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航空宇航学院2006年学术论文清单（0134）

序号	姓名	职称	单位	论文题目	刊物、会议名称	年、卷、期
1	袁慎芳 赖小松 赵　霞 徐　欣 张　亮	教授 硕士 博士 硕士 硕士	0134 0134 0134 0134 0134	Distributed structural health monitoring system based on smart wireless sensor and multi-agent technology	Smart Materials and Structures	2006.15.01
2	袁慎芳 梁大开 石立华 赵　霞 吴　键	教授 教授 教授 博士 博士	0134 0134 0134 0134	Distributed structural health monitoring technology for large engineering structure	International Joint Conference of INABIO/SMEBA 2006	2006
3	袁慎芳 彭　鸽 余振华	教授 博士 硕士	0134 0134 0134	On scattered lamb wave based damage diagnostic method	2006 Proceedings of the Second International Conference on Smart Materials & Structures in Aerospace Engineering	2006
4	吴　键 袁慎芳 赵　霞 殷　悦 叶伟松	博士 教授 博士 硕士 硕士	0134 0134 0134 0134 0134	Wireless sensor network node design for structural health monitoring applications	2006 Proceedings of the Second International Conference on Smart Materials & Structures in Aerospace Engineering	2006
5	吴　键 袁慎芳	博士 教授	0134 0134	无线传感器网络节点的设计和实现	仪器仪表学报	2006.27.09
6	彭　鸽 袁慎芳 徐颖娣	博士 教授 硕士	0134 0134 0134	Damage detection on two-dimensional structure based on lamb waves	Smart structures and systems	2006.02.02
7	彭　鸽 袁慎芳	博士 教授	0134 0134	基于主动Lamb波技术中的传感元件优化布置研究	航空学报	2006.27.05
8	赵　霞 袁慎芳	博士 教授	0134 0134	Developing multi-agent system for large structural damage detection	International Joint Conference of INABIO/SMEBA 2006	2006
9	赵　霞 袁慎芳	博士 教授	0134 0134	The design of multi-agent system for large engineering health monitoring	2006 Proceedings of the Second International Conference on Smart Materials & Structures in Aerospace Engineering	2006.09
10	常　鸣 袁慎芳	硕士 教授	0134 0134	基于HHT技术的复合材料结构损伤定位研究	宇航学报	2006.27.01
11	张恒萍 袁慎芳	硕士 教授	0134 0134	基于三维弹性理论的碳纤维板中Lamb波建模	材料科学与工程学报	2006.24.03
12	孙亚杰 袁慎芳 王帮峰	博士 教授 副教授	0134 0134 0134	Using extreme value theory to recognize damage in composite structure	2006 Proceedings of the Second International Conference on Smart Materials & Structures	2006.09
13	叶伟松 袁慎芳	硕士 教授	0134 0134	无线传感网络在结构健康监测中的应用	传感技术学报	2006.19.03
14	徐　欣 袁慎芳	硕士 教授	0134 0134	结构健康检测中压电元件的温度补偿方法	压电与声光	2006.28.06
15	梁大开 李东升 潘晓文	教授 博士后 博士	0134 0134 0134	智能结构中光纤智能夹层力学特性的实验研究	应用力学学报	2006.23.01
16	曾　捷 梁大开	博士 教授	0134 0134	Application of fiber optical surface plasmon resonance sensor for measuring liquid refractive index	Journal of intelligent material systems and structure	2006.17.8-9
17	潘晓文 梁大开 李东升	博士 教授 博士后	0134 0134 0134	Optical fiber sensor layer embedded in smart composite material and structure	Smart Materials and Structures	2006.15
18	徐明辉 梁大开 郑世杰 戴　峰 汤　林	硕士 教授 教授	0134 0134 0134	PVDF涂层建筑膜材单元结构力学性能的试验研究	实验力学	2006.21.02

