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A FRAMEWORK FOR COLLABORATIVE TOP-DOWN ASSEMBLY DESIGN

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ABSTRACT

This paper presents a system framework to support the collaborative top-down assembly design. As the first step, the framework is devised to enable distributed designers to conduct collaborative layout design, 3D skeleton design and detailed design of a product in a top-down manner in a distributed environment. To effectively support the collaborative top-down assembly design, a multi-resolution and distributed product assembly model is proposed as a product representation in the framework. With the help of the framework the designers could conduct those design activities of top-down assembly design that need plenty of collaboration such as the collaborative determination of assembly relationship and coupled structural parameters. A variation propagation mechanism is also developed to guarantee the consistency of the distributed assembly model. A preliminary system prototype based on replicated client-server architecture is implemented.

Key Words: Collaborative assembly design, Top-down design, Assembly model, Variation propagation

1 INTRODUCTION

The design of a complex mechanical product is generally carried out collaboratively by different teams or designers that are geographically distributed. This design process is usually a top-down process which goes through requirements analysis, conceptual design and detailed design. After the concept design is completed during the collaborative design process, the primary task of the designers is to collaboratively create the product assembly model according to the concept design model. It is a collaborative and evolutionary refinement process during which the designers undertaking different subassemblies or parts collaborate with each other to fulfill the product assembly design from layout design to detailed design.

Traditional CAD systems are standalone and provide only limited support for the top-down mechanical design. Therefore they can not fully support the collaborative top-down assembly design. As the rapid evolution of the global economy, a distributed CAD system which enables the designers to collaboratively accomplish the product assembly design in a top-down way is of great importance and beneficial to the product design.

A system framework that can support the collaborative top-down assembly design is presented in this paper. The rest of the paper is organized as follows. Section 2 introduces some related work. Section 3 describes the collaborative top-down assembly design process proposed in the paper. Section 4 describes the framework overview of the paper. Section 5 describes the product assembly model to support the

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collaborative top-down assembly design. Section 6~9 describe the main aspects of the framework including the layout design, the coupled structural parameter determination, the variation propagation mechanism and the collaborative design of assembly relationship. Section 10 presents a design example and the last section concludes the paper.

2 RELATED WORK

2.1 TOP-DOWN PRODUCT DESIGN

As Mäntylä [1] describes, the design of a mechanical product usually takes place primarily in a top-down fashion, where the designer first generates a rough, overall sketch of the product and its main components; later, the designer refines the sketch to a detailed level while taking into account the relevant requirements posed by strength, cost, manufacturability, serviceability, and other similar considerations. Because the existing schemes for assembly design are not flexible enough to be useful for early design. The mechanical design prototype is introduced by Gui [2]. An assembly model is developed as an instance of a mechanical design prototype. It is represented as a combination of functional model, a connector-component structural model, and a process-oriented bond graph model. Inheritance of geometry from coarse level to detailed level is provided. Similarly, Csabai [3] proposes that the exact geometry model should not be committed too early as the functionality has not been fully finalized. A top-down 3D layout design system is presented which forms a bride between the abstract nature of the conceptual design phase and the geometric nature of the detail design phase.

The top-down design is an iterative evolutionary design process during which the design information inheritance and consistency management should be significantly considered. Chung [4] presents a unified framework towards supporting a more complete design process including design specification, conceptual design, detailed design and design validation. A complete mathematical description of the design model is proposed which allows downstream tasks such as mechanism analysis to be performed without having to rebuild analysis-specific models. Brunetti [5] introduces an approach which incorporates a feature-based representation scheme for capturing product semantics handled in the conceptual design phase and linking early design with part and assembly modeling. Noort [6]develops a modeling system which uses enhanced multiple-view feature modeling. By means of feature views and ways to keep these interpretations consistent, the system supports integration of detail design of parts and assembly and enables requirements for part detail design to be taken into account during assembly design, and vice versa. Aleixos [7] proposes an approach to introduce conceptual design through top-down methodology and integrate it with final geometry. It is realized with the elaboration of product-oriented modeling guidelines, or ‘best modeling practices’, instead of CAD-oriented modeling guidelines.

The industrial CAD system Pro/E [8] provides functions to support top-down design. It consists of six major steps that are used to develop the assembly design in an organized manner. But Pro/E is standalone and difficult to support the real-time collaborative design.

2.2 COLLABORATIVE PRODUCT DESIGN

Several aspects should be considered for a collaborative product design environment, such as product information model, collaboration, the design information exchange and share and feasible system architecture and so on.

One fundamental issue in collaborative product design is the product information model which supports communication and coordination. Such product information model includes not only the geometric information but also non-geometric information such as specification, design rationale and so on. Wong [9] describes an information model called SHARED which provides multiple levels of both functional and geometric abstractions and multiple views. How to maintain consistency between the various abstractions and views is described. The product master model developed by Hoffmann [10][11] is an object-oriented repository that provides essential mechanisms for maintaining the integrity and consistency of the deposited information structures. It has several domain-specific clients and each client has a view of the product model. The mechanisms are presented for maintaining consistent distributed product views. Shyamsundar [12] presents a geometric representation called AREP for collaborative product design. There are two versions of AREP. One is the primary representation stored on the server which consists of the complete model information. The other is the secondary representation that is utilized in the client that consists of the compressed facet representation of the geometry. Chen [13] proposes the Collaborative Assembly Representation (CAR) for the Internet-based collaborative assembly modeling. Two different versions of CAR are presented called master assembly model (MAM) and slave assembly model (SAM). MAM is a complete version of CAR and is stored on the server side. SAM is a simplified version of CAR and is used for display on the client-side.

To realize a truly collaborative product design, it is crucial that designers can effectively collaborate with each other to collaboratively accomplish the product design. Kim [14] proposes ontology-based assembly design and information sharing for collaborative product development. The ontology used in heterogeneous and distributed design collaboration will explicitly and persistently represent engineering relations. It enables the design intent to be captured and shared. Zhou [15] proposes an Internet-based distributive knowledge system to meet the demand of designers on various knowledge resources. An approach of function driven knowledge search is proposed that can be used within the Internet environment. Li [16] presents a client/server framework to enable a dispersed team to accomplish a feature-based design task collaboratively. Based on a distributed feature-based representation and feature-to-feature relationships, a manipulation client and modeling server infrastructure is proposed. Henderson [17] investigates the problem of automatically satisfying constraints in product models that are distributed among a variety of CAD systems at different physical locations. Their approach supports for a broad range of constraint types encountered in design and can operate without a single, central constraint repository.

