한국 CAD/CAM 학회 논문집
제9권 제1호 2004년 3월 pp. 62-76

학술논문

Virtual Assembly Analysis Tool and Architecture for *e*-Design and Realization Environment

Kim, K.-Y.*, Nnaji, Bart O.* and Kim, D.-W.**

ABSTRACT

Many customers are no longer satisfied with mass-produced goods. They are demanding customization and rapid delivery of innovative products. Many companies are now realizing that the best way to reduce life cycle costs is to evolve a more effective product development paradigm using Internet and web based technologies. Yet there remains a gap between current market demands and product development paradigms. The existing CAD systems require that product developers possess all the design analysis tools in-house making it impractical to employ all the needed and newest tools. Hence, this paper addresses how assembly operation analysis can be embedded transparently and remotely into a service-oriented collaborative assembly design environment. A new assembly operation analysis framework is introduced and a relevant architecture and tools are developed to realize the framework. Instead of the current sequential process for verifying and validating an assembly design, a new Virtual Assembly Analysis (VAA) method is introduced in the paper to predict the various effects of joining during actual collaborative design. As a case study, arc welding and riveting processes are investigated. New service-oriented VAA architecture and its VAA components are proposed and implemented on prototype mechanical assemblies.

Key words : Assembly operation analysis, virtual assembly analysis, service-oriented architecture, *e*-design and realization, collaborative assembly design, joining process, e-tools, finite element analysis, CAD/CAM, CAE

1. Introduction

Conventionally, mechanical assembly plays a very important role in industry. Joints on a mechanical assembly are inevitable because of the restrictions on the geometric configuration of parts, as well as material properties along with the requirements of inspection, accessibility, repair, and portability[1]. Very often joints come to weak points from a mechanical or chemical viewpoint[2]. For example, many failures in fatigue or in corrosion occur at welded joints. Thus, it often needs some extra material to be added to the assembly structure, such as screws, bolts, or welding filler metal. It sometimes leads to local weakness of assemblies due to the mechanical properties of joining materials: for instance, in the heat affected zone of a weld.

*US NSF Center for *e*-Design, Pittsburgh, PA, USA
**Member, Department of Industrial and Information Systems Engineering, Chonbuk National University, Korea
- 논문투고일: 2003. 09. 16
- 심사완료일: 2003. 11. 28

To predict potential joint design problems, a trial and error method is widely used in assembly design process. The current design analysis for verifying an assembly design method is usually performed after producing a final design model. For example, a welding operation can bring the thermal expansion and distortion of a welded structure which will affect its joints and even an entire structure. If the welded structure is distorted, then precision assembly cannot be achieved. Therefore, the weld distortion should be minimized by optimizing the welding operation or by the use of an alternative joining method, such as joining with cast nodes. In another illustration, the rivet joints of an aircraft body frame should be capable of sustaining the prescribed load and/or mechanical forces in physically holding the assembly components together. If analysis indicates that stress level is not well balanced, the number of rivet joints could be optimized or an alternate joining method such as welding should be considered. The effect of joining operations, in existing design processes, is analyzed after finishing assembly modeling. If the analyses indicate that certain modification is required, then another iteration of modeling has to be carried out. This iterative process can be arduous and time-consuming.

The impact of the Internet technologies has accelerated the pace of product development and product aftermarket service. Market competition has made quality not only an objective but also a prerequisite for companies to compete in the global marketplace. Smart companies must focus on product development and service innovation as a way to satisfy a customer's need and lessen the cost and time associated with satisfying the customer. A new thinking paradigm to focus on Internet-enabled tools (*e-tools*) for collaborative product design, manufacturing, and service is becoming a new benchmark strategy for manufacturing companies to compete in the twenty-first century[3-5]. Many industries involved in the production of mechanically engineered products including aerospace, automotive, and medical device companies, have taken the lead by CAD system providers in developing strategic web-based benchmarking tools to globally integrate their product development to achieve the three key goals for competitiveness. For example, General Electric Aircraft Engines in 2000 initiated a $21 million project funded by the US National Institute of Standards and Technology's Advanced Technology Program to develop web-enabled tools that ensure interoperability of design data among various CAD systems and among their OEMs[4]. There is now a realization by many companies that product development tools need to be decentralized and be made accessible via Internet, and that technologies which can allow for virtual prototyping and simulation should be developed.

In this paper, an innovative Virtual Assembly Analysis (VAA) process is introduced. Unlike the current sequential design process used for verifying an assembly design, the VAA process integrates assembly design and analysis in collaborative product design. In addition, VAA components are developed to predict the various effects of joining in the actual assembly design stage. The information obtained from the VAA process can guide designers to make appropriate design decisions in the early stages of assembly design. Previous research has largely focused on assembly modeling and assembly process planning without considering the assembly operations and their effects in a collaborative design environment. Thus, there is a strong need to develop a methodology that integrates the assembly design and assembly operation analysis in a collaborative environment. The developed VAA framework provides an Internet-based concurrent environment for designers to predict physical effects transparently and remotely.

2. Background

An assembly is a collection of manufactured parts, brought together by assembly operations to perform one or more of several primary functions. Assembly operation is defined as the process or series of acts involved in actual realization of assembly. Joining finalizes the assembly operation and generates joints. Messler[1] divided the primary functions into three categories: structural, mechanical, and electrical. Usually, assemblies perform multiple functions, with some function being primary and the others secondary. Therefore, the joints in an assembly also perform multiple functions. The primary function of the joints in an automobile frame is to provide a structural connectivity. Also, the joints may have a secondary function by allowing certain movement corresponding to vibration of the structure. To achieve function, diverse material properties and multiple parts are often employed. In this case, joints must be created between those different components and different materials. To enable material and structural optimization, determination of appropriate joining methods and joint design are critical and can provide additional benefits, in terms of assemblablility, joinability, quality and damage tolerance by changing properties along a potential crack path, and disrupting and arresting crack propagation. Local joints should be compatible to the overall structure design. For example, if a deformation effect of a weld joint on a metal frame is propagated onto automobile windshield area, it can result in a fitting distortion problem between the window and the metal frame[7]. Understanding the physical effects of each assembly operation is very important to generating an appropriate joint design for an assembly. In this paper, the arc welding and riveting processes are selected as a case study. In the arc welding process, due to the highly localized transient heat input from arc welding, considerable residual stresses and deformations, such as welding distortion, welding shrinkage, and welding warpage occur during heating and cooling in the welding cycle[8,9]. Thousands of rivets may be used in the construction and assembly of many artifacts, such as airplanes, ships, and automobiles. Installing a rivet consists of placing a rivet in a hole and deforming the end of its shank by upsetting (heading). Even though there has been much research done to study analytically and numerically welding and riveting operations[10,11], none of these researchers have presented a methodology to analyze the assembly operations transparently and concurrently.