序号	姓名	职称	单位	论文题目	刊物、会议名称	年、卷、期
19	曾　捷 梁大开 曾振武 杜　燕	博士 教授	0134 0134 0134 0134	基于SPR光谱分析的液体折射率测量研究	光谱学与光谱分析	2006.26.04
20	芦吉云 梁大开 李东升 潘晓文	博士 教授 博士后 博士	0134 0134 0134 0134	基于光纤智能夹层传感结构的应力测量研究	实验力学	2006.21.05
21	陈仁文 顾宝成	教授 硕士	0134 0134	Researches on Cushioning Control for Smart Airbags	International Joint Conference of INABIO/SMEBA 2006	2006
22	陈仁文	教授	0134	小波变换在输油管漏油实时监测中的应用	仪器仪表学报	2005.26.03
23	袁淑娟 陈仁文	硕士 教授	0134 0134	一种基于LabWindows的新型机械臂的设计与实现	机电工程技术	2005.34.11
24	袁淑娟 陈仁文	硕士 教授	0134 0134	CAN总线网络节点的实现及应用	江南大学学报（自然科学版）	2005.04.03
25	李　伟 陈仁文 王　琛	硕士 教授 硕士	0134 0134 0134	AD7715在小型材料试验机上的应用	仪器仪表用户	2005.12.01
26	李　伟 陈仁文 刘亚婷	硕士 教授 硕士	0134 0134 0134	基于脉冲编码调制技术的智能旋翼系统	仪器仪表用户	2005.12.04
27	陈　力 陈仁文 吴敏佳	硕士 教授 硕士	0134 0134 0134	一种新型智能流量积算仪的设计	电子工程师	2006.32.08
28	陈　力 陈仁文	硕士 教授	0134 0134	AD7745在微机械电容式传感器测量电路中的应用	仪器仪表用户	2006.12.01
29	刘天健 陈仁文	硕士 教授	0134 0134	基于LonWorks总线的智能安全传感器的研究与实现	仪器仪表用户	2006.13.02
30	王　笑 陈仁文	硕士 教授	0134 0134	Research on net flow measurement based on TCP/IP protocol	2006 Proceedings of the Second International Conference on Smart Materials & Structures in Aerospace Engineering	2006.09
31	朱海霞 陈仁文	硕士 教授	0134 0134	Miniaturization of an active vibration control system based on piezoelectric transformers	2006 Proceedings of the Second International Conference on Smart Materials & Structures in Aerospace Engineering	2006.09
32	冯　飞 陈仁文	硕士 教授	0134 0134	基于ANSYS的某发动机叶片的振动模态分析	仪器仪表用户	2005.12.06
33	王　琛 陈仁文	硕士 教授	0134 0134	基于i2Chip芯片的网络传输系统的研究	仪器仪表用户	2005.12.04
34	郑世杰 王晓雪	教授 讲师	0134 外校	基于固体壳单元的功能梯度材料板壳主动控制模拟仿真	航空动力学报	2006.21.06
35	王帮峰 李　迎 施益峰	副教授 硕士 硕士	0134 0134 0134	复合材料结构健康主动监测中激励信号的优化	南京航空航天大学学报	2006.38.05
36	王帮峰 李　迎 蒋雅娜	副教授 硕士 硕士	0134 0134 0134	含传感器脱粘损伤的智能结构响应特性分析	压电与声光	2006.28.05
37	龚　科 王帮峰	硕士 副教授	0134 0134	Experimental Research on the Thermoelectric Characteristic of Thermoelectric Power for Piezoelectric Micro-Jet Actuator	International Joint Conference of INABIO/SMEBA 2006	2006
38	秦　霞 王帮峰	硕士 副教授	053 0134	Numerical Analysis on Two Kinds of Cymbal Membranes for Piezoelectric Micro-flow Actuator	International Joint Conference of INABIO/SMEBA 2006	2006
39	周　勇 王帮峰	博士 副教授	0134 0134	Research on Fluidic Dynamic Characteristics of the Piezoelectric Synthetic Jet Actuator	International Joint Conference of INABIO/SMEBA 2006	2006
40	周　勇 王帮峰	博士 副教授	0134 0134	Research on Geometric Parameters and Fluidic Characteristics of the Piezoelectric Synthetic Jet Actuator	2006 中俄航空气动与强度学术会议	2006