The typical system architecture supporting collaborative product design can be classified as client/web–server based and Agent/service based. Bidarra [18] presents a framework that supports synchronous collaborative sessions via the Internet. The design of a single component and specification of assembly relations is supported by corresponding specialized web-client. Shyamsundar [19] proposes a three-tier client-server based collaborative design environment which has an intermediate server that turns forward the requests from the client to the application server. The OpenADE presented by Lyons [20] is an open architecture that provides standard interfaces that allow it to link to commercial and noncommercial design tools such as parametric design systems, virtual reality environments, assembly analysis tools, and assembly process planners. Mori [21] proposes an architecture in which engineering design agents interact with each other, exchange design information and keep track of state information to assist with collaborative design. A coordination algorithm focusing on the history of design states and operations is presented.

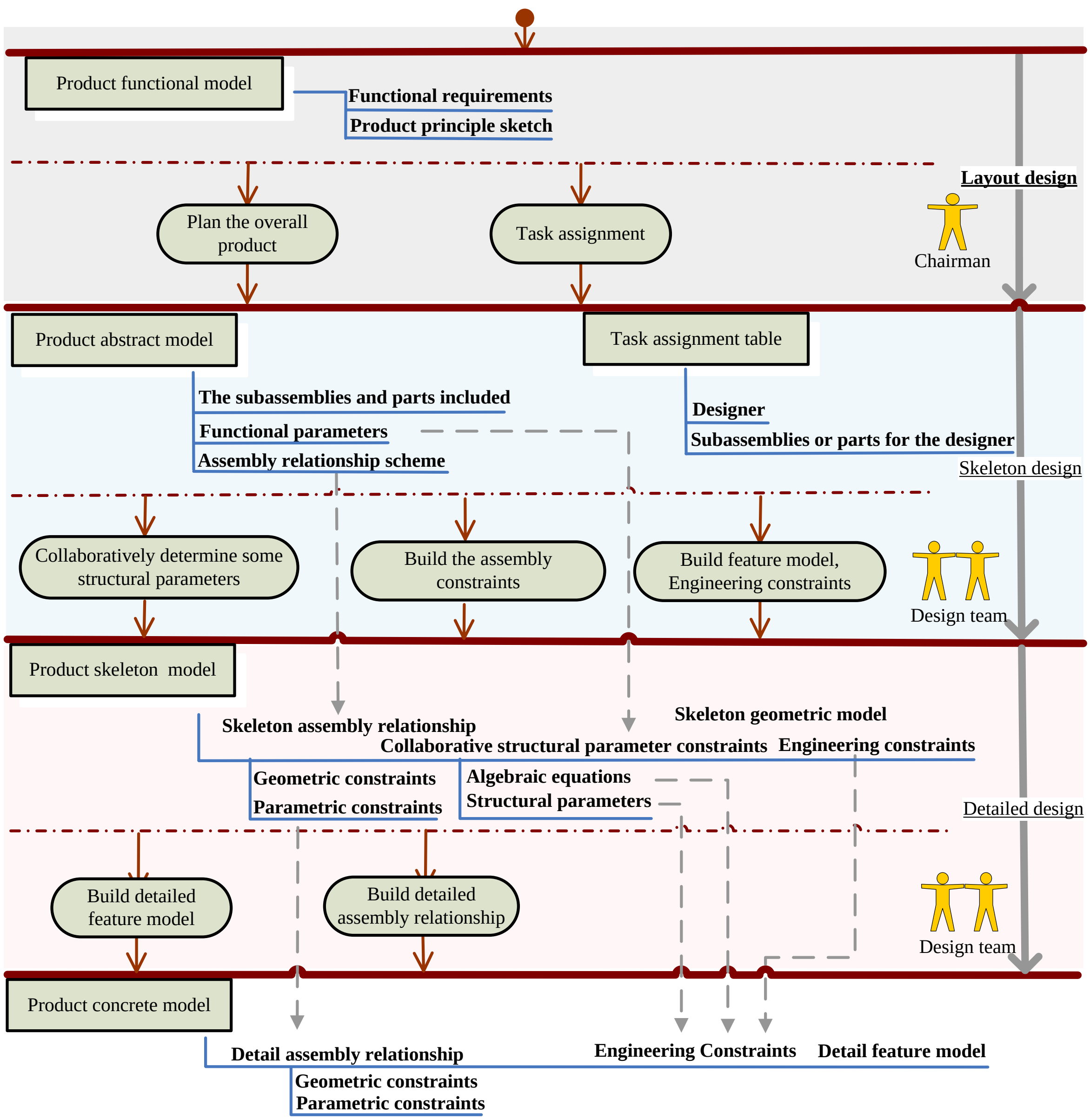


Figure 1: The schematic of collaborative top-down product assembly design

3 COLLABORATIVE TOP-DOWN ASSEMBLY DESIGN

Because of the complexity of the collaborative top-down product design, as the first step, our research currently focuses on the design process after the concept design. It is divided into three main design phases: the layout design, the skeleton design and the detailed design, as shown in Figure 1.

1. Layout design. Layout design is accomplished by the chairman whose main design activities can be summarized as following: a) Select a collection of key parts and subassemblies and establish specifications of their relationships according to the concept design results to set up a layout model of the design; b) Assign the subassemblies and key parts in the layout model to different designers according to the human resource.

2. Skeleton design. Skeleton design is collaboratively accomplished by the designers. At this design stage the 3D skeleton of the product is created which overlooks some detail to avoid resorting to the final geometry too early. The main design activities at this design stage can be summarized as following: a) Determine the structures of the key subassemblies or parts, and then calculate some key structural parameters according physical principles; b) Collaboratively determine the assembly relationship schemes which usually are specifications without final geometric or parametric constraints; c) Determine the overall geometric shapes and positions for the key subassemblies and parts of the product.

3. Detailed design. At this design stage, the designers fully accomplish the detailed assembly design. The main design activities of this design stage can be summarized as following: a) Accomplish the final structure of the product with some new subassemblies or parts; b) Create the detailed feature models of all the parts; c) Collaboratively finalize the assembly relationships with assembly constraints and parametric constraints.