2.1 Virtual Prototyping

Prototyping technologies are emerging as powerful tools to shorten the product design and development process[12]. Virtual prototyping has been in steady development since the 1970s[13], and implies the testing and analysis of 3D solid models on computing platforms. Several researchers have attempted to integrate CAD and analysis tools. Su and Amin[14] proposed CGI (Common Gate Interface) based system for executing software programs via Internet and tested their system on a gear optimization software package. They acknowledged that their system inherited the limitation of CGI approach, i.e. speed and multiple user handling. However, they did not discuss a transparent analysis methodology to capture physical effect of assembly operation on heterogeneous computing environment. Gee[15] proposed an agent based system to integrate CAD, FEM (Finite Element Modeling), and CFD (Computational Fluid Dynamics) in distributed and heterogeneous computing systems. Even though they presented a framework for the integration between CAD and analysis systems, they did not discuss about how to capture the mathematical and physical implication of joining operations in a collaborative design environment. Goriatchev *et al.*[16] developed a distributed system for CFD simulation. They used Java-enabled technology to achieve a distributed computation environment. Nevertheless, none of researchers addressed the integration between joining design and analysis to consider the various effects of assembly operation during conceptual assembly design process in Internet-based collaborative assembly design environment.

2.2 Collaborative engineering

Collaborative Engineering offers substantial benefits for new product development, so many companies are taking a strong interest in the collaborative approach. However, it is still not fully clear how it can be implemented in industry, particularly for geographically distributed participants who may be using a disparate range of computer systems[17-19]. Collaborative design engineering is just emerging as a viable alternative to the traditional design process, in which a product design must be developed via an iterative process between designers, manufacturers, marketing people, and ultimately customers. This emergence can be linked to the recent outburst of growth in the development of Internet and associated technologies such as the object-oriented programming tools, as well as the rapid advancements made in computing technology that have led to the proliferation of powerful and yet affordable computers. Consequently, there is focus on researching collaborative engineering systems, and this has yielded a few commercial systems, even though they are currently inadequate to support the desired product assembly design and analysis environment in a collaborative assembly design environment[20-23].

Existing research is mainly focused on the feasibility for product design and manufacturing collaboration by the aids of networked computers in a distributed environment. The importance of design collaboration has gained attention of industry[4,21,22]. Meanwhile, the possibility of distributed environment for product designers and manufacturers has been studied by several academic research groups. CyberCut[24] allows remote designers to access distributed servers and perform functions of CAD, CAPP, and CAM through the World Wide Web (WWW), in which design, planning, and fabrication agents communicate using direct socket connections. Boujut *et al.*[25] presented a distributed design system for the design of forged parts. The CAD application developed by their group functions as a coordination tool in the design process of forged parts, and allows different "actors" to access specific knowledge and impose their own constraints on the product. COCAD-

CAM[26] allows two geographically dispersed CAD/CAM users to work together on co-designing through distributed CAD/CAM modules. Mervyn *et al.*[27] employed Java RMI (Remote Method Invocation) and XML technologies to realize an interactive fixture design system. However, their works have limitation to evaluate assembly models with respect to manufacturability, assemblability, and joinability. No provision is made for the transparent execution of design tests such as finite-element analysis.

Instead of looking at various engineering tools from a traditional computation viewpoint, Nnaji *et al.*[28] focused on the engineering implication of those tools from a more abstract level. This approach assures good openness for collaborative design and engineering systems and their view of design collaboration is service-oriented. Internet is no longer a simple network of computers. From an application perspective, Internet is a network of potential services, it can be regarded as a complex system of service chains. Computer-aided design and engineering tools can be hooked up to the design platform over Internet and provide certain services resulting in a distributed product development environment. This incorporates different engineering services and makes them available for automatic transactions in a collaborative product design environment. This product development environment is called an "*e*-design and realization environment."

3. Service-oriented Collaborative Design and Realization

Collaborative design tools are needed to improve the collaboration among distributed groups, endorse knowledge sharing, and assist better decision making. In a service-oriented collaborative architecture, CAD/CAM/CAE tools can be linked by Internet to form a distributed product development environment, which incorporates different engineering services and makes them available for transparent transactions in product development. Each design tool for a designer system can be a server that provides certain services requested by clients, either within or external to the designer system[28]. As shown in Fig. 1, servers within the system have a peer-to-peer relationship with each other.

Service is defined as a process that provides a functional use for a person, an application program, or another service in the system. Services should be specified from the functional aspect of service providers. To make an existing tool available online or to build a brand new tool for such a system, services associated with this tool should be defined. The service transaction among service providers, service consumers, and the service manager within this architecture is illustrated in Fig. 2. Once a service is registered at a central administrative manager, called the service manager, it is then available within the whole system. This process is *service publication*. When a service consumer

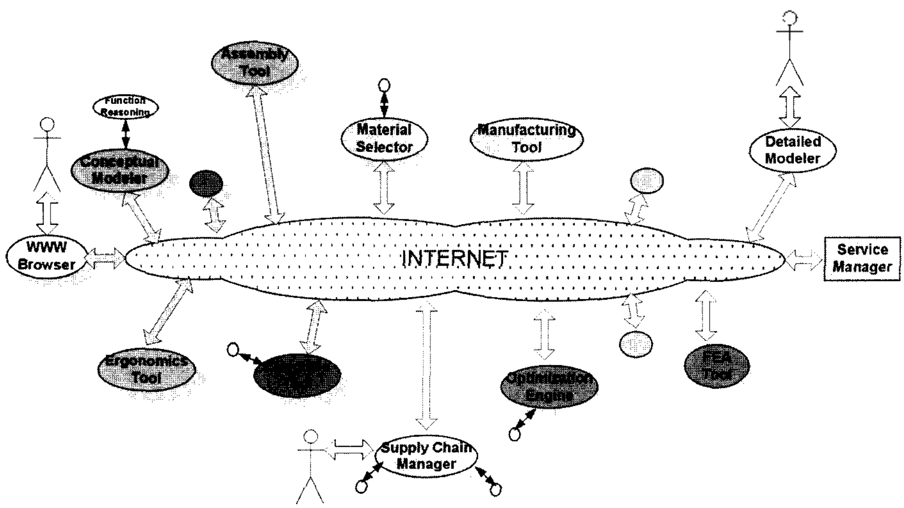


Fig. 1. Peer-to-peer relationships in service-oriented architecture.

