Research Journal of Applied Sciences, Engineering and Technology 6(16): 3001-3010, 2013
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: January 09, 2013 Accepted: January 31, 2013 Published: September 10, 2013

A Comprehensive Optimum Design Method of Monitorability-based Design for Mechanical System Using Collaborative Theory

[1, 2]Sheng Chenxing, [3]Zhang Yuelei, [1, 2]Yan Xinping and [1, 2]Liu Jie
[1]Key Laboratory of High Performance Ship Technology of Ministry of Education (Wuhan University of Technology), Wuhan, China
[2]Reliability Engineering Institute, School of Energy and Power Engineering, Wuhan University of Technology, Wuhan, China
[3]Unit 94270 of PLA, Jinan, China

Abstract: The study aims to investigate the mechanical system optimum design based on collaborative theory. Due to the complexity of the modern machinery, mechanical systems are readily to damage when unexpected failures occur on important components. It is therefore, critical to monitor the machine state for preventing the impending faults. The key issues to realize the feasible and reliable mechanical condition monitoring is information acquisition, which relies on the available design of the detection devices. Literature review indicates that an extensive attention has been put on the so called Monitorability in the systematic design of mechanical systems. Monitorability is emphasized that in the original design of mechanical systems one should consider available information acquisition property. Moreover, monitorability-based design is known as a design attribute of mechanical system worldwide. However, less work has been done in this field. In this study, a novel method based on collaborative theory is proposed for the monitorability design. The connotation and application of collaborative theory for monitorability design are discussed in details. The information synergy model and organization framework of monitorability-based design are established by using computer technology and network technology. The experiments demonstrate the effectiveness of the proposed monitorability design system for a more powerful optimum design of mechanical systems and show a promising future for the industrial applications.

Keywords: Collaborative theory, monitorability-based design, mechanical system, product design

INTRODUCTION

With the rapid development of science and technology, mechanical systems are growing larger, its working environment is becoming more complex and its importance is becoming more important (Zhang *et al*., 2010a; Zhang and Yan, 2010; Li *et al*., 2010, 2011a, 2011b, 2012a). During the operation process of them, loss and damage are very heavy once the fault occurs. In order to deal with these challenges, some proprietary attributes of mechanical system are more required by users of mechanical system except performance requirements, function requirements and quality requirements of products. Safety, reliability and intelligence of mechanical system is more attention based on accomplishing high-efficient and reliable operation and minimum the life cycle cost of mechanical system (Liang *et al*., 2009; Yan *et al*., 2010; Yu *et al*., 2010; Li *et al*, 2012b, 2012c). At the same time, the users of mechanical system put forward higher request to monitorability of it. Monitorability-based design of mechanical system as a design attribute is emphasized day by day (Zhang *et al*., 2010a).

Monitorability of mechanical system can be achieved during the whole lifecycle of it including design phase, manufacturing assembly phase and application phase until to scrap phase of mechanical system. Monirorability of mechanical system is affected seriously if monitorability-based design is neglected in any phase and especially design phase during the life cycle. If monitroability-based design task on important parts and components of mechanical system is neglected during design phase and these shortcomings are found after the mechanical system is put to use, loss and damage are heavy (Du and Chen, 2005; Gu *et al*., 2006; Li *et al*., 2006; Xin and Bao, 2007; Guo, 2009; Zhang *et al*., 2010b). Now how to carry out monitorability-based design is becoming a problem during design process of complex mechanical system.

In order to investigate a optimum way to design mechanical systems, a comprehensive and optimal monitorability-based design method based on collaborative is presented from the view of product design in this study. In order to accomplish monitorability-based design task in every phase in the machine design process, the details of the design framework and the workflow have been described. The

Corresponding Author: Sheng Chenxing, Key Laboratory of High Performance Ship Technology of Ministry of Education (Wuhan University of Technology), Wuhan, China

experimental analysis results demonstrate the effectiveness of the proposed monitorability design system for a more powerful optimum design of mechanical systems and show a promising future for the industrial applications.

COLLABORATIVE THEORY

Collaborative theory is called collaborative learning or synergetics. The theory is raised by a famous physicist and a professor named Haken from University of Stuttgart, Germany. Collaborative theory is an emerging discipline, which has been gradually formed and developed to study the common characteristics of different things and coordination mechanism on the base of multi-disciplinary research, since the 70s of the 20th century. The theory is an important branch of Systems Sciences, which is focused on the various system's similarity from disorder into order. It is based on the latest achievements of modern science- systems theory, information theory, cybernetics, catastrophe theory, etc, learned the disipative structure, introduced a method of combination of statistics and dynamics, proposed multidimensional phase space theory through the analysis of different areas, built a set of mathematical models and treatment programs, described the common law of the various systems and phenomena in the transition from disorder to order, on the transition from micro to macro. It is mainly studied how synergies through its own internal and occur spontaneously time, space and the ordered structure function, in the case of the open systems far from equilibrium with the outside world in the material or energy exchange.