4 A FRAMEWORK TO SUPPORT THE COLLABORATIVE TOP-DOWN ASSEMBLY DESIGN

4.1 REQUIREMENTS FOR THE COLLABORATIVE TOP-DOWN ASSEMBLY DESIGN

Considering the collaborative top-down assembly design's characteristics, the following requirements must be satisfied to enable a collaborative CAD system to support this design process.

1. A product assembly model to support the collaborative top-down assembly design process. It should represent not only the detailed design information such as geometry model, but also high level information of the layout design and the skeleton design. Furthermore, the product assembly model should be able to be distributed at different locations.

2. An effective machnism of achieving the design information inheritance and evolution during the design process.

3. The ability for the designers to communicate and collaborate with each other to avoid design conflicts.

4. The consistency guarantee of the assembly model based on the variation propagation among all the clients and the server.

4.2 OVERVIEW OF THE FRAMEWORK

The collaborative top-down assembly design is an iterative refinement process with a lot of distributed assembly model operations, especially geometry model operations. Mostly the designer works on his/her own subassembly or part which can be processed locally while for those operations which affect other designers' subassemblies or parts, a central server is needed. Based on these considerations, a system framework to support the collaborative top-down assembly design is proposed as shown in Figure 2, which is a replicated client-server based architecture. The server is responsible for the global design information management. The client provides the ability for the designer to interactively do some design work and is responsible for local design information management. A command based information exchange method between the server and the clients is adopted as the clients and the server have similar functional components.

Two layers can be distinguished for the system: the kernel layer and the communication layer.

The kernel layer:

The ground of the kernel layer is some functional modules that are similar to that of the traditional CAD system including the feature modeler, geometry engine, constraint engine and global ID generator. The feature modeler provides the ability for feature modeling such as adding features, removing features, or modifying the parameters of features. It is constructed based on a commercial geometry engine. The constraint engine located at the server is responsible for constraints solving. It has the ability to solve the geometric constraints and parametric constraints. Because the constraints usually need to be solved globally, the constraint engine is not deployed at client. Global ID generator is used to produce the global object ID to ensure the object ID to be identical all over the clients and the server.

To support the collaborative top-down assembly design, the kernel layer has some extended functional modules relying on the modules discussed above. They are summarized as following.

Assembly modeler: it is responsible for assembly modeling in a top-down method such as collaboratively define the assembly relationship, product structure design and assembly feature and assembly constraint design.

Layout design module: it is responsible for the assembly layout design which is accomplished by the chairman.

Coupled structural parameter manager: It is responsible for the designers to collaboratively determine the coupled structural parameters.

Collaboration manager: it supports the designers to coordinate with each other. Usually it will invoke other functional component to accomplish the collaboration.

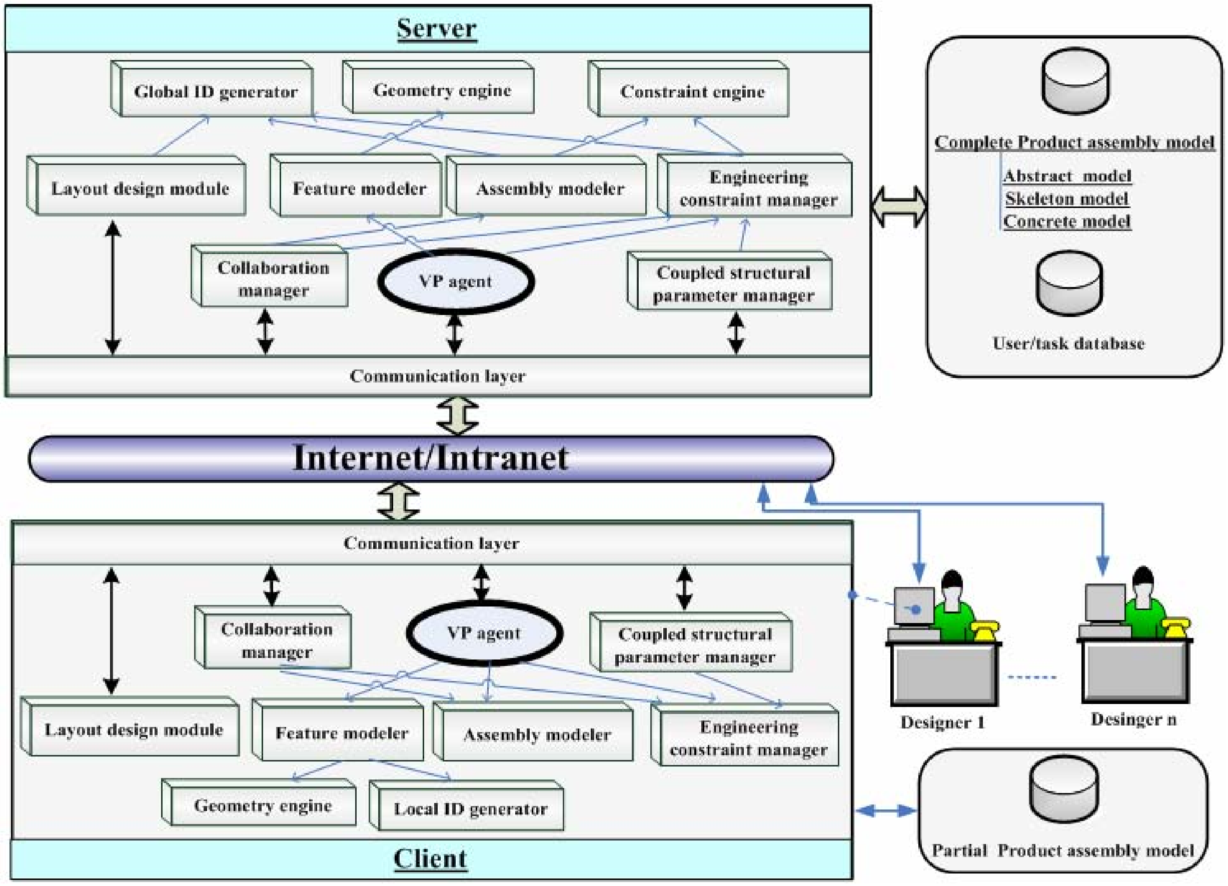


Figure 2: The system architecture for the collaborative top-down assembly design

Variation propagation agent: it is responsible for the design variation propagation which guarantees the consistency of the product assembly models of the clients and server.