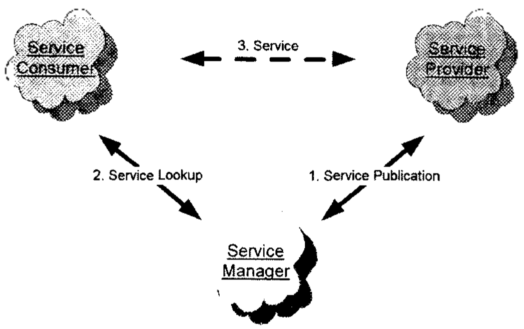


Fig. 2. Service triangular relationship.

within the system needs a service, it will request a lookup service from the service manager. This process is *service lookup*. If the service is available, the service consumer can request the service from the service provider by the aid of the service manager. Most importantly, this triangular service relationship should be built at run-time. The service consumer (client) does not know the name, the location, or even the way to invoke the service from the service provider (server) during the system and tools development period.

Service providers that provide different services such as finite element analysis (FEA), computational fluid dynamics (CFD), and material properties, can be developed independently. As shown in Fig. 1, servers that can provide different engineering services are linked by Internet. Each node in this network can both require and provide certain services; thus, it can be both a client and a server at different times. This client/server relationship is determined at run-time, so the system is open for the future expansion and extension, in case more services are available.

The collaboration between engineering tools is established and executed based on the characteristics of services that can be provided. For example, the relationship between a CAD tool and a FEA tool is based on the FEA service that the FEA tool can provide for the CAD tool. The service manager, on the other hand, offers service publication and lookup for service providers and consumers. The notion of service-oriented collaboration lets the collaborative assembly design and analysis system have appropriate flexibility.

In this paper, VAA is realized and implemented on the service-oriented collaborative product design architecture that allows for customers, suppliers, assembly designers, engineers, and other stakeholders to participate in product design over Internet.

4. Virtual Assembly Analysis (VAA)

Many current customers are demanding customization and rapid delivery of innovative products. Companies now realize that the best way to reduce life cycle costs is to evolve a more effective product development paradigm using Internet and web based technologies[4,29]. Yet there remains a gap between these current market demands and current product development paradigms[5]. The existing CAD systems require that a product developer possess all the design analysis tools in-house making it impractical to employ all the needed and newest tools.

The virtual assembly analysis (VAA) concept is introduced to predict the various effects of joining during actual assembly design. The VAA process is a transparent and remote assembly analysis process utilized in a service-oriented collaborative assembly design environment. Fig. 3 illustrates the concept of VAA. An *e*-designer, who participates in the service-oriented collaborative design, can request analysis services through Internet/Intranet. An analysis service provider solves the analysis problem requested and provides the results to the *e*-designer. This VAA process is embedded into the distributed assembly design environment and it can guide designers to make appropriate design decisions. It generates an assembly design for joining and eliminates the time-consuming feedback processes between the assembly design and analysis processes. In this research, the VAA process is realized in a service-oriented product development architecture. In the service-oriented architecture, each engineering tool, such as mechanical analysis solvers can be a server that provides certain services

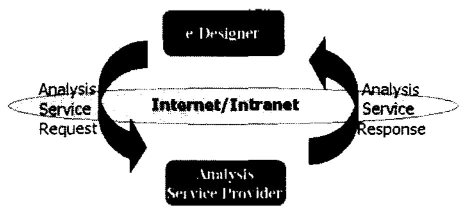


Fig. 3. Virtual assembly analysis.

requested by clients.

4.1 Service-oriented VAA Architecture

To realize VAA in a service-oriented architecture, an appropriate VAA service triangular relationship should be developed. In this triangular service relationship, each analysis service provider has its own service defined and published at the service manager. For example, an Assembly Design (AsD) engine and the VAA tool provide the services of assembly functional specification, engineering relations construction, and design presentation to end users. Many third-party analysis solvers can serve as the analysis service provider; the ANSYS solver provides the services of structural nonlinearites, heat transfer, dynamics, electromagnetic analyses, etc., and the CFX solver provides the services of CFD. During the process of service, one service provider may require some other services from other service providers. It then will send a service request to the providers, which provide these additional services. This service chain action should be transparent to the end consumer. For instance, when a design engineer completes the design of two parts, he/she may want to build an assembly model based on the part models. The detailed modeler then calls the assembly procedure.

When the assembly model is finished, the design engineer may want to do further mechanical analysis of the assembled parts by calling the service of a FEA tool through the VAA tool. The locations of various service providers are not known until run-time and the relation between the service consumers and the service providers is built dynamically. This relation can be viewed as a service chain, which connects service providers with client/server affiliation. Fig. 4 illustrates the service-oriented VAA architecture. An *e*-designer who participates in Internet-based collaborative assembly design, can request analysis services through Internet/Intranet. An analysis service provider solves the analysis problem requested and provides the results to the *e*-designer. As shown in Fig. 4, the VAA architecture consists of four major service components, i.e., VAA tool, Pegasus Service Manager, *e*-design brokers, and service providers.

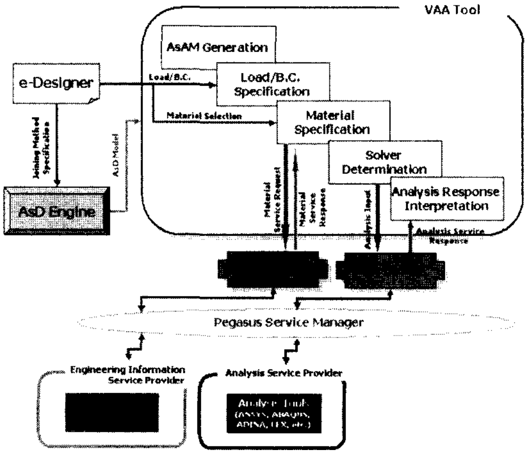


Fig. 4. Service-oriented VAA architecture.

4.2 VAA Tool

The VAA tool is an interface of VAA processes. When the designer wants to know physical effects of the specified joining, the VAA tool is triggered. If the designer does not possess any analysis tools in house, and/or has not any expertise in mechanical analysis, the designer can request VAA services remotely and transparently by using this VAA tool. The assembly operation analysis setup process is cumbersome and requires certain level of expertise. This process can be automated by imposing assembly/joining information on an assembly design model and extracting assembly analysis information from the assembly design model. Kim *et al.*[30] developed an assembly design formalism to persistently capture assembly/joining information in collaborative assembly design.

4.2.1 Assembly design formalism and assembly design model generation

The assembly design formalism specifies assembly /joining relations symbolically and it is used as the mechanism to perform product assembly design tasks. This assembly formalism is comprised of five phases: spatial relationship specification, mating feature extraction, joint feature formation and extraction, assembly feature formation, and assembly engineering relation construction. By interactively assigning *spatial relationships*, the designer can assemble components together to make final products and infer the degrees of freedom remaining on the components. In assigning *spatial relationships*, the mating features are defined and extracted from the parts. Mating feature extraction is a preliminary step to capturing joining information. This process provides geometric information directly related to assembly operation. However, the mating feature is not sufficient to represent a joining operation. The joint feature captures the information of actual joining operations. The designer can specify specific joining methods and constraints, such as welding conditions and fixture locations in joint features. After joint features are generated, assembly features are formatted. The purpose of assembly feature formation is to group the mating features and joint features together and thus integrate the data embedded at the component design stage with new assembly information for subsequent processes such as assembly violation detection, process planning, etc. Having designated spatial relationships, mating features, and joint features, the system can then trace back to the component design stage to determine from which design features these mating features originate and their design specifications.

