages, it is adopted as the communication language of our agent-based system.

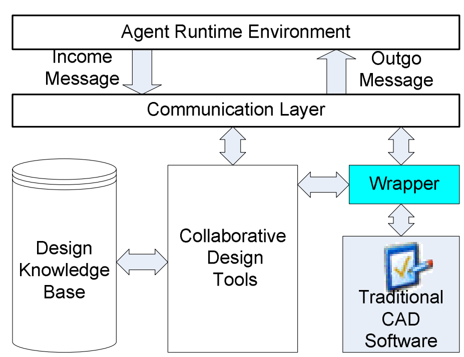


Figure 3. Components of a design agent

During the design task execution period, incoming messages from the communication layer are processed, then, actions will be taken according to the current status and the design knowledge stored in the design knowledge base. Human designers may be needed to confirm a certain design operation, deal with some design conflicts collaboratively with other design agents or only by themselves.

IMPLEMENTATION OF THE SYSTEM AND A DESIGN SCENARIO

Our agent-based system supporting collaborative product design is now being implemented on a network of PCs with Windows 2000/XP and Linux operating systems. Java is chosen as the primary programming language for the system implementation. The choice of Java language is based on many of its attributes that make it ideal for implementing intelligent agents and multi-agent systems. These specific features include its object-oriented style, support for threads, distributed objects, architecture-neutral, network-centric design and network access, and code portability. C++ is also used as the programming language for the integration of legacy systems. JNI (Java Native Interface) serves as the glue between Java-written applications and C++-wrapped native applications. JADE[1] (Java Agent DEvelopment Framework) which is a software framework fully implemented in Java language is utilised to develop the agent-based system. Currently, Inventor®, as one of the most popular CAD systems, is being encapsulated into our design agents through Inventor® COM API. FIPA ACL serves as the agent communication language. MySQL™ is used by the product data management agent as the database system for storing product data and design knowledge. The XML Schema has been used to represent the collaborative product data model.

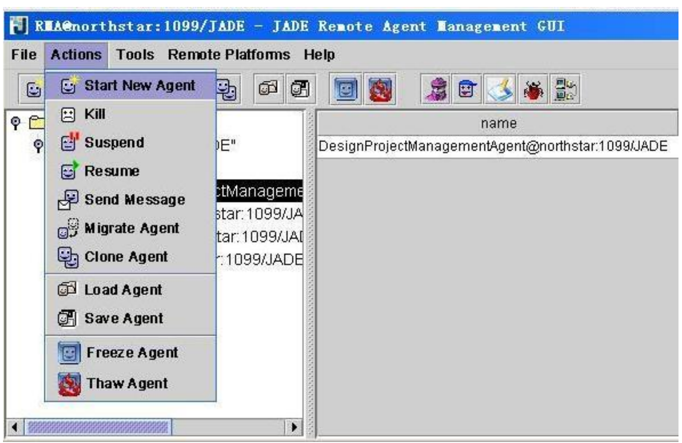


Figure 4. Main interface of the agent manager (JADE agent runtime environment)

The interface of our agent manager (JADE agent runtime environment) is shown in Figure 4. All the agents can register themselves in the agent manager and their life cycle can be controlled through this interface.

[1] JADE is a framework to develop multi-agent systems in compliance with the FIPA (Foundation for Intelligent Physical Agents) specifications. (http://jade.cselt.it)

The interface of design project management agent is shown in Figure 5. A design project to design a dinning table and chairs has been planned and scheduled. A design task tree can be easily established and the relationship among design tasks can be visually managed with the help of design project management agent.

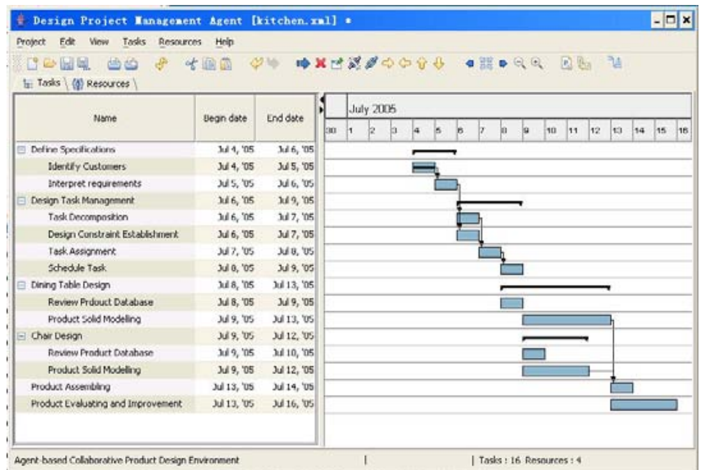


Figure 5. Main interface of the design project management agent

Next, we take a design scenario whose design objective is to design a dining table seating six persons and the chairs to illustrate how collaborative product design can be supported using our proposed system. The final design output should meet the following design specification:

Due to ergonomic reason, to let the users feel comfortable to dine when seating on the chair, the vertical distance between H1 - the height of the top surface of the dining table, and H2 - the height of the seat of the chair, should be within the range [200, 400] (mm).