The communication layer:

Communication layer is used by the components to send or receive data through the network. The components that have the ability to use the network are illustrated in the figure 2.

Because the responsibilities for the clients and the server are different, the assembly models stored are different. For the server, a complete assembly model is stored which contains the whole information of the assembly model. On the other hand, a partial assembly model is stored in each client which only contains the information that is necessary for the designer to accomplish his/her design task. Furthermore, the database containing the information about the designer and task assignment result is deployed at the server.

5 THE COLLABORATIVE ASSEMBLY MODEL SUPPORTING COLLABORATIVE TOP-DOWN ASSEMBLY DESIGN

To effectively support the collaborative top-down assembly design, following requirements for the assembly model should be considered: contain the design information required by all the three design stages; support the assembly model distribution at the server and the clients. According to the above requirement analysis, we put forward a product assembly model, as shown in Figure 3.

5.1 COLLABORATIVE ASSEMBLY MODEL SUPPORTING ALL THE THREE DESIGN STAGES

Our product assembly model is a hierarchical object oriented model, each level of which corresponds to the representation for a design stage of all the design stages.

The primary objects for the layout design include the AbstractPart, AbstractSubassembly and AbstractAssemblyRel. They are used to represent the abstract level of the part, subassembly and assembly relationship. AbstractPart and AbstractSubassembly contain such information as the name, the functional description and so on. AbstractAssemblyRel is a specification for the assembly relationship which includes the desired functional outcome such as the assembly scheme, assembly method and so on.

The objects for the skeleton design mainly include the SkeletonPart, SkeletonSubassembly, SkeletonAssemblyRel and Engineeringconstraint. SkeletonPart and SkeletonSubassembly refer to the FeatureList to represent their skeleton shapes as feature models. SkeletonAssemblyRel represents the assembly relationship information for the skeleton assembly model such as the geometric and parametric constraints. EngineeringConstraint is used for the calculation of some structural parameters and contains some parameters and the constraint network expressed as algebraic equations.

The basic objects for the detailed design are the ConcretePart, ConcreteSubassembly and ConcreteAssemblyRel. ConcretePart has the detail feature model which uses a boundary representation for its geometry model. ConcreteSubassembly is the detail representation of the subassembly which includes subassemblies and parts it contains and the internal assembly constraints. ConcreteAssemblyRel contains the detailed assembly constraints such as geometric and parametric constraints.

5.2 THE ASSEMBLY MODEL DISTRIBUTION ON SERVER AND CLIENTS

To support the collaborative top-down assembly design, the assembly model should be distributed at the server and the clients. Different assembly model information is stored at the server and clients according to their requirements.

The assembly model on the server is a complete assembly model including the whole assembly model information. To indicate how the assembly objects are distributed each subassembly or part points to a ClientContext object. It indicates the client's information associated with the designer such as the designer ID, status and address and so on. The LocalID and GlobalID are used to ensure the distributed object ID to be identical all over the distributed system. The LocalID is the ID that is generated and maintained by the client while the GlobalID is produced and managed by a central component located at the server. To refer to an object, the ID path is used which includes the ID sequence from the root to the object in the product model tree.

Because the design task of different designer is different, the assembly model at different client is different. A partial product assembly model is adopted to represent the assembly model distributed at the client which is dynamically loaded according to the designer's design information requirement. Since different subassemblies and parts of the assembly model are interrelated, during the design process a designer needs to be aware of others' design information that has correlation with his/her design task. Base on this, the partial product assembly model includes both the information of the subassemblies or parts undertaken by the designer and those having correlations with them. This is illustrated in Figure 4 in which the client assembly model for designer A contains not only all the information of subassembly A which is designer A's design task but also all the information of subassembly B because subassembly B and A are correlated through assembly relationship. It should be pointed out that every client also has the abstract assembly model of the whole product. So in Figure 4 the abstract assembly model of subassembly C is also included in the client assembly model of designer A.