Collaborative theory as a research co-existence of different disciplines for the purpose of the essential features of system theory has been widely used, with its broad or universal applicability in a variety of different systems of self-organization of the analysis, modeling, forecasting and decision-making process. After decades of development, Collaborative theory has been developed rapidly in physics, chemistry, economics, sociology, management areas, computer areas, the natural sciences and other disciplines. It has been widely used in engineering, agricultural production, management, product design and development (Zhang *et al*., 2010a), business management, social organization and management and operational command. Hence huge economical and social effects can be produced.

MONITORABILITY-BASED DESIGN

The connotation of monitorability-based design for mechanical system: Mechanical system is taken as research object in the context. From a view of simple

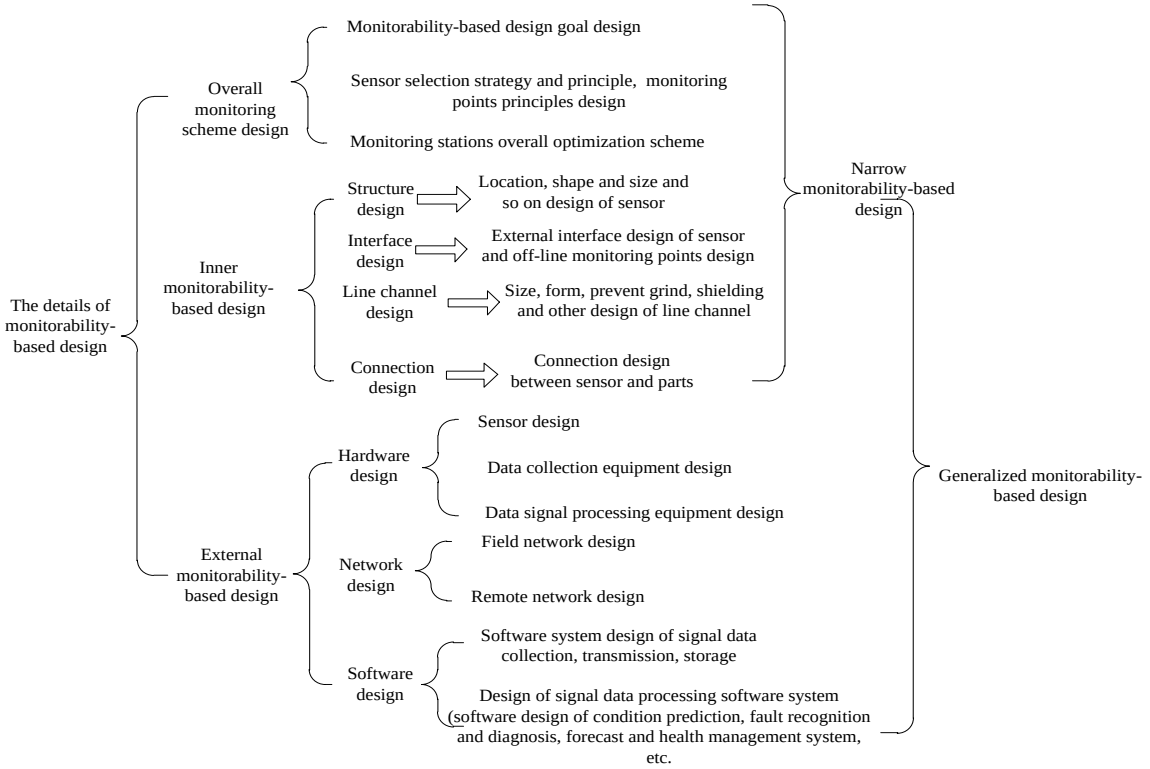

Fig. 1: Connotation of monitorability-based design for mechanical system

parts, it is hard to describe the function and meaning of monitorability-based design. Mechanical system monitorability means to select the best monitoring points and sensors by proper monitoring methods and considering monitorability problems clearly at the product design stage and finishing the embedded design when product design principles (including function, structure, shape and design) satisfied under the existed technics and methods.

Its mechanical system monitorability design content mainly contains three factors showed in Fig. 1 the whole system requirement and design, system inner design (inherent monitorability and analysis) and system external design.

Application effects of monitorability-based design on mechanical system: Monitorability-based design is one important part of product design on mechanical system products. It is important basis and key link to achieve condition monitoring and fault diagnosis for mechanical systems. Application and implementation of the theory is important to achieve condition based maintenance of mechanical system, can improve the fault prediction and health management ability for mechanical system, also can provide foundation and basic conditions for achieving reliability centered autonomous maintenance. At the same time, application and implementation of the theory has important significance to improve accuracy and technologies of condition monitoring, reduce maintenance costs and save security costs for mechanical system. All in, application and implementation of monitorability-based design has much something to do with design development, safe and reliable operation, maintenance comprehensive logistics safeguard and the life cycle cost of mechanical system. It is a key technology to ensure reliability indicators, maintainability indicators, safety indicators, security indicators and economic indicators of mechanical system. Important significance of monitorability-based design is shown in Fig. 2.