序号	姓名	职称	单位	论文题目	刊物、会议名称	年、卷、期
41	王义昌 王帮峰	硕士 副教授	0134 0134	Single Phase Half-Bridge Inverter Based on PWM Method for Piezoelectric Micro-flow Actuator	2006 Proceedings of the Second International Conference on Smart Materials & Structures in Aerospace Engineering	2006.09
42	张 燕 王帮峰	硕士 副教授	0134 0134	Damage Identification of Composite Structure using Hilbert-Huang Transform and Artificial Neural Network	2006 Proceedings of the Second International Conference on Smart Materials & Structures in Aerospace Engineering	2006.09
43	沈 星 王鑫伟 In Lee	副教授 教授	0134 0132 外校	Experimental study of RAINBOW actuators made of PSZT	Journal of Intelligent Material Systems and Structures	2006.17.08-09
44	沈 星 冯 伟	副教授 硕士	0134 0134	Fabrication and properties of antiferroelectric RAINBW actuator	Chinese Journal of Mechanical Engineering	2006.19.01
45	沈 星 Jae-Hung Han In Lee	副教授	0134 外校 外校	Study of a reduced and internally biased oxide wafer PZT actuator and its integration with shape memory alloy	Smart Materials and Structures	2006.15.04
46	沈 星 刘永刚 裘进浩	副教授 博士 教授	0134 053 0134	Study Of Reduced Composite PZT For Large-Displacement Actuators	2006 Proceedings of the Second International Conference on Smart Materials & Structures in Aerospace Engineering	2006.09
47	沈 星 刘永刚 裘进浩	副教授 博士 教授	0134 053 0134	RAINBOW压电陶瓷与形状记忆合金的集成	金属热处理	2006.31.08
48	沈星 Qing Li Jianzhong Chai 刘学强 王鑫伟	副教授 副教授 教授	0134 外校 外校 0121 0132	Study Of Rainbow Actuator And Its Integration With SMA	International Joint Conference of INABIO/SMEBA 2006	2006
49	沈 星 刘永刚 陈 勇 徐志伟	副教授 博士 副教授 副教授	0134 053 053 0134	交叉指型压电纤维复合材料的有限元设计分析	第二届中国航空学会青年科技论坛文集	2006
50	刘卫民 陈 勇 刘永刚 沈 星	硕士 副教授 博士 副教授	053 053 053 0134	交叉指形电极压电纤维复合材料的优化设计	机械工程材料	2006.30.02
51	刘永刚 沈 星 赵东标 陈 勇 裘进浩	博士 副教授 教授 副教授 教授	053 0134 053 053 0134	测控用压电纤维复合材料仿真研究	测试技术学报	2006.20.增
52	冯 伟 沈 星 裘进浩	硕士 副教授 教授	0134 0134 0134	基于压电阻抗技术的结构健康检测研究	测试技术学报	2006.20.增
53	高 健 沈 星 裘进浩	硕士 副教授 教授	0134 0134 0134	Experimental Study of the Structure Health Monitoring Based on Piezoelectric Impedance Technology	2006 Proceedings of the Second International Conference on Smart Materials & Structures	2006.09
54	季 赛 沈 星 沈 超	博士 副教授	0134 0134	基于粗糙集和相似度量的CBR检索方法	计算机工程与应用	2006.00.13
55	裘进浩 Gael Sebald Makoto Yoshida Daniel Guyomar Kaori Yuse	教授	0134	Comparison of active, semi-passive and passive noise isolation of a plate bonded with piezoelectric elements	Journal of Advanced Science	2006.18.02
56	裘进浩 Masakazu Haraguchi	教授	0134	Vibration Control of a Plate using a Self-sensing Pieoelectric Actuator and an Adaptive Control Approach	Journal of Intelligent Material Systems and Structures	2006.17
57	倪青松 熊 克	硕士 教授	0134 0134	MCS-51单片机与GPS-OEM板的串行数据通讯的实现	仪器仪表用户	2006.13.03

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Distributed structural health monitoring system based on smart wireless sensor and multi-agent technology