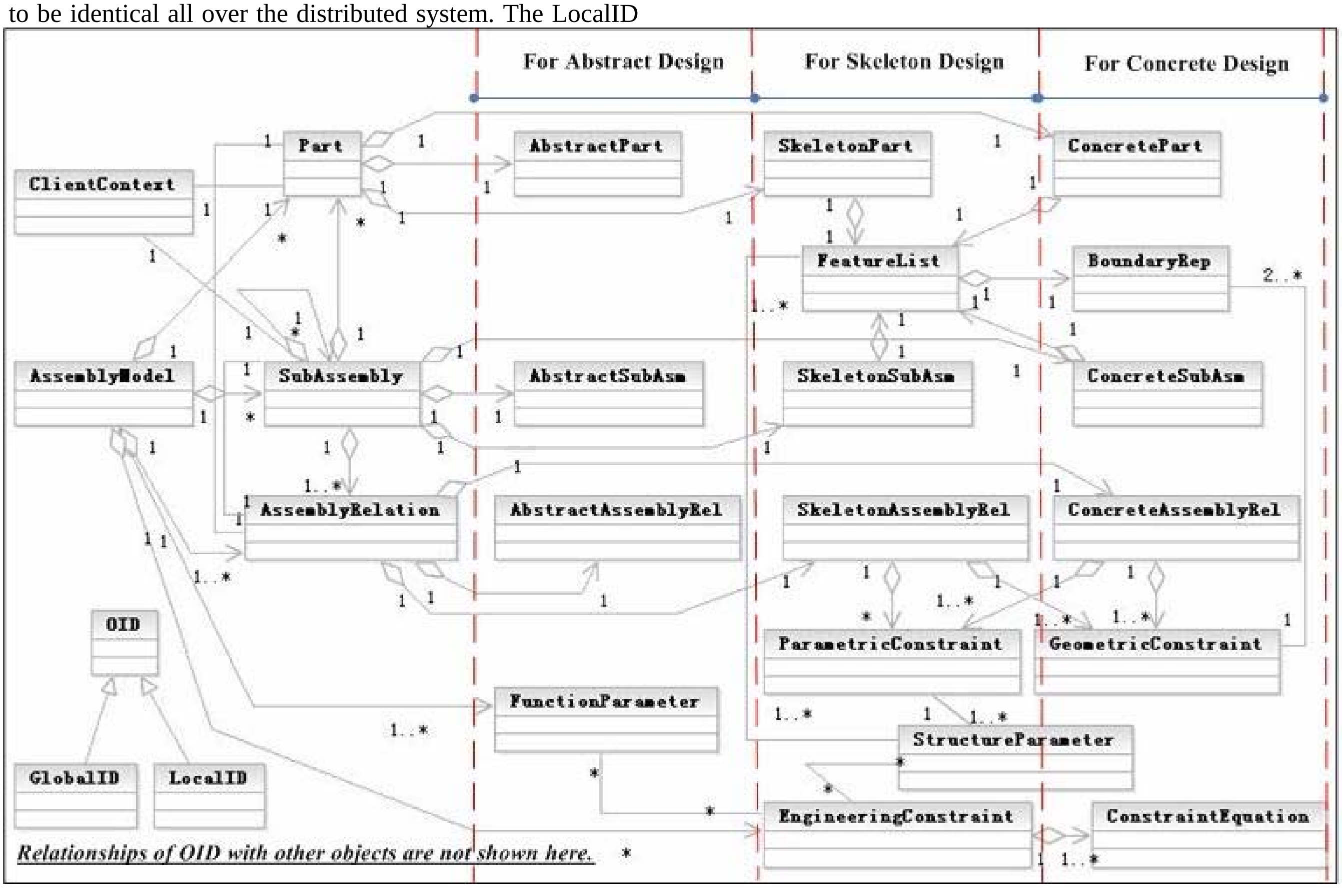


Figure 3: Class diagram of the collaborative assembly model

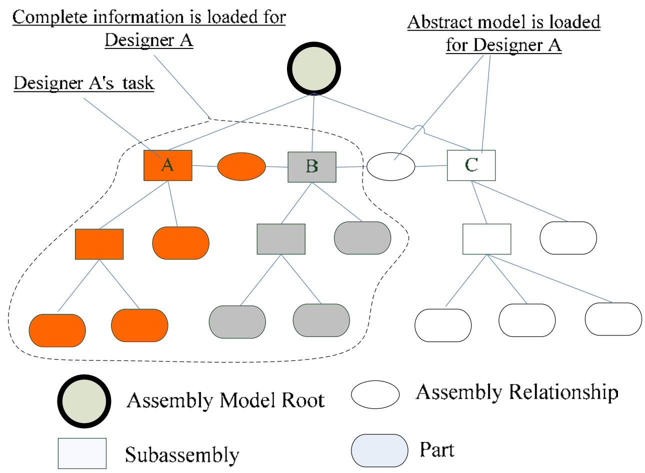


Figure 4: Illustration of the assembly model at Client

6 SYMBOL BASED LAYOUT DESIGN

The main task of layout design is to set up the abstract assembly model which mainly contains the key subassemblies and parts together with their assembly relationships. The subassemblies and parts contained in the abstract model have no geometry model and the relationships are only specifications focusing on the desired functional outcome without geometric or parametric constraints.

The layout design module provides the ability of creating symbol based abstract assembly model. The subassemblies or parts are represented as standard symbols which are curt 2D sketches. They have engineering meanings that can be understood by the engineers. A symbol library is adopted to support the symbol based layout design which is extensible in that the designers can define their own symbols if needed.

To improve the usability, the intuitive drag and drop user interaction paradigm is adopted. It enables the designers to create the symbolic subassemblies and parts and add specifications to the symbols.

7 COLLABORATIVE DETERMINATION OF COUPLED STRUCTURAL PARAMETERS

Before building the 3D skeleton of the product, the designers firstly have to figure out the key structural parameters. And all the coupled parameters must be collaboratively determined by different designers. The designers collaborate with each other to establish the constraint network involving both functional parameters and structural parameters. The constraint network is solved and the results of the parameters are sent back to the related designers to be checked collaboratively. Figure 5 shows the architecture of the collaborative determination of coupled structural parameters

As shown in Figure 5, the coupled structural parameter manager (CSPM) on the server and the client is responsible for the collaborative determination of coupled structural parameters. The CSPM on the server is responsible for the management of the related structural parameters, functional parameters and constraints. Also it resorts to the constraint engine to solve the constraint network and returns the outcome to the CSPMs of the clients. The CSPM on the client supports the designer to interactively manage the parameters and the constraint network. The CSPMs of the server and client communicate with each other in order to accomplish their task such as refresh the constraint network; retrieve the parameter results and so on.

8 AGENT BASED DESIGN VARIATION PROPAGATION

Variation propagation is the process during which the design variations initiated by any designer at client are instantly monitored by the server, and the server then updates the assembly models of both the server and clients accordingly. Its ultimate target is to ensure the distributed assembly model to be consistent. To address this issue an agent based approach for variation propagation is adopted. Through the interactions and cooperation of the agents located at the clients and the server, the system achieves automated and intelligent variation propagation. Its overall architecture is shown in Figure 6.

As shown in Figure 6, anytime the assembly model is changed at one client, the server will immediately know it because the server VP (variation propagation) agent keeps on monitoring the variations of all the clients. Then the server VP agent infers all the objects that will be affected and the related clients. To update its own assembly model, the server VP agent

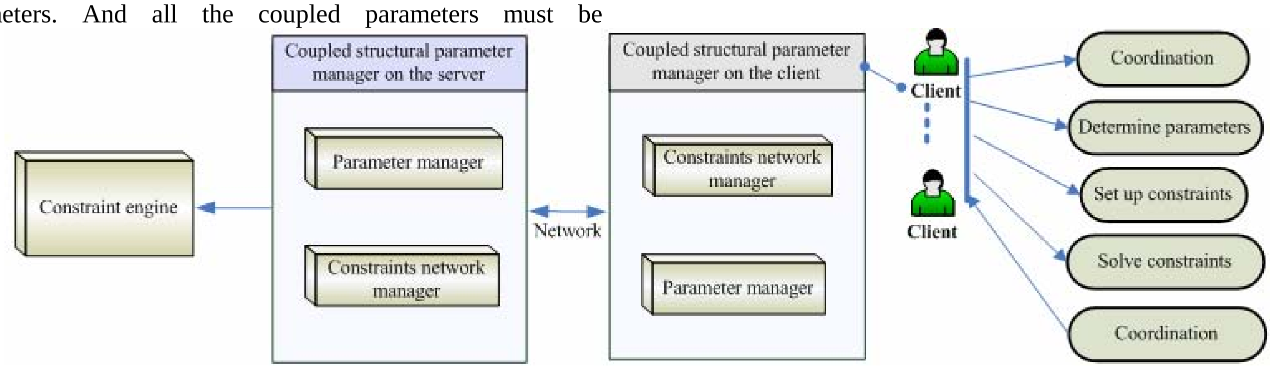


Figure 5: Collaborative determination of coupled structural parameters

assigns the variation request to corresponding functional components. To update the assembly model of the related clients, the server VP agent sends the necessary information to the clients whose VP agents then update the client assembly models accordingly. To accomplish the variation propagation, a command based method for data exchange between the client and sever is adopted. It directly transmits commands between the client and server and greatly reduces the data to be transferred through the network.