The chairs can be packed under the dining table to save room when there is no person using them.

We suppose a design team consisting of one manager (Manager1) and two designers (Designer1 and Designer2) are responsible for this design project.

1. Through interaction with project management agent, Manager1 describes and decomposes the design task into two design tasks, plans and schedules these two tasks by assigning task 1, design of the dining table, to Designer1, and task 2, design of the chair, to Designer2 (Figure 5). Then, the project management agent begins to track the design process.
2. Upon receiving design tasks, Designer1 and Designer2 can start the design work and update the design progress through Design Management Agent in time. Status of task being carried out including ahead of schedule, on schedule, behind schedule, or any other change will be communicated to involved team members by Design Management Agent.

3. Suppose Designer1 receives his/her design task, he/she first searches the product data base according to the specification of the task. If there are existing designs matching the design requirements, then, those designs would be shown. Desinger1 can accept one of those designs or simply reject all of them. When he/she rejects the design or there is no matching design, he/she must create a new design with the assistance of design agent. We name the dining table and chair designed by Designer1 and Designer2 as DiningTable1 and Chair1 respectively.
4. Suppose the initial product assembly – Assembly1, is built by adding one DiningTable1 and one Chair1. Then, four design constraints are defined according to previously described design specification as followed (Figure 6 and Table 1):

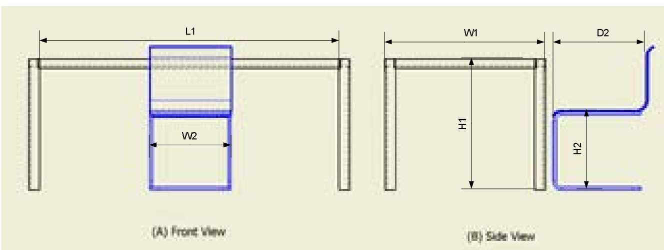


Figure 6. Design of a dining table with a chair

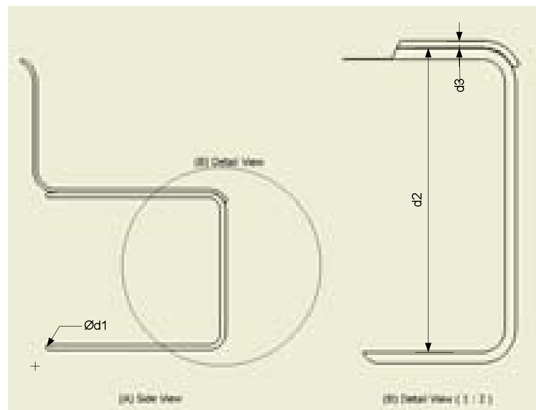
Table1. Design constraint set defined

Constraint 1	DiningTable1.H1-Chair1.H2 <= 400
Constraint 2	DiningTable1.H1-Chair1.H2 >= 200
Constraint 3	DiningTable1.L1 * 2 – Chair.W2 * 6 >= 0
Constraint 4	DiningTable1.W1 – Chair1.D2 >= 0

Abbreviation:

H1: Height of the table top
W1: Width of table top
W2: Width of chair seat
L1: Lengthwise distance between table legs
H2: Height of the chair seat
D2: Depth of chair seat

5. Designer2 defines some design variables as the form of mathematical equation of product design parameters among which design variable H2 is defined as followed with the support of design agent (Figure 7):
6. Suppose that design variable H1 takes the value of 730mm and the design parameters of current Chair1 instance state take the following values: d1 = 30 mm, d3 = 15 mm.
7. We assume that a design decision is made by Designer2 and this design decision is to assign a value of 460mm to design parameter d2 of Chair1.
8. The design coordination event will be triggered to check the consistency of design constraints against design constraint network. With the support of constraint management agent, the DiningTable1 is found to be referenced by Assembly1. Then, the design constraints defined for Assembly1 are evaluated to check their consistency. Design Constraint 2 is found to be violated. Designer1 and Designer2 are found to be involved in this design constraint. An event would be triggered to notify Designer1 and Designer2 of this constraint violation and conflict resolution suggestion.
9. After negotiation with Designer1 through design communication agent, Designer2 makes another design decision by assigning a new value of 390 to design parameter d2. This time, no constraint violation is found by the design coordination agent. Product data state is updated to reflect the design decision by product data management agent.
10. When all design subtasks are all finished, their design solutions will be assembled and checked according to the relations and constraints with respect of the design specification and assembly requirement. If any conflict occurs, the designers have to resolve it by negotiation with the help of the communication agent and the design coordination agent. This process will repeat until a globally desired design solution is reached (Figure 8).