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Abstract
This paper presents a new parallel distributed structural health monitoring technology based on the wireless sensor network and multi-agent system for large scale engineering structures. The basic idea of this new technology is that of adopting the smart wireless sensor with on-board microprocessor to form the monitoring sensor network and the multi-agent technology to manage the whole health monitoring system. Using this technology, the health monitoring system becomes a distributing parallel system instead of a serial system with all processing work done by the central computer. The functions, the reliability, the flexibility and the speed of the whole system will be greatly improved. In addition, with wireless communication links instead of wires, the system weight and complexity will be lowered. In this paper, the distributed smart wireless sensor network is designed first based on the Berkeley Mote Mica wireless sensor platform. Two kinds of sensor have been adopted: piezoelectric sensors and electric resistance wires. They are connected to a Mica MPR board though a designed charge amplifier circuit or bridge circuit and MTS101 board. Seven kinds of agents are defined for the structural health monitoring system. A distributed health monitoring architecture based on the defined agents is proposed. Finally, a composite structural health monitoring system based on a Mica wireless platform and multi-agent technology is developed to evaluate the efficacy of the new technology. The developed system can successfully monitor the concentrated load position or a loose bolt position.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Much attention has been focused in recent years on the research of structural health monitoring technology since it provides a reliable, efficient and economical approach to increase the safety and reduce the maintenance costs of engineering structures. These structures range from aging fleets of aircraft and ship structure to civil structures, such as bridges, highways and tall buildings. A lot of developments have been made proving that the structural health monitoring technology is a promising one [1–5]. However, so far, most of the developments on the structural health monitoring technology have been made on small size structures.

For next generation structural health monitoring systems applied on large scale structures, different kinds of density sensor networks are required to be adopted to monitor different structure parameters, such as stress, stain, displacement, acoustic, pressure, and temperature. Density sensors use different theories and have different functions. The information each sensor gets is limited; so is its local signal processing ability. Besides, real large scale engineering structures are very complicated systems to be estimated. Hence to reduce the weight of the sensor networks, to coordinate and manage the density sensor networks, to fuse the information from different kinds of sensors to take advantage of different estimation methods to make a reliable estimation of the whole structure at an acceptable speed is still a challenge.

In this paper, a distributed parallel structural health monitoring concept is proposed based on the smart wireless sensor network and multi-agent system. By adopting a smart sensor with embedded microprocessors and wireless communication links, a portion of the signal processing and computation can be done locally and simultaneously; thus the whole structural health monitoring system turns out to be a parallel system instead of the traditional serial system. With such a kind of parallel computation structure, the amount of information that needs to be transmitted over the network will be greatly reduced and the system speed will be improved. Besides, with wireless communication links, the information can be communicated in a wireless way which will reduce the weight of the sensor network, and thus facilitate densely distributed sensing. Multi-agent technology is adopted to organize and coordinate the density sensor networks and the information they obtain. Multi-agent systems over the past few years have been regarded as crucial technology not only for effectively exploiting the increasing availability of diverse, heterogeneous and distributed information sources, but also as a framework for building large, complex and robust distributed information processing systems which exploit the efficiencies of organized behavior [6, 7]. Their advantages are appropriate for application to a large scale structural health monitoring system with a density sensor network. By structuring a multi-agent based health monitoring system, the system will have the following advantages: speed up due to concurrent processing, fewer communication bandwidth requirements because processing is located nearer the source of information, more reliability because of the lack of a single point of failure and finally, and easier system development due to modularity.

Section 2 introduces the work done on the distributed smart wireless sensor network based on the Berkeley Mote Mica wireless sensor platform. Two kinds of sensor usually adopted in the structural health monitoring system, piezoelectric sensors and electric resistance wires, are connected to a Mica MPR board though a charge amplifier circuit or bridge circuit and MTS101 board. In section 3, seven kinds of agents are defined for the structural health monitoring system. A distributed health monitoring architecture based on the defined agents is proposed. Finally, in section 4, a composite structural health monitoring system based on the Mica wireless platform and multi-agent technology is developed to evaluate the efficacy of the new technology. The developed system can successfully monitor the concentrated load position or a loose bolt position.