Monitorability-based design using the life cycle theory: Monitorability-based design tasks exist in the whole life cycle of mechanical system products (Zhang *et al*., 2010a). The design process shown in Fig. 3 is kind of complex system engineering. The design includes structure design, line design and software system design, etc. In a word, the engineering is a comprehensive technology using multidisciplinary integration including modern design technology, system engineering theory, condition monitoring and fault diagnosis technology, computer technology, sensor technology and other technology disciplines.

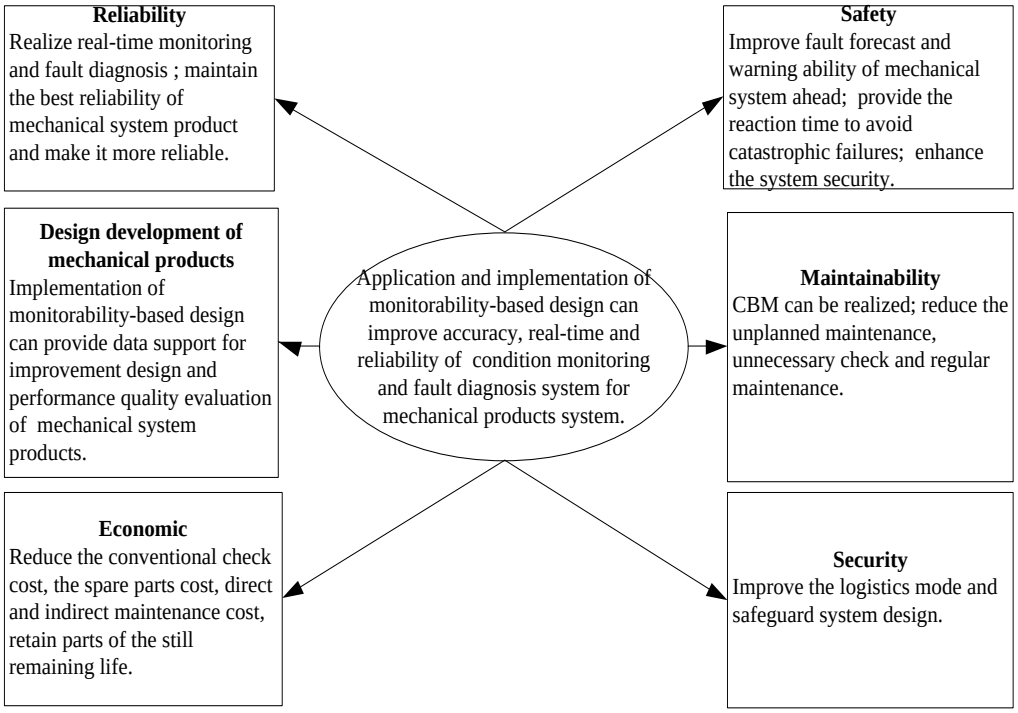

Fig. 2: Application significance of monitorability-based design theory

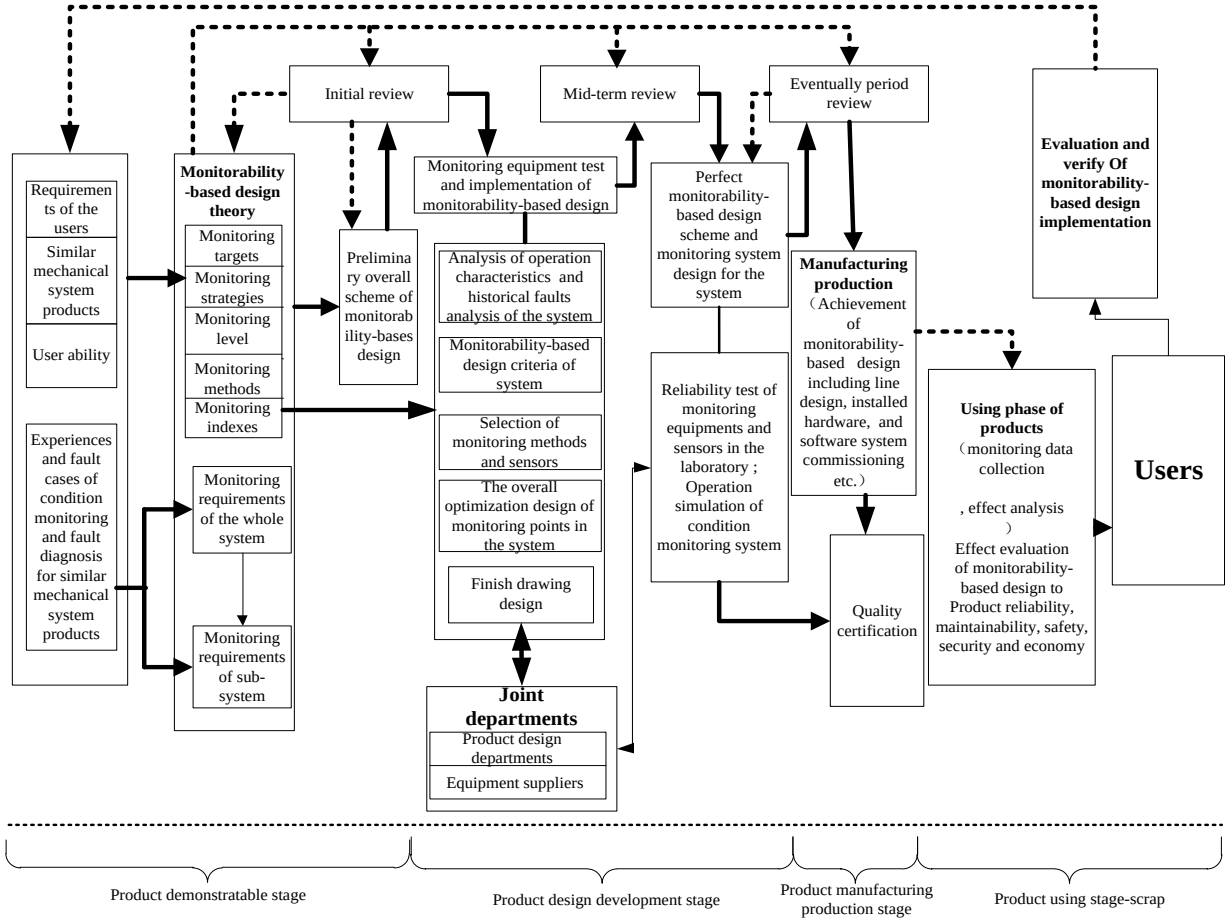

Fig. 3: Structure of monitorability-based design via the whole life cycle theory

MONITORABILITY-BASED DESIGN USING COLLABORATIVE THEORY

The synthesis model of monitorability design methods: Monitorability is a kind of property of the Mechanical system products which penetrate the entire life of produce demonstration, design, production, manufacture, use, maintenance-to scrap (Zhang *et al*., 2010a). The same as the function, appearance, performance, operation, reliability, maintainability and supportability design, monitorability-based design is an integral part of product design of mechanical systems. The work of monitorability-based design is closely related and interaction with performance and other proprietary property design of mechanical systems. So monitorability-based design is complicated system engineering during design process of a complex mechanical system. For the realization of the monitorability-based design work in the mechanical system conduct design process orderly and efficient, the synthesis model of monitorability-based design methods based on synergetics is established and shown in Fig. 4. The model makes use of coordination theory point of view that monitorability-based design can be freed from the chaotic in a complex mechanical system design work, realizing monitorability-based design work and the performance of mechanical systems design and other proprietary property of the design achieve design work can monitor the performance of mechanical systems design and other proprietary property of the design work effectiveness and efficient and orderly proceed, to achieve optimization, coordination, integration effect, so as to effectively protect the, development cycle, product quality of the mechanical system design, Improve the reliability, maintenance, monitorability of mechanical systems.

The monitorability-based design methods based on synergetics: The monitorability-based design is activities throughout the life cycle of mechanical