From the generated assembly features, assembly engineering relations, including assembly/joining relations, are automatically extracted and mating bonds (MB) are generated. A MB is a data structure representing mating pair and its mating conditions. Assembly engineering relations of the entire assembly are constructed based on the assembly features after specifying the spatial relationships and joining relationships between components. The MBs and an Assembly Relation Model (ARM) are used to represent the engineering relationships on the entire structure. A detailed description can be found in[30]. From the AsD model, the VAA tool automatically generates an Assembly Analysis Model (AsAM) including the analysis variables, such as environmental variables, loading/boundary conditions, and material properties.

4.2.2 Assembly analysis model (AsAM) generation

To integrate assembly design and assembly operation analysis, the assembly design models should be translated to an assembly analysis models. There have been some researches conducted to integrate product design and analysis. Peak *et al.*[31] presented a multi-representation architecture of intension of CAD-CAE integration. As an information-intensive mapping between design models to analysis models, a product model-based analysis model is researched and a framework to achieve design-analysis associativity is proposed. Rémondini *et al.*[32] developed a mechanical analysis module to generate an analysis data model from a geometric data model and mechanical information. Even though their methodology can be solutions for limited sense of CAD-CAE integration, they have not presented methods to integrate assembly design and assembly operation analysis to capture the physical effects of joining in the distributed assembly design environment. To perform VAA, the assembly/joining information necessary to assembly operation analysis can be extracted using an assembly-analysis solution model to explain physical phenomena based upon the assembly/joining information. The assembly-analysis solution model (AASM) is an implantation of mapping functions (Ω) of assembly design and joining analysis. It translates an assembly design model (AsDM) to an AsAM: ${}_{AsDM}\Omega_{AsAM}$. Information essential for an assembly analysis is extracted from the AsD model, which is generated by the assembly design formalism.

The material of the assembly components from the joint features is translated to the material property for AsAM. Through this mapping, the material property for the specified material name is automatically assigned from a material library. If the resident material library does not have the information about the specified material, the material service can be invoked through the service-based architecture; a designer does not need to hold all material information in-house.

According to the assembly model information and assembly engineering information, additional geometric features, such as a weld bead for welded joints and a rivet for riveted joints, can be generated for detailed joint modeling. This detailed joint modeling provides realistic representation for engineering analyses. The configuration of the joint geometric features can be determined automatically from the assembly model information and assembly engineering information. For rivet joints, the designer specifies the location, head type, and radius of the rivet and the AsD model contains the information. For welded joints, the cross-sectional area of the weld bead can be determined from the existing theoretical relationships between the welding condition and the material properties imposed in the AsD model.

4.3 Pegasus service manager

The Pegasus service manager collaborates with third-party analysis servers (service providers), such as ANSYS, to achieve the VAA process. In this paper, Common Object Request Broker Architecture (CORBA) is used to realize the service-oriented architecture for VAA. CORBA[33] is an architecture and specification for creating, distributing, and managing distributed program objects in a network. It allows programs at different locations and developed by different vendors to communicate in a network through an "interface broker". An ORB (Object Request Broker) acts as a "broker" between a client request for a service from a distributed object or component and the completion of that request. The ORB allows a client to request services from a server program or object without having to understand where the server is in a distributed network or what the interface to the server program looks like.

Service publication and lookup are the primary services provided by the service manager of VAA. Service publication includes *name publication*, *catalog publication* and *implementation publication*, which are provided for service providers. Name publication service is similar to the "white-page" service provided by telephone companies, by which the name of the service provider is published. Catalog publication service is similar to the "yellow-page" service where both the name and the functional description of the service provider are published. Implementation publication service is the procedure by which the service provider makes its implementation and invocation of services public so that clients can invoke the service dynamically. Correspondingly, service lookup includes *name lookup*, *catalog lookup* and *interface lookup*, which are for service consumers. Name lookup service is provided so that consumers can locate the service providers based on the service names. Catalog lookup service is for those consumers who need certain services according to their needs and specifications but do not know the names of the services. Interface lookup service provides a way such that consumers can check the protocols of how to invoke the service in the case that clients do not have the knowledge of the service in advance.

Within the system, data transfers and transactions among servers can be completed based upon various distributed computing protocols, such as Hypertext Transfer Protocol (HTTP), Common Object Request Broker Architecture (CORBA), Distributed Component Object Model (DCOM), etc. Currently, the VAA architecture is implemented by CORBA. CORBA serves as a bond to integrate the whole system and provides good features of openness for collaborative computation. The components in the distributed system have peer-to-peer relationships with each other. From the end users' outlook, distributing application components between clients and servers does not change the look and feel of any single application, meaning, the system provides end users with a single system image.

4.4 *e*-Design brokers

The *e*-design brokers handle service invocation and service result conveyance through Pegasus service architecture. The brokers reside in local sites; each client, such as the VAA tool, and each service provider needs the brokers to request or register service. The VAA tool can request the services by invoking these service brokers with relevant service inputs, such as analysis input files and material names. It minimizes the code modification of a service requesting system and provides plug-and-play capability. Before the VAA process, the analysis service providers register their service through an *e*-design broker at each server site. When VAA service is requested by an *e*-designer, the VAA tool sends a request with an analysis input to the *e*-design broker at the client site and the *e*-design broker conveys the request to the Pegasus service manager. After an analysis result is obtained from the analysis service provider, the Pegasus service manager informs the client's *e*-design broker and conveys the result to the *e*-designer.

4.5 Service providers

The Pegasus service manager and the service providers play key roles in the VAA service chain management. The Pegasus service manager allocates service resources according to service consumers' demand and service providers' capability and capacity, while service providers respond the requested service.

In this paper, two types of service providers are considered: material service providers and analysis service providers. A specialized material service provider can provide the material properties, which are usually too cumbersome to store in the assembly designer's site. The *e*-designer can request a certain material properties from the engineering material service provider by specifying material name or certain material specifications. Any available engineering material library can provide relevant material properties to the client. To perform VAA to predict the physical effects of the joining, FEA tools, such as ANSYS, ADINA, and ABAQUS, can provide various FEA services. Generally, FEA tools allow certain command-based external analysis inputs. Depending upon the FEA tools and analysis types, different sets of commands and analysis procedures are needed. Appropriate analysis procedures, including specific analysis commands, can be provided from available analysis service providers through an analysis procedure service. In this research, typical analysis procedures considering the characteristics of joining methods are investigated and appropriate analysis procedures are pre-determined. Analysis service providers provide analysis procedure templates based upon the analysis procedures.

