Computers in Industry 65 (2014) 585–597

Contents lists available at ScienceDirect

Computers in Industry

journal homepage: www.elsevier.com/locate/compind

A web services-based multidisciplinary design optimization framework for complex engineering systems with uncertainties

C.W. Liu *, X.X. Jin [1], L.S. Li [2]

School of Mechanical & Automotive Engineering, Fujian University of Technology, No. 3 Xueyuan Road, University Town, Minhou, Fuzhou City 350108, PR China

ARTICLE INFO

Article history:
Received 27 July 2011
Received in revised form 24 November 2013
Accepted 15 January 2014
Available online 7 February 2014

Keywords:
Web services
Multidisciplinary design optimization
Integrated data model
Workflow
Complex engineering system
Uncertainty

ABSTRACT

With the increased complexity of complex engineering systems (CES), more and more disciplines, coupled relationships, work processes, design data, design knowledge and uncertainties are involved. Currently, the MDO is facing unprecedented challenges especially in dealing with the CES by different specialists dispersed geographically on heterogeneous platforms with different analysis tools. The product design data integration and data sharing among the participants and the workflow optimization hamper the development and applications of MDO in enterprises seriously. Therefore, a multi-hierarchical integrated product design data model (MiPDM) supporting the MDO in web environment and a web services-based MDO framework considering aleatory and epistemic uncertainties are proposed in this paper. With the enabling technologies including web services, ontology, workflow, agent, XML, and evidence theory, the proposed framework enables the designers geographically dispersed to work collaboratively in the MDO environment. The ontology-based workflow enables the logical reasoning of MDO to be processed dynamically. Finally, a proof-of-concept prototype system is developed based on Java 2 Platform Enterprise Edition (J2EE) and an example of supersonic business jet is demonstrated to verify the web services-based MDO framework.

1. Introduction

With the complexity of engineering systems, more and more disciplines, objectives, variables, constraints, coupled relationships and highly nonlinear optimization function are involved, which has become a computation-expensive and intractable problem. Fortunately, the emergence of multidisciplinary design optimization (MDO) in 1980s provides the solutions for CES. MDO is a methodology for the design of systems in which strong interaction between disciplines motivates designers to simultaneously manipulate variables in several disciplines [1]. It takes the coupled relationships of different domains into account adequately and simultaneously during the design process, and reduces much time and design cost than other sequential design approaches, attracting much interests in related researches of multidisciplinary design optimization. MDO has been developed and widely applied in many domains, including ship building, automobile engineering, electronics engineering and large-scale mechanical and electrical products, although it was originally devised to design aircrafts.

The engineering design involves multiple disciplines, design process, various analysis tools and lots of participants working on heterogonous platform and dispersed geographically. Thus, an integrated and collaborative environment for MDO is essential. In addition, MDO is inherently a multi-step process and refers to various types of design data and knowledge, analysis tools, optimization algorithms, computer aided design (CAD) and other design resources [2]. Finally, the tightly coupled relationships among disciplines cause the organizational challenge is another key problem. How to organize and integrate all the elements and resources is always a complex and time-consuming task, which is viewed as the biggest challenge from the birth of MDO to now. Therefore, an integrated MDO environment is necessary to conduct such processes more conveniently and efficiently.

To address the issue, several distributed, heterogeneous MDO frameworks are proposed. A number of key requirements (such as the architectural design, problem formulation construction, problem execution, and information access) are reviewed in [3]. A web/agent-based multidisciplinary design optimization environment-WebBlow is developed in [4]. Some enabling technologies including software agents, internet/web, and XML are adopted. Their objectives are to provide a powerful solution for

* Corresponding author. Tel.: +86 180 6068 9726; fax: +86 591 2286 3018.
E-mail addresses: cwliu2000@sina.com (C.W. Liu), jinxiaoqiong_2013@163.com (X.X. Jin), liliansheng1981@163.com (L.S. Li).
[1] Tel.: +86 138 3267 0367.
[2] Tel.: +86 152 1033 6906; fax: +86 010 8666 1931.

0166-3615/$ – see front matter
http://dx.doi.org/10.1016/j.compind.2014.01.003

project managers and designers working on multiple design projects to share product information and knowledge. The Collaborative Distributed Computing Environment (CDCE) [5] is a three-tier architecture and web-Java based framework to enable parallel applications written in PVM, pPVM, and MPI. The characteristics of collaborative design and control, convenient operations, working on heterogeneous platforms and flexibility are also discussed. A web services-based MDO framework enabling the synthesis of available disciplines and cross-disciplines resources for MDO via the Globus Toolkit is proposed [6]. It provides the organic and autonomous execution of MDO. However, the data management and uncertainties management are not addressed, which will affect the execution efficiency and reliability of optimization solutions. A problem solving environment (PSE) portal for multidisciplinary design optimization is proposed [7]. The PSE adopts the Globus Toolkit ver. 4.0 and web services techniques to enable the designers to utilize the design resources conveniently and orderly with the help of workflow management system. However, most of them only concentrate partial aspects of MDO, not providing a generic MDO framework.