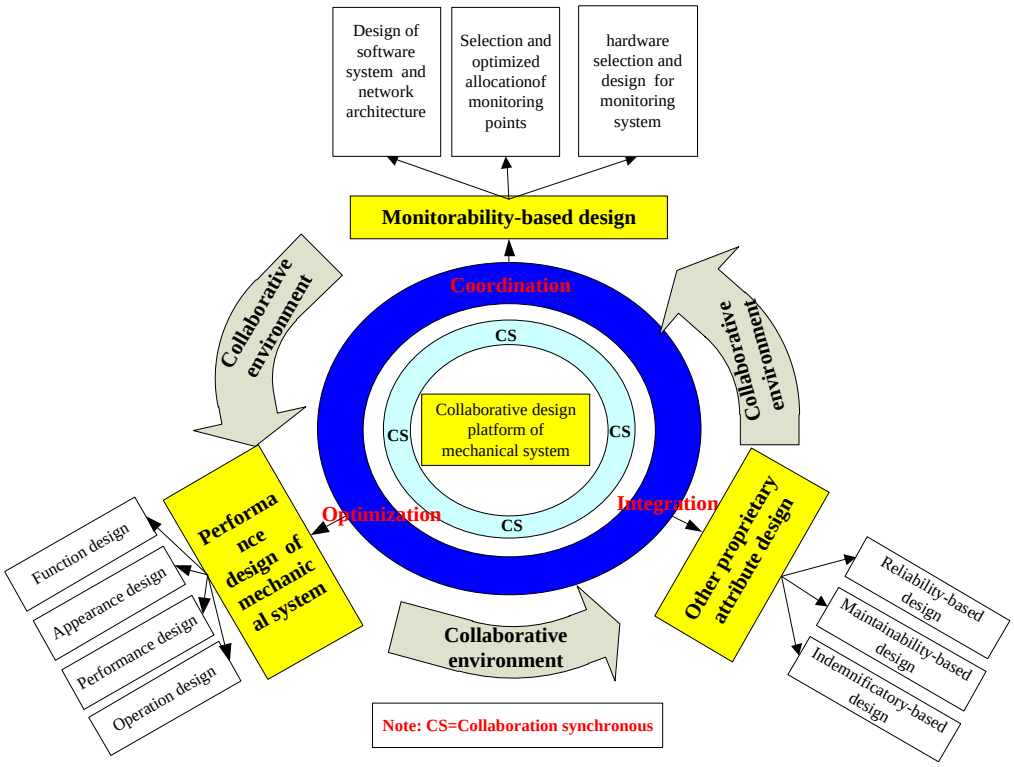

Fig. 4: The synthesis model of monitorability-based design methods based on synergetics

system and the implementation and control of which are exist in each stage of mechanical system design. The monitorability-based design methods based on synergetics is a method that the monitorability-based design of mechanical system is carried out under collaborative platform of mechanical system produce design (the synthesis model of monitorability-based design methods based on synergetics) using the theoretical point of view. It is the use of computer technology, network technology realizing monitorability-based design work and the performance of mechanical systems design and other proprietary property of the design. It completely optimizes, coordinates, integrates, overcome limitations of time and space, security monitorability-based design work effectiveness and efficient and orderly proceed. It also realized the performance design of mechanical systems and other proprietary property of the design collaboration, such as technical requirements, organizational structure, business processes, data information, software tools and etc.

- **Synergy of technical requirements:** The requirements of monitorability-based design of the mechanical system are same as its function, performance, reliability and maintainability design.

The key characteristics of mechanical products as required in the mechanical system design requirements should be clear of the requirements of monitorability-based design. Requirements of monitorability-based design can be monitored not only contains the index design should also include qualitative design and analysis requirements. The basic principles of monitorability-based design requirements developed should be clear, measurable, enforceable, traceability checks and verifiable. Monitorability projects penetrate the entire development cycle of the system of activities, each level of the product should be realized and controlled monitorabilitily from the perspective of the system.

- **Synergy of organization system:** Organizational system of monitorability-based design collaborative should include the organization and responsibilities of Synergistic. Responsibility of monitorability-based design can not be isolated. It should be proceeded whit the function of product design requirements through the various stages of the product at the same time. Mechanical product designer is the subject of functional design and exclusive property design. Professionals of monitorability-based design are the important

support and guarantee for realizing monitorability-based design. Organizational and the responsibility system of monitorability-based design should be collaborative whit product design, quality, testing and other departments work.

- **Synergy of business processes:** The process of monitorability-based design can not be isolated, its work program should permeate in mechanical product development process of all the aspects. That is the project of monitorability-based design the same as other work are integrated into the important documents of the mechanical product development process.
- **Synergy of data information:** Performance design information of the mechanical system is input data of monitorability-based design and other proprietary property design. Because the information generated from monitorability-based design and other proprietary property design work service in the design of mechanical systems and monitorability-based design is interaction whit other attributes of the design. So it should be keep pace with real-time collaboration between monitorability-based design and other proprietary attributes and performance design in the process of mechanical system product design.
- **Synergy of software design:** In the process of mechanical system design software tools needed coherence, which will help to the data sharing, transfer, exchange, integration and optimization. The software tool also requires not only the integration of software and interface technology development, business processes also need to adaptive re-design.

INFORMATION SYNERGY MODEL AND STRUCTURAL MONITORABILITY BASED ON SYNERGETICS

- **The basic information flow model of monitorability-based design:** The engineering implement of monitorability-based design based on synergetics concern to many people and departments, such as user, device manufacturers, technology market, the design department, manufacturing, logistics and other departments. Between the various departments the field in space and time are interdependent and mutual restraint. Problems of every aspect will affect the design process and applied effects of monitorability-based design. A wide range of data is transfer between them and a complex information chain network formed. The basic information flow framework model between each department is in Fig. 5.

Architecture and network architecture of monitorability-based design based on distributed resource environment: The work of monitorability-based design is mutual influenced and constraint, closely related to the performance of mechanical systems design and other proprietary property design.