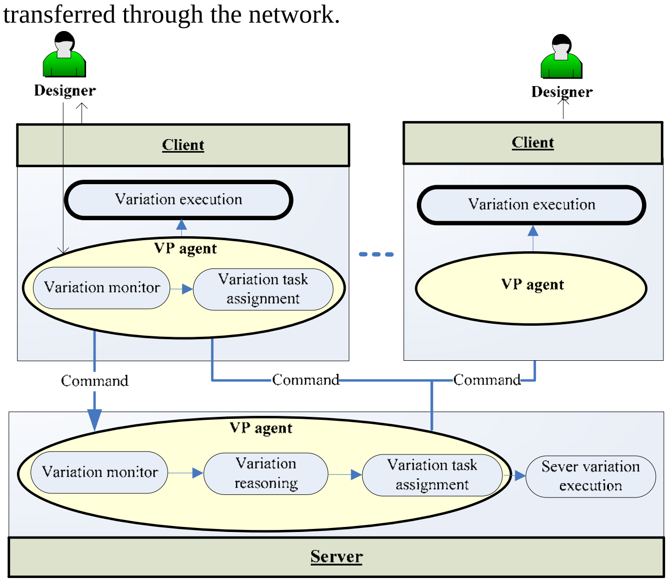


Figure 6: Agent based variation propagation architecture

9 COLLABORATIVE DEFINITION OF ASSEMBLY RELATIONSHIP

During the design process, for an assembly relationship whose relevant subassemblies or parts belong to different designers, it has to be collaboratively defined by the designers. This is a process during which the designers collaboratively define the assembly relationship from the skeleton design stage to detailed design stage. As shown in Figure 7, the process mainly includes the abstract assembly relationship define, the skeleton assembly relationship define and the concrete assembly relationship define. Initially the abstract assembly relationship is created which has no actual geometric constraints or parametric constraints. At the skeleton design stage, the designers discuss with each other to determine the assembly method and construct some assembly constraints. At the detailed design stage detail geometric and parametric constraints are collaboratively determined by the designers, necessary features for the constraints are created by the corresponding designers, and then the actual constraints are defined and the concrete assembly relationship is finalized.

The assembly modeler is the main component that supports this collaborative assembly relationship definition. It is responsible for the construction and modification of the assembly relationship and the assembly constraints such as the geometric and parametric constraints. The difference between assembly modelers of the clients and the server is that the latter will resort to the constraint engine to solve the assembly constraints while the former not. During the collaborative assembly relationship definition process, it is necessary for the designers to discuss with each other, modify their feature model for the assembly constraints. Such work can be done with the help of the system components of collaboration manager and feature modeler.

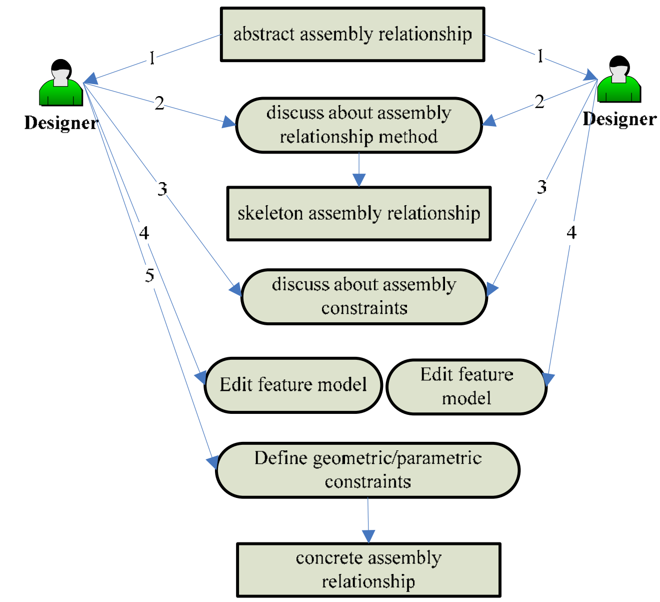


Figure 7: Collaborative definition of assembly relationship

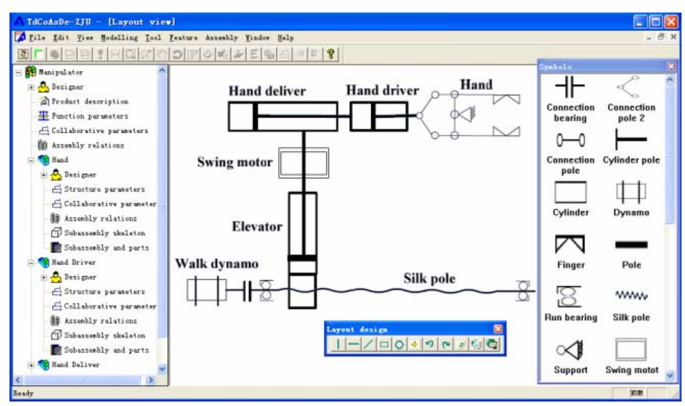


Figure 8: Abstract assembly model created by the chairman

10 A COLLABORATIVE TOP-DOWN DESIGN EXAMPLE

The process of a number of designers collaboratively design a manipulator in a top-down way is given as an example. Initially the chairman describes an abstract assembly model as shown in Figure 8 according the result of the concept design and assigns different subassemblies to different designers. The chairman creates the abstract assembly model with the layout design tool. The abstract assembly model created by the chairman in Figure 8 includes five key subassemblies. Each subassembly includes the specification such as the name, function request, function parameters and so on. The abstract assembly model also includes the assembly relationships which describe the desired outcome that emphasizes particularly on the functional aspects.