2. Distributed smart wireless sensor network

In this work, the Mote Mica wireless smart sensor platform is adopted for the development of sensor systems. Besides the advantages of the small physical size, low cost and low power consumption, this sensor platform also has open source hardware/software, making it easy and flexible for users to develop their expected functions. The Mote Mica sensor

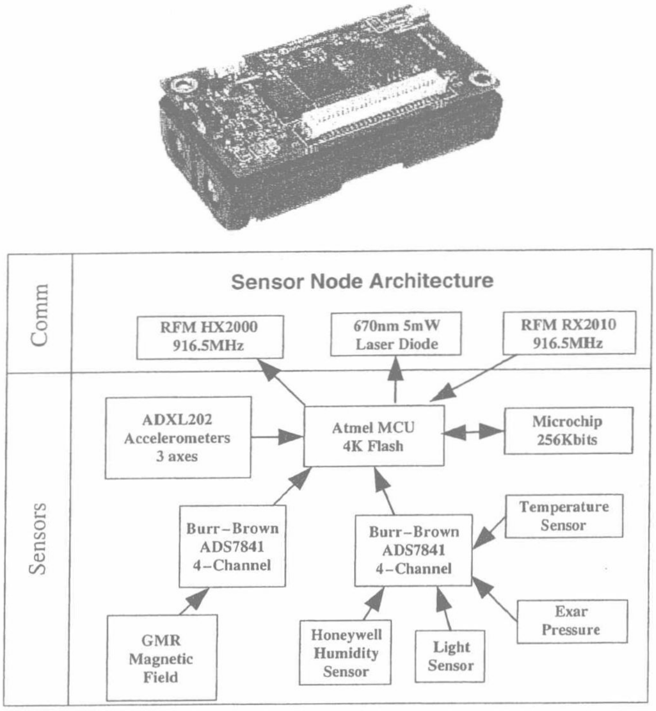

Figure 1. Mica smart wireless sensor platform and its basic block diagram.

system is developed by University of California at Berkeley under the network embedded software technology (NEST) program supported by the US Defense Advanced Research Projects Agency (DARPA). Figure 1 shows the Mote Mica wireless smart sensor platform and its basic block diagram.

The hardware of Mica consists of a small, low-power radio and processor board (known as a mote processor/radio, or MPR, board) and one or more sensor boards (known as a mote sensor, or MTS, board). The combination of the two types of board forms a networkable wireless sensor. The MPR board includes a processor, radio, A/D converter, and battery. The processor is an ATMEL ATMEGA 128L. It has 128 KB of flash memory and 4 KB of SRAM. The processor has three sleep modes: idle, which just shuts the processor off; power down, which shuts everything off except the watch-dog; and power save, which is similar to power-down, but leaves an asynchronous timer running. Power is provided by any 3 V power source, typically two AA batteries. The radio on the MPR module consists of a basic 916 MHz ISM band transceiver, antenna, and collection of discrete components to configure the physical layer characteristics, such as signal strength and sensitivity. It operates in an ON/OFF key mode at speeds up to 50 kbps. Control signals configure the radio to operate in either transmit, receive, or power-off mode. The radio contains no buffering, so each bit must be serviced by the processor in time. The MPR modules contain various sensor interfaces, which are available through a small 51-pin connector that links the MPR and MTS modules. The interface includes an 8-channel, 10-bit A/D converter; a serial UART port; and an I^2C serial port. This allows the MPR module to connect to a variety of MTS sensor modules, including MTS modules that use analog sensors as well as digital smart sensors [8–10].

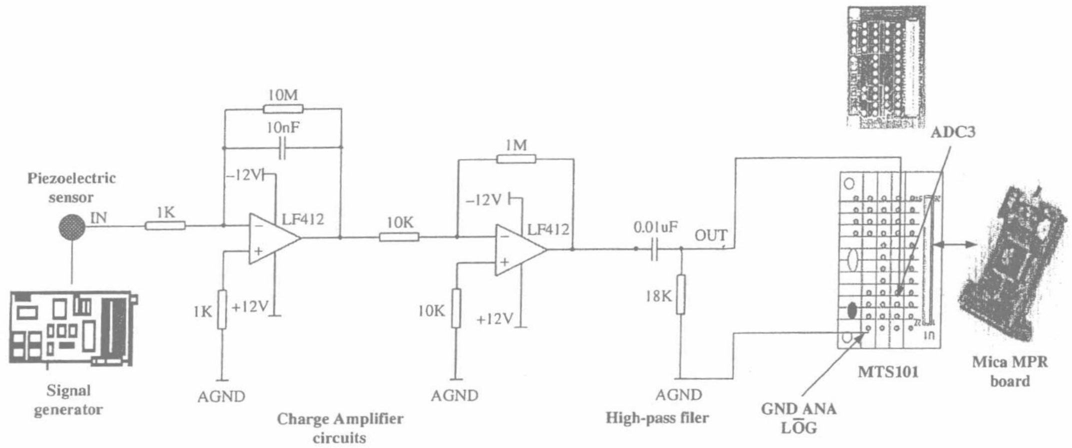

Figure 2. The connection of piezoelectric element, change amplifier, the MTS101 and the Mica MPR board.