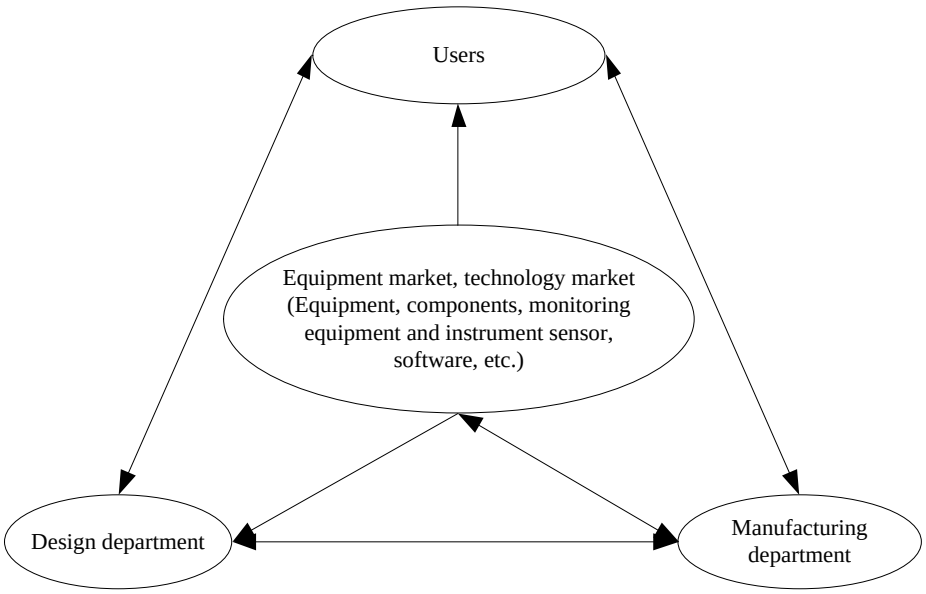

Fig. 5: The basic information flow model of monitorability-based design

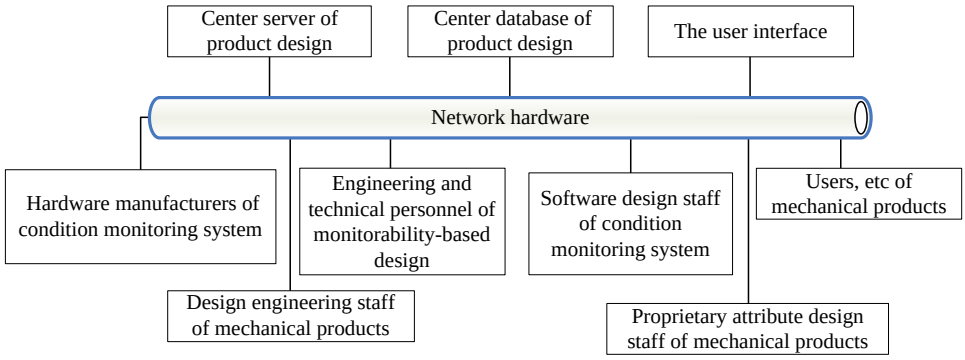

Fig. 6: Composition roles of monitorability-based design

Besides complicated exchange of information between various departments that is show in the basic information flow model of monitorability-based design, information exchange and sharing between various departments is also a quite complex network. So the key to methods of monitorability-based design based on synergetics in the process of mechanical system design is how to realize variety data information transfer and exchanged which required in the technical requirements, organization, business processes, data and software tools collaborative. That is realizing information flexible exchange and share between participants in the process of monitorability-based design of mechanical product. Because participants of monitorability-based design are distributed in different places. At the same time they are independent in physics. Information each participant owned is interaction one another. Information needs of each participant are transparent. Thus, all participants work form a distributed resource environment, the participants of monitorability-based design are together using computer technology, communication technology and information technology with a large number of computers through the network, which realize the information synergy and sharing between the participants and form a distributed resource system of monitorability-based design and description, registration, authorization, billing, update, delete, conflict, user authentication, user satisfaction, collection, dynamic authority and weight adjustments function characteristic of distributed resources environment that needed to resolve (Zhang *et al*., 2010a). Therefore, the framework of monitorability-based design of distributed resource environment based on synergetics established in this study includes the role in Fig. 6.

Scattered, isolated resources environment of monitorability-based design can synthesis of a real system of distributed resources. From the current technical conditions and platform of monitorability-based design at point of view pre-construction of the investment, the organizational structure of a single center be used in this study. The case that participants of monitorability-based design work coordination is shown in Fig. 7. This structure has a single resource service center. Different resource providers are registered in the service center for resources. Resource requester access distributed resources through the Web server platform. Different functional nodes connect by wide area network. So the system provides a virtual workspace, eliminates the time and space constraints and links the participants of monitorability-based design together. They can exchange information with each other and share objects for collaborative operations and complete a common task.

The cooperation design and realization of work information of monitorability-based design: Vb.net language is adopted as a development tool based on the characteristics of distributed resource environment and the network architecture built above. The collaboration capabilities of information flow in the distributed resource environment of monitorability-based design work based on synergetics is realized by use of P2P technology.