When the designers logon the clients, the entirely abstract assembly model is transferred to each of them. The client will then prompt the designer about his/her design task according to the name of the designer. Then the designers collaboratively accomplish the assembly design which goes through the skeleton design and detailed design.During the skeleton assembly design process, the main work of the five designers is to collaboratively determine some coupled structural parameters, collaboratively determine those assembly relationships that connect the subassemblies belong to different designers, collaboratively set up the overall shape of the manipulator. This is illustrated in Figure 9 and 10.

Figure 9 shows the skeleton assembly model of the manipulator. In the figure, (S) is the complete assembly skeleton model located at the server; the skeleton models located at the clients are showed in C1~5. As shown in the figure, the skeleton model located at each client includes not only that of the subassembly undertaken by the designer, but also that of the subassemblies related to the designer through the assembly relationships. Figure 9 also shows how designer 1 and designer 2 collaboratively define the assembly relationship. Using the conference tool shown in Figure 9(D), the designers can discuss about the assembly relationships, then one of them, supposing designer 1, defines a assembly relationship called ‘Rod connection’, as shown in Figure 9(E).

Figure 10 shows how designers collaboratively determine the coupled structural parameters. As shown in the figure, some crucial structural parameters such as L_b, L_c, a, b and so on are constrained by the algebraic equations shown in this figure. These parameters are collaboratively determined as the parameters are concerned by both designer 1 and 2. The screenshots illustrates how designer 1 and designer 2 work together to determine the coupled parameters and construct the algebraic equations.

The collaborative concrete assembly design is illustrated in Figure 11, 12 through showing the collaborative design of designer 1 and designer 2.

In Figure 11, some parts’ feature model is copied from the skeleton model such as the ‘bracket’, the ‘palm’. Then their detailed feature models are created. To finalize the assembly relationships, designer 1 and 2 discuss with each other about the detailed assembly constraints. Then they agree to use ‘bolt connection’ to connect the ‘bracket’ and the ‘palm’. Then each of them modifies the corresponding part and creates the geometric constraints and parametric constrains, as shown in Figure 11.

Figure 12 shows how design variation propagation is accomplished. Suppose that designer 1 finds out that D6 shown in Figure 11 is too small to bear the strength, so he/she modifies D6 after discussing with designer 2. This results in the chain changes of the parameters D1, D2…D5. The modified assembly models at the clients two designers locate at are shown in Figure 12.

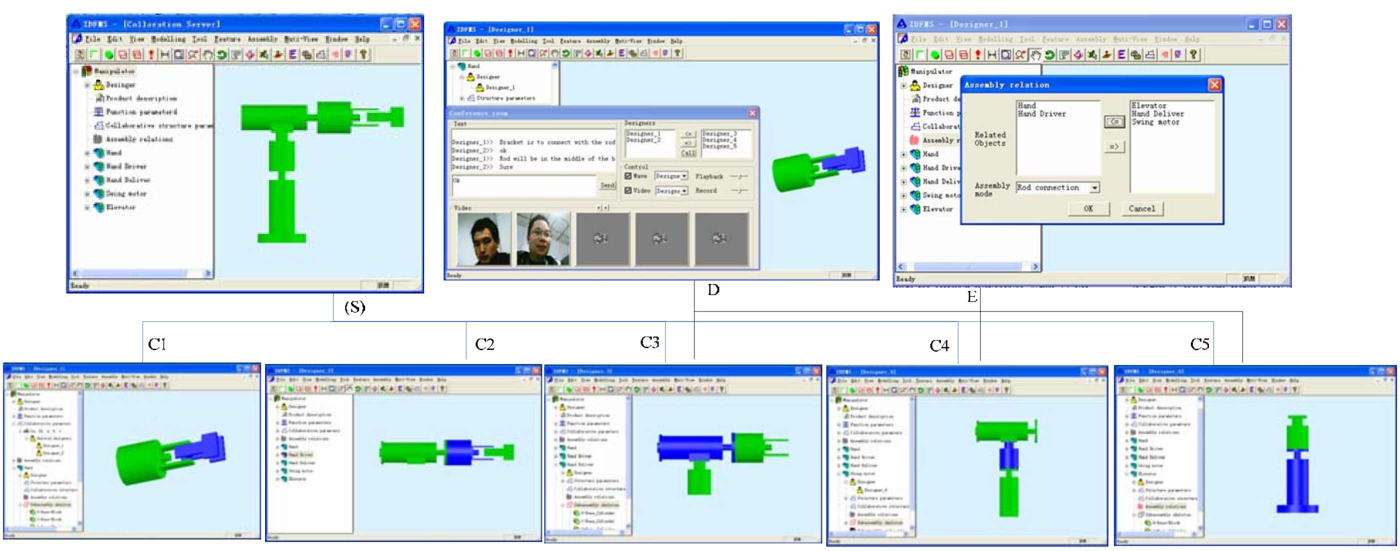
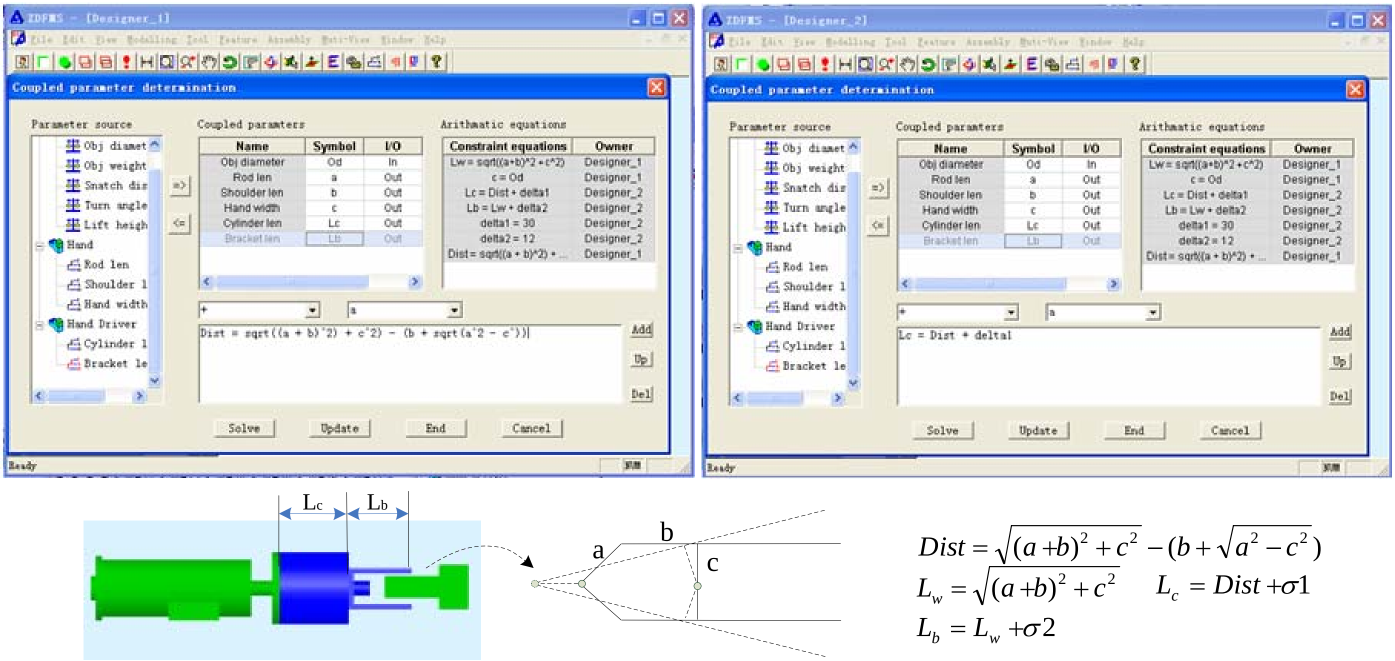