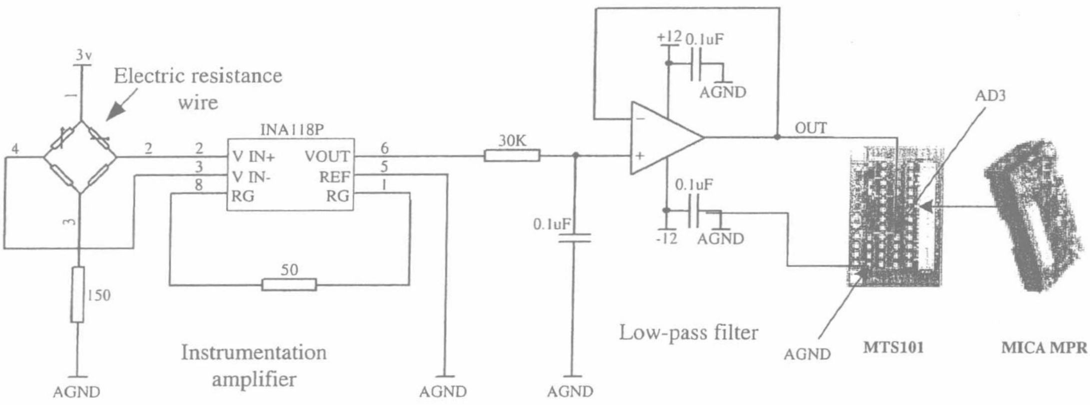

Figure 3. The connection of the electric resistance wire, amplifier, filter, the MTS101 and the Mica MPR board.

The software system of the Mote Mica is Tinyos (Tiny Operation System). This is an open-source operating system designed for wireless sensor networks. It features a component-based architecture which enables rapid innovation and implementation while minimizing code size as required by the severe memory constraints inherent in sensor networks. TinyOS's component library includes network protocols, distributed services, sensor drivers, and data acquisition tools. TinyOS's event-driven execution model enables fine-grained power management yet allows the scheduling flexibility made necessary by the unpredictable nature of wireless communication and physical world interfaces.

Though the MTS boards of the Mica Mote currently provide several kinds of sensing elements, such as light, temperature, two-axis acceleration, and magnetic sensors, these sensors are not suitable for the present work. In structural health monitoring, different sensing elements are chosen for different monitoring objectives. Piezoelectric elements and optic fiber sensors are two kinds of popular element usually adopted. The electric resistance wires are also used because of their cheap price and stable performances. Considering the monitoring objective in this paper, the possibility to be connected to Mica, the weight and the size of the sensor elements, piezoelectric ceramics and electric resistance wires are adopted as sensor elements in this research. In order to connect these two kinds of element to Mica Mote, MTS101 boards are chosen. MTS101 is a basic sensor board compatible with Mica which has only a light sensor and a temperature sensor. The signals from other sensing elements can be linked to this area and input to the Mica MPR board through its 51-pin connector.

Charge amplifiers are designed for the piezoelectric elements and bridge circuits are designed for the electric resistance wires. Since the piezoelectric elements are used to monitor the dynamic signal, high-pass filters are also designed to eliminate the low frequency noise, such as the 50 Hz electric line noise. The connection of the piezoelectric elements, the change amplifier, the filter, the MTS101 and the Mica MPR board is shown in figure 2. Figure 3 shows the connection of the electric resistance wire, the bridge circuit, the amplifier, the filter, the MTS101 and the MPR board. A instrumentation amplifier INA118 is adopted to amplify the output from the bridge circuit. The INA118 is a low power instrumentation amplifier offering excellent accuracy from Burr-Brown company. Its versatile 3-op amp design and small size make it ideal for a wide range of applications. Electric resistance wires are usually adopted to monitor the static signal, thus a low-pass filter is designed to eliminate the high frequency noise.