At present, a number of software packages and commercial software served as MDO frameworks have emerged both in academia and industry. The representative works of academia are Interdisciplinary Design and Optimization (FIDO) [8] from NASA Langley Research Centre and the Intelligent Multidisciplinary Design and Optimization (IMAGE) from Georgia Tech Aircraft System Design Lab (ASDL). The Process Integration and Design Optimization (PIDO) software which is driven by ModelCenter from Phoenix Integration Inc. and iSIGHT products from Engineous Software Inc. are reviewed as the representatives of the commercial MDO framework. The former provides a heterogeneous distributed environment which adopts the analysis server to control all kinds of application programs such as commercial CAD tools, Matlab, Ansys and other analysis tools. The latter is the most popular MDO software for practical engineering design at present. It can be integrated with tools, such as the CAD, CAE, and PDM, no matter what kind of platform the designer uses. With the MDO Language (MDOL), clients can develop a customized environment according to the MDO problem and preferences of users. Both the ModelCenter and iSIGHT provide the design of experiments techniques (DOE), approximation methods, optimization algorithms, sensitivity analysis method and quality engineering methodologies. In addition, the design and definition of MDO strategy is feasible under the ModelCenter and iSIGHT environment.

Indeed, the current PIDO tools provide more optimization methods and algorithms and thus have lots of advantages. However, little emphasis is put on the data management, workflow design (especially the ontology-based workflow) and uncertainty analysis (considering both aleatory and epistemic uncertainties simultaneously). In addition, it does not provide a satisfactorily convenient and intuitive environment for users, although it can be integrated with a number of CAD/CAE tools. Meanwhile, some of the frameworks mentioned above are not generic but designed to solve a specific problem. Some of them only support fundamental aspects of collaborative design in which the interaction among design activities is predefined. More importantly, most of them lack uncertainty reasoning and aggregation, which can influence the reliability of complicated products.

In this article, we propose a multi-hierarchical integrated product design data model (MiPDM). As it describes, the MiPDM is designed in a structural tree with hierarchical level. The model integrates each process of MDO and represents all kinds of forms and formats data uniformly, which facilitates the data management and sharing among the participants over internet. A five-tier web services-based MDO (Web-MDO) framework is proposed considering both aleatory and epistemic uncertainties, which aims at providing a collaborative environment and convenient, intuitive interface, integrating all the scattered design resources, guaranteeing the well-organized execution of MDO process with the workflow management system and standard web technologies.

The remainder of the paper is structured as follows. Some functional requirements of MDO framework and basic concepts of web services, software agents, ontology and evidence theory are summarized in Section 2. The MiPDM model is proposed in Section 3, which supports the integration and sharing in the Web-MDO environment. The five-tier Web-MDO framework includes architecture, MDO agents and ontology-based workflow management are addressed in Section 4. The graphical user interface (GUI) and system implementation with a demonstrative example of supersonic business jet is presented in Section 5 and Section 6 concludes the paper.

2. Functional requirements and basic concepts

In this section, some functional requirements of MDO framework and fundamental concepts (such as web services, software agents, ontology, and evidence theory) adopted in this paper are summarized and addressed.

2.1. Requirements of MDO framework

Currently, MDO is facing the challenges of model complexity, information exchange complexity, computational complexity, and organizational complexity in dealing with the CES. Thus, a MDO framework capable of dealing with mass calculations, supporting efficient collaboration, organizing MDO process well, integrating all the required design resources developed in various languages on different platforms, permitting the participant dispersed geographically working collaboratively in a convenient and efficient way become essential. Therefore, some requirements of MDO framework are summarized and discussed from a functional perspective.

In this paper, six functional requirements are summarized.

(1) *Integration*. With a broader sense, the integration here contains the data integration, tools integration and process integration. Data integration provides a common framework which can integrate all the design documents, design data, system and subsystem data. Tools integration means that the MDO framework should provide interface for different users no what language and commercial software they use. Finally, the design process integration is to integrate all the design process and repeated iterations during the whole MDO process.
(2) *Intelligence*. The intelligence of MDO framework may be classified into two aspects. One is the intelligent of workflow based on knowledge reasoning and web services composition strategy. Another is the intelligent optimization algorithms (such as the GA, PSO, and ACO) which are adopted in dealing with large scale and coupling CES. Of course, the ideal MDO framework is more powerful in advising the user to choose the most suitable algorithm according to the practical requirements of MDO.
(3) *Distributed working environment*. The MDO may be carry out by different design group dispersed geographically on heterogeneous platforms. Therefore, the cross-platform and heterogeneous operations are the important requirements of MDO framework. In addition, the MDO framework should provide a collaborative environment permitting the designers, managers and decision makers to work concurrently. Meanwhile, the data and information transmission among different group,