- **The design of system function:** For the realization of the participants of monitorability-based design collaboration in aspect of the technical requirements, organizational structure, business processes, data information, software tools and other information. The system should have the functions of sending and receiving (text, video, audio, documents, images, etc.) information, searching and adding the role of monitorability-based design, querying historical information and

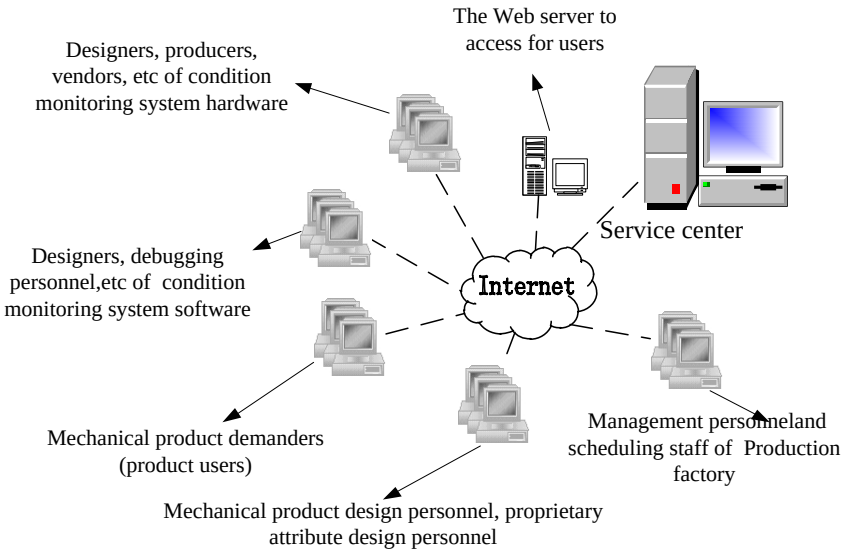

Fig. 7: The organizational network architecture of monitorability-based design based on synergetics in distributed resources environment

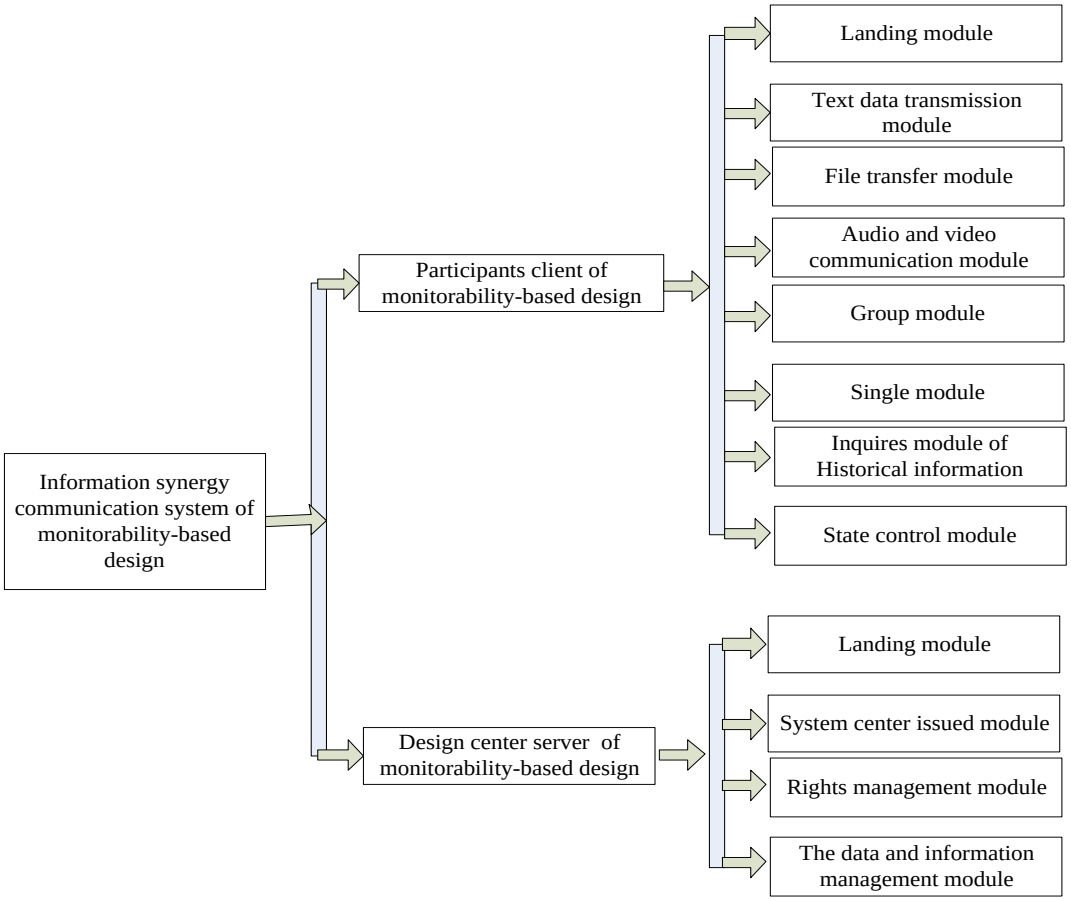

Fig. 8: Functional modules of collaborative communication system

managing information. The system can be divided into the following functional modules as shown in Fig. 8.

- **System Design and the main interfaces:** Reference QQ, POPO chat tools, the main interface of the program are designed as similar to the layout of the chat dialog format in this system. According to needs of information transfer and sharing of monitorability-based design, the main interface is divided into the main interface of dual role collaborative exchange of information and multi-role collaborative exchange of information.