5. Implementation and Validation

The VAA architecture and components are developed to realize the VAA process. This VAA process predicts the physical effects of joining processes, in which the VAA tool is embedded into assembly design processes in collaborative product design environments. To realistically predict physical effect of joining, appropriate analysis procedures are required. The next sub-section describes examples of VAA procedures.

VAA for assembly operations requires specific analysis methodology and procedures. In this research, as a case study a thermo-structural analysis is used to understand the thermal and structural behavior of the welding operation. In addition, structural analysis is employed to predict various structural phenomena of the riveting operation. To enable VAA for specific joining processes, proper analysis procedures must be pre-investigated and built into an analysis procedure library.

To enable VAA, four major service components serve in the developed architecture: the VAA tool, transaction manager, service brokers, and third-party analysis service providers. In this research, the Pegasus service manager is used as a transaction manager.

In this demonstration, the VAA tool is implemented on AI*Workbench environment of ANSYS,

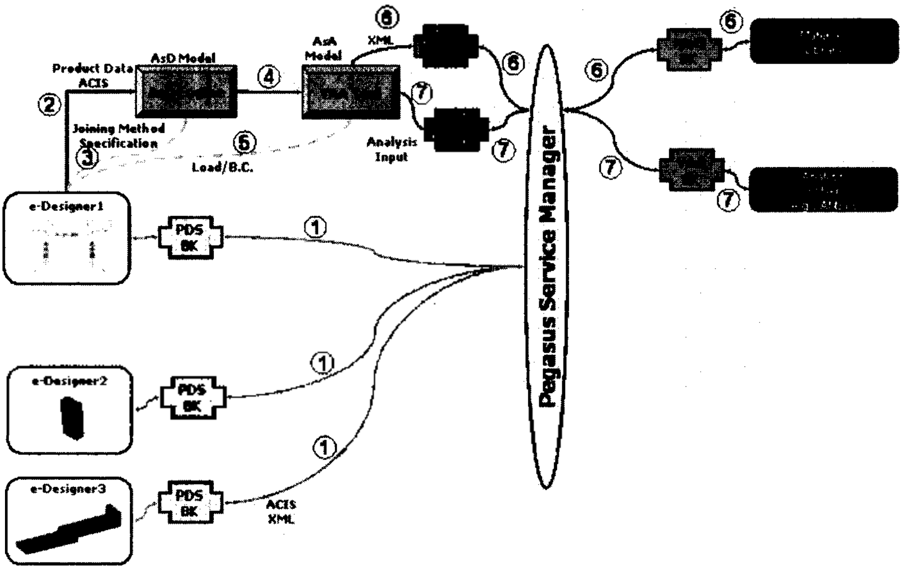


Fig. 5. Service transactions in VAA.

Inc. The ANSYS solver is employed as the analysis service provider. Engineering material information is represented in XML format in the material database. The Pegasus service manager is implemented in Java. *e*-Design brokers are implemented in C++. IONA's ORBacus implementation of CORBA is used in the service architecture.

Fig. 5 illustrates the transaction flow of services for VAA. Detailed processes are described below. The numbers in the figure stands for the index of each process.

STEP 1: *e*-Designers can exchange product data, such as AsD models, and select assembly components through the Product Data Sharing (PDS) service (①) (Explained thoroughly in Chapter 3).

STEP 2: The selected assembly components are loaded in an AsD engine to generate joints (②). The system integrator, *e*-designer 1, can specify joining methods on the assembly (③).

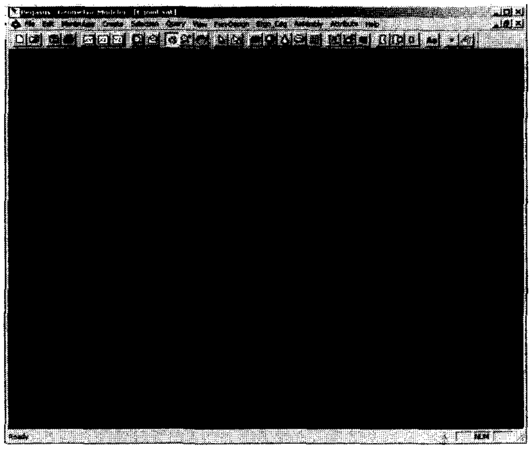
STEP 3: When the *e*-designer wants to know physical effects of the specified joining, the VAA tool is triggered and a newly generated AsD model is sent to the VAA tool (④). From the AsD model, the VAA tool extracts analysis information and generates an AsAM. The designer can add additional loading and boundary conditions (⑤).

STEP 4: If the material specified in the AsD model does not exist in local database, the material property is obtained from remote material libraries though the service-oriented architecture. The designer can also request a certain material to be entered in the VAA tool. The VAA tool dynamically requests the service by invoking the material service broker (Mtl BK) with relevant material information (⑥).

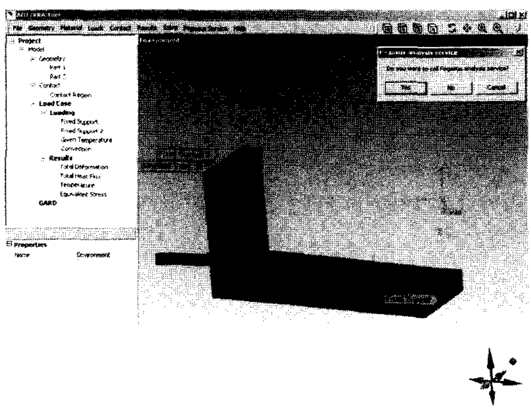
STEP 5: Once the VAA inputs are ready, the VAA tool invokes the VAA service broker (VAA BK) with the VAA input. When the analysis is completed, the analysis service provider returns the analysis results to the VAA tool (⑦).

As shown in Fig. 5, PDS service, material service, and VAA service are accomplished through service brokers (i.e., PDS broker, material broker, and VAA broker). These service brokers at the user's site handle service invocation and service result conveyance through the service-oriented architecture. The VAA tool can request the services by invoking these service brokers with relevant service inputs, such as analysis input files and material names. Fig. 5 also illustrates how the service brokers are used in the service architecture. For example, *e*-designers can exchange product data, such as AsD models, through PDS service and select assembly components by using the PDS service.