Design Variable **H2**: (Height of the chair seat)
H2 = d2 + d1 *2 + d3
(Note: d1 is the diameter of the circle-shaped profile of a sweep feature which forms the supporting structure of the chair seat.)

Figure 7. Design variable definition

From this design scenario, we can find that the product design project can be well managed and the design process can be coordinated effectively with the support of our agent-based system. Violation of design constraints can be informed in time and the cooperation of distributed designers can be well facilitated.

Note that in the design process described above, only the designer has the right to make any design decisions that he/she wishes at any stage of the design process and our system is not intended to automate the design process, but provide support to human designers in terms of design knowledge, conflicts propagation and design plan change notification during task executing period through cooperating with other agents during the design process.

Figure 8. Final design of a set of dining table and chairs

CONCLUSIONS

In this paper, on the basis of the problem identification and the reviews of the research in relevant areas, a computational model of collaborative product design management is proposed firstly. Then, a new framework of collaborative design which adopts an agent-based approach to facilitate the management and coordination of collaborative product design process via the cooperation of a network of intelligent agents is proposed. The system architecture of our proposed system is presented and a formation of design agent is described in details. A real design example is used to illustrate how collaborative design is supported. As the system is still being fully implemented, more experiments are required to be carried out in order to test and improve our system. In the future testing of our approach and software, we intend to involve designers in the process with design examples of more substantial scale than the dinning table and chairs presented in this paper since we believe that a design-oriented approach needs to be taken in order to identify those key tasks that need collaboration and support by software agents.

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REFERENCES

Cutkosky, MR, Engelmore, RS, Fikes, RE, Genesereth, MR, Gruber, TR, Mark, WS, Tenenbaum, JM and Weber, JC: 1993, PACT: An experiment in integrating concurrent engineering systems, IEEE Computer, Vol. 26(1), pp. 28–37.

Frazer, JH: 2001, Design Workstation on the Future, Proceedings of the Fourth International Conference of Computer-Aided Industrial Design and Conceptual Design (CAID &CD 2001), International Academic Publishers, Beijing, pp. 17-23.

Goldmann, S: 1996, Procura: A Project Management Model of Concurrent Planning and Design, Proceeding of WET ICE'96, Stanford, CA.

Lander, SE: 1997, Issues in Multiagent Design Systems, IEEE Expert, Vol. 12(2), pp. 18-26.

Liu H, Tang MX, Frazer JH: 2002, Supporting evolution in a multi-agent cooperative design environment, Advances in Engineering Software, Vol. 33 (6), pp. 319-328.

Park, H, Cutkosky, M, Conru, A, and Lee, SH: 1994, An Agent-Based Approach to Concurrent Cable Harness Design, Artificial Intelligence for Engineering Design, Analysis and Manufacturing, Vol. 8(1), pp. 45-62.

Parunak, HVD: 1998, What can agents do in industry, and why? An overview of industrially-oriented R&D at CEC, In M. Klusch, and G. Weiss, (Eds.) Cooperative information agents II: Learning, mobility and electronic commerce for information discovery on the Internet: Second International Workshop, CIA'98, Springer, Paris, France, pp. 1–18.

Petrie, C, Cutkosky, M, Webster, T, Conru, A, and Park, H: 1994, Next-Link: An Experiment in Coordination of Distributed Agents, Position paper, AID-94 Workshop on Conflict Resolution, Lausanne.

Rosenman, MA and Wang, F: 2001. A Component Agent Based Open CAD System for Collaborative Design, Automation in Construction, Vol. 10(4), pp. 383–397.

Shen, W and Wang, L: 2003, Web-Based and Agent-Based Approaches for Collaborative Product Design: an Overview, International Journal of Computer Applications in Technology, Vol. 16(2/3), pp. 103-112.

Shen, W and Barthes, JP: 1997, An experimental environment for exchanging engineering design knowledge by cognitive agents, In M. Mantyla, S. Finger and T. Tomiyama (Eds.), Knowledge intensive CAD-2, Chapman and Hall, pp. 19–38.

Tang, MX: 1997, A Knowledge-based Architecture for Intelligent Design Support, International Journal of Knowledge Engineering Review, Vol. 12(4), pp. 387-460.

Wang, JX, and Tang MX: 2005, Knowledge Representation in an Agent-Based Collaborative Product Design Environment, Proceedings of the 9th International Conference on Computer Supported Cooperative Work in Design (CSCWD 2005), Coventry, UK, pp. 423–429.