CONCLUSION

Monitorability-based design as a mechanical product system design is an important organic component and has significance in improving the system of intelligence, reliability, product innovation and improving competitiveness. The project of monitorability-based design in full life cycle is a very complicated system. It is a Complex system engineering that overall realizing the mechanical system performance design and other proprietary property design coordination of space and time in the design process, including technical requirements, organizational structure, business processes, data, software resources and other collaborative design. It directly affects the whole process of product design and quality assurance. The design method is proved to be effective and good through the using in design of on-line monitoring system for marine power machinery system.

- It is ensure the engineering applications implementation of mechanical product of monitorability-based design in full life cycle and realizing monitorability-based design work, the mechanical system performance design and other proprietary property design coordination in the process of mechanical product of monitorability-based design using the synergetics.
- Information data transmission of monitorability-based design is protected by using the sub-step theory. It is easy to accomplish monitorability-based design engineering implementation effectively in mechanical system. It overcomes restrictions of time and space to participants of monitorability-based design and participants can obtain information and data of monitorability-based design timely and reliably.

ACKNOWLEDEMENT

This project is sponsored by the grants from the National Natural Sciences Foundation of China (NSFC) (No. 50975213), the National High Technology, Research and Development Program 863 (No.2011AA110202). the Projects of International Cooperation and Exchanges NSFC (No. 50311120207) and the Program of Introducing Talents of Discipline to Universities (No. B08031). The authors are grateful for the editors and anonymous reviewers.

REFERENCES

Du, X. and W. Chen, 2005. Collaborative reliability analysis under the framework of multidisciplinary systems design. Optimizat. Eng., 6: 63-84.

Gu, X., E. John and C. Penninger, 2006. Implicit uncertainty propagation for robust collaborative optimization. J. Mech. Design Trans. ASME, 128: 1001-1013.

Guo, J., 2009. Collaborative conceptualisation: Towards a conceptual foundation of interoperable electronic product catalogue system design. Enterp. Inform. Syst., 3: 59-94.

Liang, Z., Y. Lin and J. Shang, 2009. Collaborative multidisciplinary decision making based on game theory in ship preliminary design. J. Marine Sci. Technol., 14: 334-344.

Li, S., R. Ning and H. Wang, 2006. Study and realization on virtual collaborative design environment for assembly. Chinese J. Mech. Eng., 42: 129-134.

Li, Z., X. Yan, C. Yuan, J. Zhao and Z. Peng, 2010. The fault diagnosis approach for gears using multidimensional features and intelligent classifier. Imeche. Sem. Worldwide, 41: 76-86.

Li, Z., X. Yan, C. Yuan, J. Zhao and Z. Peng, 2011a. Fault detection and diagnosis of the gearbox in marine propulsion system based on bispectrum analysis and artificial neural networks. J. Mar. Sci. Appl., 10: 17-24.

Li, Z., X. Yan, C. Yuan, Z. Peng and L. Li, 2011b. Virtual prototype and experimental research on gear multi-fault diagnosis using waveletautoregressive model and principal component analysis method. Mech. Syst. Signal Pr., 25: 2589-2607.

Li, Z., X. Yan, Y. Jiang, L. Qin and J. Wu, 2012a. A new data mining approach for gear crack level identification based manifold learning. Mechanika, 18: 29-34.

Li, Z., X. Yan, Z. Guo, P. Liu, C. Yuan and Z. Peng, 2012b. A new intelligent fusion method of multidimensional sensors and its application to tribosystem fault diagnosis of marine diesel engines. Tribol. Lett., 47: 1-15.

Li, Z., X. Yan, C. Yuan and Z. Peng, 2012c. Intelligent fault diagnosis method for marine diesel engines using instantaneous angular speed. J. Mech. Sci. Technol., 26(8): 2413-2423.

Yan, L., Z. Li, X. Yuan and S. Xiong, 2010. Method of robust multidisciplinary design collaborative decision. J. Mech. Eng., 46: 168-176.

Yu, J., J. Cha, Y. Lu, W. Xu, N. Li and M. Sobolewski, 2010. Distributed collaborative design system for complex product. J. Central South Univ. Sci. Technol., 41: 539-545.

Xin, M. and X. Bao, 2007. CAS-based social network analysis for collaborative management in the green supply chain network system. Int. J. Netw. Virtual Organisat., 4: 446-458.

Zhang, Y. and X. Yan, 2010b. The research of optimal monitoring point placement for health monitoring of dredger based on analytic hierarchy process. Proceeding of the IEEE Prognostics and Health Management Conference, pp: 1-4.

Zhang, Y., X. Yan, C. Yuan and X. Bai, 2010a. Study of monitorability-based design in menchanical equipment. J. China Mech. Eng., 21(20): 2500-2504.

Zhang, Y., X. Yan and C. Yuan, 2010b. On the design of monitoring of mechanical system. Ship Ocean Eng., 39(2): 78-81.