The developed VAA tool (see Fig. 6-a) is used as an interface to capture assembly and joining specification. When the designer wants to know physical effects of the joining, the VAA tool is



(a) Assembly design model



(b) Assembly analysis model

Fig. 6. Assembly models for VAA.

triggered to interpret the AsD model. From the AsD models, the VAA tool automatically generates an AsAM including the analysis variables, such as environmental variables (e.g., as convection and fixed support), loading condition (e.g., given temperature and force/pressure), and material properties (e.g., Young's modulus, specific heat, and thermal expansion coefficient) (see Fig. 6-b). The joining parameters (such as welding conditions and welding speed) are extracted from the AsD model and relevant analysis variables are obtained and assigned to the AsAM. For example, the degrees of freedom at fixture locations are restricted as fixed supports. Temperature at the specified weld seam is estimated from the welding condition. Through this analysis setup process, the designer can impose additional analysis constraints on the assembly analysis model in the VAA tool.

The locations of various service providers are not known until run-time. The relation between the service consumers (such as the VAA tool) and the service providers is built dynamically. The Pegasus service manager allocates service resources according to service consumers' demand and service providers' capability and capacity. Fig. 7 shows an implementation of the Pegasus service manager.

A specialized material service provider can provide the material properties, which are usually too cumbersome to store in the assembly designer's site. Here, an engineering material service provider has this information and offers engineering material lookup services. To perform VAA to predict the

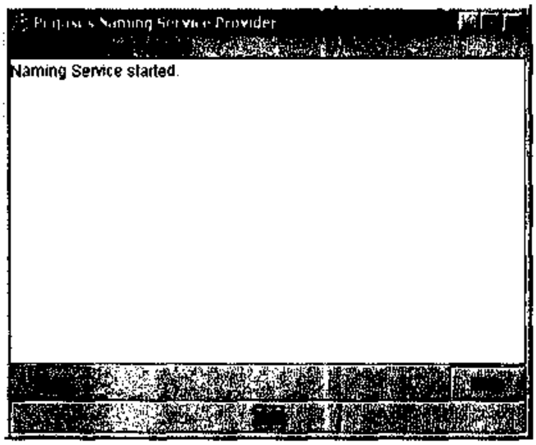


Fig. 7. Pegasus Service Manager.

physical effects of the joining, the VAA tool (transparent to the analysis service provider) looks up and acquires the material information on the specified material type from the remote engineering material service provider.

Once the complete AsAM is generated, and VAA service can be invoked. VAA input for available VAA service providers is generated by the VAA tool considering specified joining method's characteristics and analysis preferences. In this research, predetermined analysis procedures are used for VAA. Determining appropriate analysis procedures is very important for obtaining realistic analysis results. The service-oriented architecture provides an environment in which new analysis procedures are easily acquired from remote analysis service providers. This VAA service, which is provided by the analysis service providers (Fig. 8), such as ANSYS, ADINA, and ABAQUS, can be invoked remotely through the Pegasus service

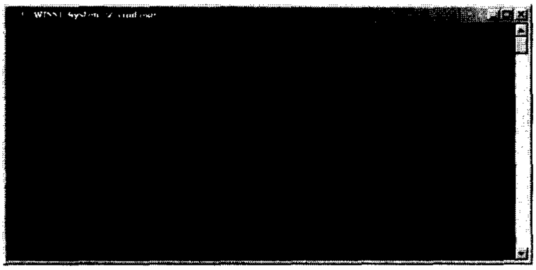


Fig. 8. VAA service provider.

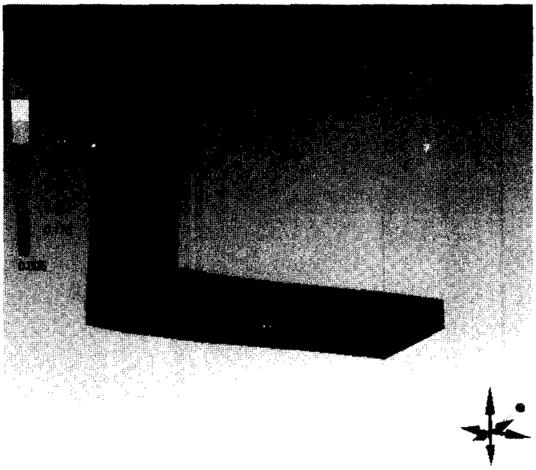


Fig. 9. Equivalent stress and deformation obtained from VAA service.

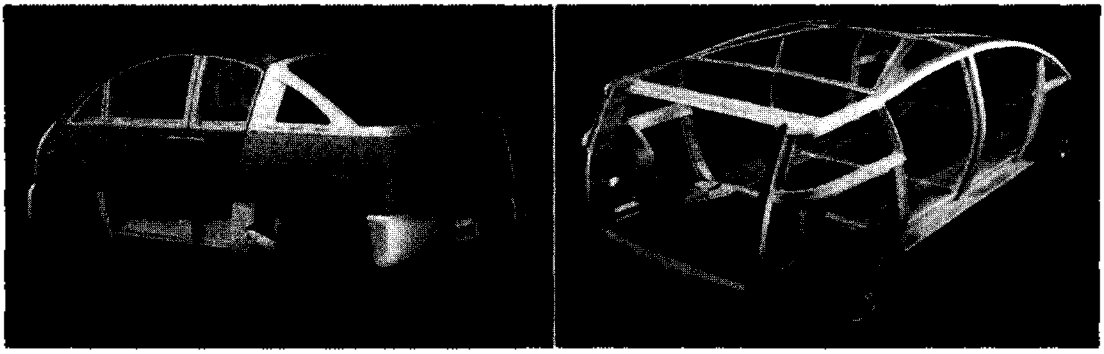


Fig. 10. Aluminum concept car and body frames[34].

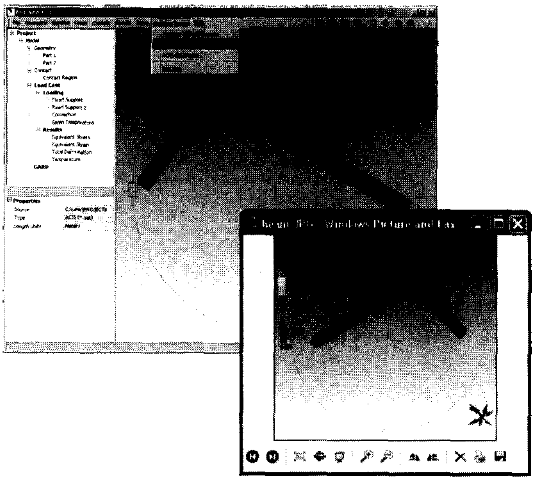


Fig. 11. VAA for a welded extruded frame.