3. Distributed health monitoring architecture based on multi-agent technology

The concept of agent is very important in both artificial intelligence and mainstream computer science. The agent can be termed as a hardware- or software-based computer system which has the properties of autonomy, social ability, reactivity, and pro-activeness. Multi-agent systems are computational systems in which two or more agents interact or work together to perform some set of tasks or to satisfy some set of goals. A multi-agent system is viewed as a crucial technology not only for effectively exploiting the increasing availability of diverse, heterogeneous and distributed information sources, but also as a framework for building large, complex and robust distributed information processing systems which exploit the efficiencies of organized behavior. In a multi-agent based distributed system, each component or subsystem is changed to an agent. Though the information each agent obtains is not integrated or precise and its information processing ability is limited, since each agent has the knowledge of the whole system structure and also the knowledge of other agents' resources, functions, and structures, with the social ability and reactivity, different agents can cooperate with each other to develop effective and efficient problem-solving strategies [6, 7].

To apply multi-agent technology to a distributed structural health monitoring system, each component or subsystem in the structural health monitoring system should be changed to an agent. According to the subsystem's functions, seven kinds of agent are defined as follows for the structural health monitoring system.

Sensing agents: responsible for monitoring structure parameters, such as stress, stain, displacement, acoustic, pressure, and temperature. Sensing agents can be implemented by smart sensors with an on-board microprocessor.

Signal processing agents: responsible for processing data monitored by sensing agents and extracting signatures to estimate the structure state. Signal processing agents can be implemented by software or hardware and software together.

Estimation agents: responsible for estimating the structure state or life time using signatures extracted by signal processing agents. Estimation agents can be implemented by software.

Fusion agents: data from different sensor agents are processed by different signal processing agents and estimated by different estimation agents. Data from the same sensor agents can also be processed using different signal processing agents and estimated by different estimation agents. Thus fusion agents are required to fuse all the results from different methods to obtain the most reliable and precise conclusion. Fusion agents can be implemented by software.

Communication agents: responsible for managing the communications among different agents. Communication agents can be implemented by software or hardware and software together.

Coordination agents: responsible for the coordination of a group of agents, such as confliction solving, measurement time synchronization, decision making on resource share methods, and negotiation methods. Coordination agents can be implemented by software.

Interface agents: responsible for the communication with users, including parameter setting, user command input, globe estimation result demonstration, local estimation result demonstration, and alarm. Interface agents can be implemented by hardware and software together.

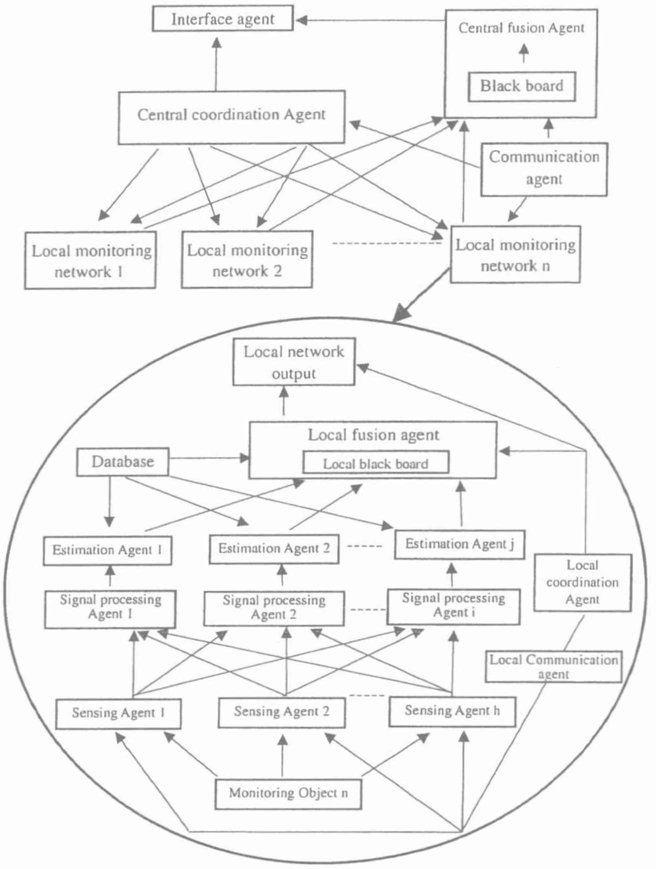

Figure 4. Multi-agent based distributed structural health monitoring architecture.