Figure 9: The collaborative 3D skeleton design



$$Dist = \sqrt{(a+b)^2 + c^2} - (b + \sqrt{a^2 - c^2})$$

$$L_w = \sqrt{(a+b)^2 + c^2} \qquad L_c = Dist + \sigma 1$$

$$L_b = L_w + \sigma 2$$

Figure 10: The collaborative determination of the coupled structural parameters

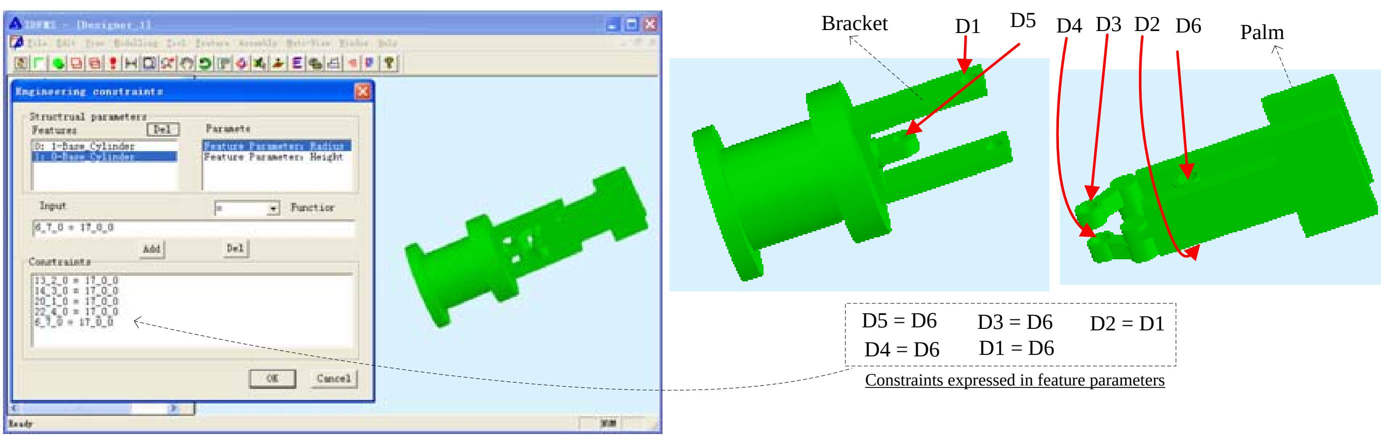


Figure 11: Collaborative definition of assembly constraints and engineering constraints

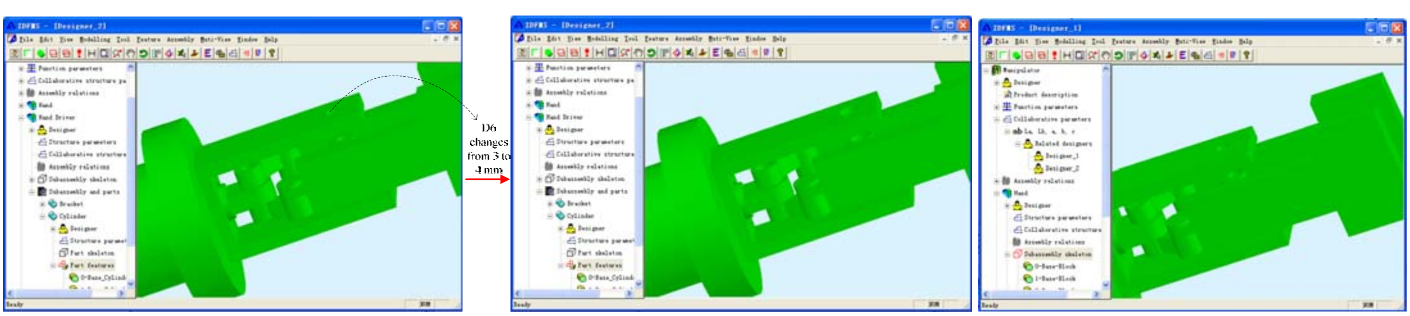


Figure 12: Design variation propagation after D6 is modified

11 CONCLUSIONS AND FUTURE WORK

In this paper we present a framework supporting the collaborative top-down assembly design. The contributions of this paper are summarized as follows:

1. The proposed framework enables distributed designers to conduct collaborative layout design, 3D skeleton design and detailed design of a product in a top-down way in a distributed environment, and supports collaborative determination of coupled structural parameters and collaborative definition of assembly relationships.

2. A collaborative product assembly model that can effectively support the collaborative top-down assembly design is given..

3 A variation propagation mechanism which can assures the consistency of the distributed assembly model during the collaborative top-down assembly design is developed.

Our future work will focus on:.

1. Manage the collaboration information to enable the users to collaborate with each other more efficiently.

2. Find an approach to automatically detect the conflicts caused by the design variations.

3. Consider the information security during the design process so that the design information is given only to the designers having sufficient right.

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