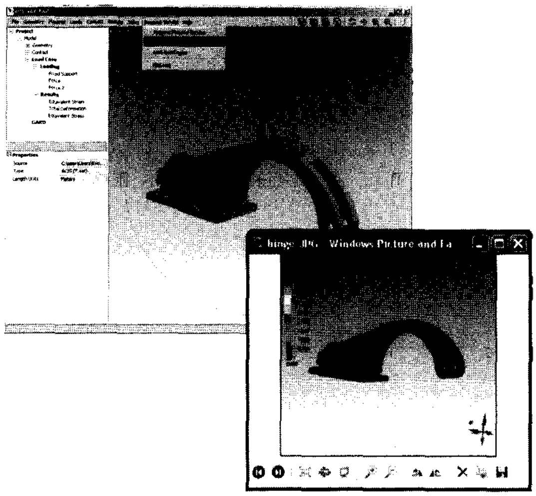


Fig. 12. VAA for a hinge with three rivets.

manager. When the analysis is completed, the analysis service provider (see Fig. 9) returns the analysis results (e.g., output files, animation movies) to the VAA Broker, eventually to the VAA tool (see Fig. 5).

The VAA framework is also implemented on realistic examples, such as an aluminum space frame assembly for an automobile (Fig. 10) and hinge assembly with rivet joints (Fig. 12). The welded frame is made up of thin walled aluminum beams with rectangular sections and flat planer sections. Aluminum alloy (such as 6061 or 6063) extrusions have been considered as materials. Moreover, recent emphasis on lightweight environmentally sound car design has opened up the possibility of substituting lower-density corrosion-resistant recyclable aluminum for steel in car bodies[34]. However, the high distortion of aluminum alloy is a difficult problem to overcome to achieve precision manufacturing. For example, aluminum alloys 6061-T6 and 6063-T6 have a deformation index of 0.01 (worse) against an index of 1.0 for mild steel[35]. Fig. 11 illustrates a simple car frame model in the VAA tool and the VAA result. The result clearly shows the deformation of this structure and stresses concentrated at the welded joint. Deformation beyond allowable tolerance will be indicated easily. Based on the result, the designer can make a decision on whether this joining method is feasible using this nominal geometry.

As another illustration, a hinge assembly with rivet joints is used[36]. The material of the hinge is a structural steel. Fig. 12 shows a structural VAA result for the hinge joint. Based upon this result, although stresses are concentrated on the top component and the stress affects one of rivets, the designer can clearly see that this joint is robust in this specific test environment.

6. Conclusions

In this work, a new assembly analysis framework, *virtual assembly analysis* (*VAA*) and VAA architecture and components has been developed to predict the physical effects of selected joining processes in an integrated, collaborative design environment. The contributions of this research are summarized as follows:

1. The VAA process transparently and remotely integrates assembly design and assembly analysis. It eliminates the time-consuming feedback processes between assembly design and assembly analysis. The information obtained from VAA helps a designer generate an assembly design for joining.
2. The VAA can differentiate assembly design with other types of joints. For example, different effects of a weld and a glue joint can be examined in the early stage of assembly design.
3. By using VAA architecture, an assembly designer does not need to possess all mechanical analysis capabilities in house. VAA services can be invoked transparently and remotely through a service-oriented VAA architecture.
4. The developed service-oriented VAA architecture is scalable and extendable. This architecture provides an environment, in which new analysis tools and information are easily acquired from remote analysis service providers.

In this paper, pre-determined finite element analysis procedures are used to predict the physical effects of joints such as displacement and residual stress. Determining an appropriate joining analysis procedure is very important for obtaining realistic analysis results. In this work, various actual situations in welding such as welding directions, welding sequences, and weld layers were not considered. Detailed and realistic analysis methodology can provide in-depth information of welding behavior to a designer. As a case study, a set of joining methods (i.e., arc welding and riveting) are selected and investigated. To realize VAA for additional joining methods, various issues need to be investigated, such as mapping between the assembly design model and the assembly analysis model, and determination of efficient and realistic joining analysis methods considering the joining characteristics. Future research work has to be directed toward assembly analysis procedures to secure more analysis flexibility. Since design and analysis models contain critical information about products, a secured and trusted relationship between a client and a service provider is a very important consideration to realize an *e*-design paradigm. The security and trust management is one of major research areas in the US NSF Center for *e*-Design.

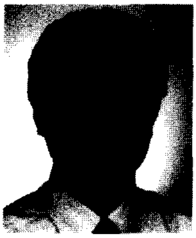
Acknowledgement

This research was supported in part by the Office of Naval Research, U.S. Department of Defense (Grant Number: N00014-02-1-0649).

References

1. Messler, R. W., 1993, *Joining of Advanced Materials*, Butterworth-Heinemann.
2. LeBacq, C., Brechet, Y., Shercliff, H. R., Jeggy, T. and Salvo, L., "Selection of Joining Methods In Mechanical Design," *Materials and Design*, Vol. 23, pp. 405-416, 2002.
3. Jack Welch, Jack Welch and GE, *Business Week*, Oct. issue 1996.
4. FIPER, *National Institute of Standard Technology Annual Review on FIPER*, General Electric Aircraft Engines, Springdale, OH, December 12-13, 2001.
5. Pegasus, NSF IUCRC for *e*-Design: Strategic Planning Meeting, Pittsburgh, PA, USA, Dec 9 to 10, 2003, www.e-designcenter.info., 2003.
6. CATIA, Tolerance Analysis for Flexible Assembly, CATIA, Version 5 Release 9, Training material, May 2002.
7. Nnaji, B. O., Gupta, D. and Kim, K. Y., "Welding Distortion Minimization for an Aluminum Alloy Extruded Beam Structure Using a 2D Model," *ASME Journal of Manufacturing Science and Engineering*, accepted, June 2003.
8. Masubuchi, K., *Analysis of Welded Structures: Residual Stresses, Distortion, and their Consequences*, (New York: Pergamon Press Inc.), pp. 60-236, 1980.
9. Moon, H. S. and Na, S. J., "Optimum Design Based on Mathematical Model and Neural Network to Predict Weld Parameters for Fillet Joints," *Jr. of Manufacturing Systems*, Vol. 16, No. 1, pp. 13-23, 1997.

10. Tsai, C. L., Park, S. C. and W. T. Cheng, Welding Distortion of a Thin-Plate Panel Structure, *Welding Journal*, pp. 156-165, May 1999.
11. Rahman, A. *et al.*, "Boundary Correction Factors for Elliptical Surface Cracks Emanating from Countersunk Rivet Holes," *AIAA Journal*, Vol. 38, No. 11, pp. 2171-2175, 2000.
12. Pratt, M. J., "Virtual Prototypes and Product Models in Mechanical Engineering," *Proc. IFIP WG 5.10 on Virtual Environments and their Applications and Virtual Prototyping*, pp. 113-128, 1994.
13. Chua, C. K., Teh, S. H. and Gay, R. K. L., "Rapid Prototyping Versus Virtual Prototyping in Product Design and Nanufacturing," *Int. Jr. of Advanced Manufacturing Technology*, Vol. 15, pp. 597-603, 1999.
14. Su, D. and Amin, N., "A CGI-based Approach for Remotely Executing Large Program for Integration of Sesign and Manufacture Over the Internet," *Int. Jr. of CIM*, Vol. 14, No. 1, pp. 55-65, 2001.
15. Gee, K., "Vehicle Analysis Using an Agent-based Analysis Tools Framework," *Proceedings of the ASME 2001 Design Technical Conferences: DETC2001/CIE-21290*, Pittsburgh, PA, September 9-12, 2001.
16. Goriatchev, V. *et al.*, "Net Informational and Computational System for CFD Researchers," *Proceedings of the ASME 2001 Design Technical Conferences: DETC2001/CIE-21283*, Pittsburgh, PA, September 9-12, 2001.
17. Krishnamurthy, L. and Law, K. H., "A Data Management Model for Collaborative Design in a CAD Environment," *Engineering with Computers*, Vol. 13, pp. 65-86, 1997.
18. Rojas, E. M. and Songer, A. D., "Web-centric Systems: A New Paradigm for Collaborative Engineering," *Journal of Management in Engineering*, Vol. 15, No. 1, pp. 39-45, 1999.
19. Florida-James, B., Rossiter, N. and Chao, K. M., "An Agent System for Collaborative Version Control in Engineering," *Integrated Manufacturing Systems*, Vol. 11, No. 4, pp. 258-266, 2000.
20. Cutkosky, M. R., Tenenbaum, J. M. and Glicksman, J., "Madefast: Colloaborative Engineering over the Internet," *Communication of ACM*, Vol. 39, No. 9, pp. 78-87, 1996.
21. Mueller, A., Technical White Paper: "Shared Engineering with OneSpace from CoCreate," January 25, 1999.
22. PTC, (Online) "PTC Windchill Pro/INTERLINK Datasheet", http://www.ptc.com/products/windchill/engineering/ds_prointralink.htm, (2/15/00).
23. Godh, R., (Online) "Collaborative Product Modeling on the Internet," http://smartcad.me.wisc.edu/groups/internet/, 2002.
24. Smith, C. S. and Wright, P. K., CyberCut: A World Wide Web Based Design-to-fabrication Tool, *Journal of Manufacturing Systems*, Vol. 15, No. 6, pp. 432-441, 1996.
25. Boujut, J. F., Tichkiewitch, S. and Blanco, E., "Integration of Downstream Actors in the Design Process Using a Dedicated Expert CAD Tool for Forged Parts," *Concurrent Engineering Research and Applications*, Vol. 5, No. 4, 1997.
26. Kao, Y. C. and Lin, G. C. I., Development of a Collaborative CAD/CAM System, *Robotics and Computer-Integrated Manufacturing*, Vol. 14, No. 1, pp. 55-68, 1998.
27. Mervyn, F., Kumar, S. A., Bok, S. H. and Nee, A. Y. C., "Development of an Internet-enabled Interactive Fixture Design System," *Computer-Aided Design*, Vol. 35, pp. 945-957, 2003.
28. Nnaji, B. O., Wang, Y., Kim, K. Y. and Muogboh, O. S., PEGASUS: A Service-Oriented Product Design and Realization Engineering System Over the Internet, submitted to *IIE Transactions*, 2003.
29. 2002 International iSIGHT Users' Conference and FIPER Workshop, Washington, D.C., July 15 to July 18 2002.
30. Kim, K. Y., Wang, Y., Muogboh, O. S. and Nnaji, B. O., 2003, "Design Formalism for Collaborative Assembly Design," the Special Issue of the *Computer Aided Design* on Distributed CAD, accepted, June 2003.
31. Peak, R. S., Fulton, R. E., Nishigaki, I. and Okamoto, N., "Integrating Engineering Design and Analysis Using a Multi-representation Approach," *Engineering with Computers*, Vol. 14, pp. 93-114, 1998.
32. Rémondini, L., Léon, J. C. and Trompette, P., "High-level Operations Dedicated to the Integration of Mechanical Analysis within a Design Process," *Engineering with Computers*, Vol. 14, pp. 81-92, 1998.
33. Siegel, J., *CORBA 3: fundamentals and programming*, 2nd ed., John Wiley & Sons, Inc., 2000.
34. Ashley, S., "Contour: The Shape of Cars to Come?" *Mechanical Engineering*, Vol. 113, No. 5, pp. 36-44, May 1991.
35. Radaj, D., *Heat Effects of Welding*, Springer-Verlag, New York, USA, pp. 21-23, 1992.
36. Lee, K., Lee, S. and Lee, J., "Internet-based Remote Cooperative Ship Design System," *Trans. of the Society of CAD/CAM Engineers, Society of CAD/CAM Engineers*, Vol. 6, No. 3, pp. 198-205, 2001.



Kim, K.-Y.

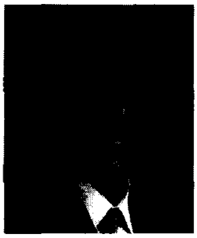
2003-Present: A research assistant professor, United States National Science Foundation (NSF) Industry/University Cooperative Research Center (I/UCRC) for e-Design, University of Pittsburgh.

1998-2003: Department of Industrial Engineering, University of Pittsburgh, PA (Ph.D.)

1996-1998: Department of Industrial Engineering, Chonbuk National University (M.S.)

1991-1995: Department of Industrial Engineering, Chonbuk National University (B.S.)

Interested area: Design and Manufacturing Engineering, Internet-based Design Collaboration, and Virtual Prototyping and Simulation.



Nnaji, Bart O.

1996-Present: Professor, Department of Industrial Engineering, University of Pittsburgh, PA, USA

1986-1996: Professor, Department of Industrial Engineering, University of Massachusetts at Amherst, USA

1981-1983: Industrial Engineering and Operations Research, Virginia Polytechnic Institute and State University, Blacksburg, Virginia (Ph.D.)

1980-1982: Industrial Engineering and Operations Research, Virginia Polytechnic Institute and State University, Blacksburg, Virginia (M.S.)

1977-1980: Physics (graduated 1st in the class & with distinction), St. John's University, New York (B.S.)

Interested area: Concurrent Engineering, Robotics & Robotic Assembly, Applications of Artificial Intelligence to Robotics & CAD/CAM, Internet-based Design Collaboration

Kim, D.-W.

1988-Present: Professor, Department of Industrial and Information Systems Engineering, Chonbuk National University

1992-1994: Department of Precision Engineering, Hokkaido University, Japan (Ph.D.)

1982-1984: Department of Industrial Engineering, KAIST (M.S.)

1978-1982: Department of Industrial Engineering, Seoul National University (B.S.)

Interested area: Robotic Process Planning, Compound Semiconductor Manufacturing, Production Planning and Scheduling, Intelligent Manufacturing System