With the above definitions, a multi-agent based distributed structural health monitoring architecture is proposed as shown in figure 4. This is a hierarchical architecture. The central coordination agent in the first layer is responsible for coordinating the work of every local monitoring network. The central fusion agent fuses the monitoring results from every local network and gives a global estimation result of the whole structure. The interface agent is also in the first layer. Every local monitoring network monitors a portion of the structure. Some monitor the same portion, but monitor different parameters or use different methods. Their estimation results will be fused by a local fusion agent. For example, for the same portion of the structure, both optic fiber sensors and piezoelectric sensors can be used to monitor the structure damage. For the estimation methods, neural network based methods, mechanical model based methods, and wavelet analysis based methods can all be adopted to estimate the data from optic fiber sensors or piezoelectric sensors. Every sensor and estimation method has its own advantage and limitation. By fusing their results, the estimation will be more reliable and precise. For the information fusion in both the central fusion agent and local fusion agent, a method called black board can be adopted. The basic meaning of the black board in a fusion agent is similar to the black board in a classroom. In the present work, the fusion agent is realized by the software in the microprocessor. Thus, the black board

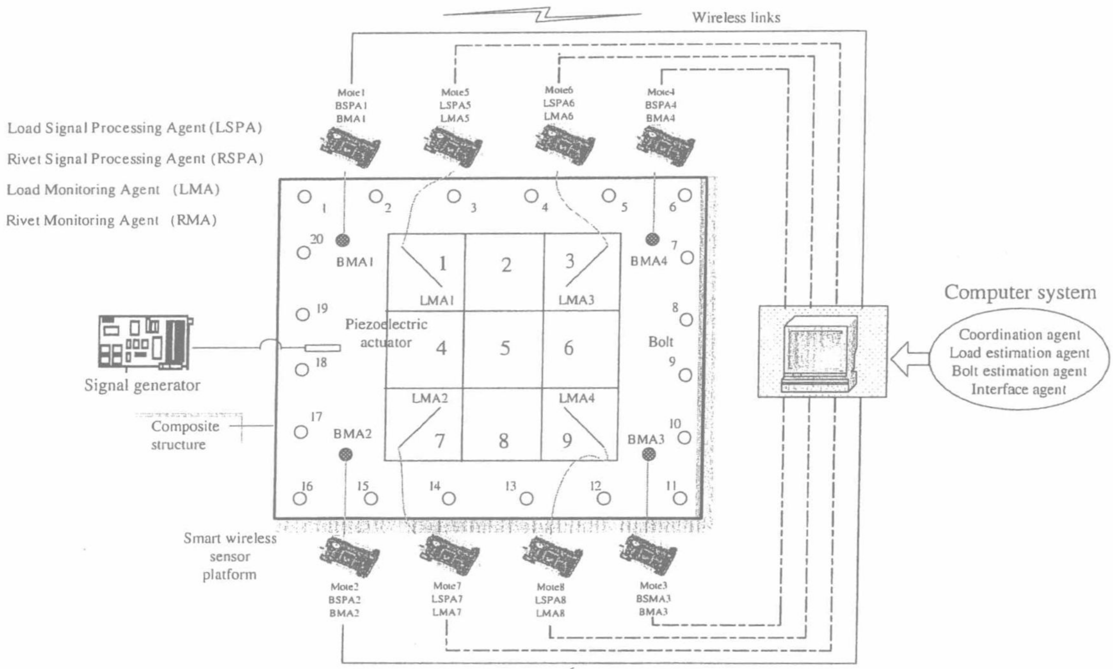

Figure 5. Setup of the composite health monitoring system based on wireless sensors and multi-agent system.

refers to a special memory reserved in the microprocessor's ROM. Though different estimation agents make their own decisions, when they try to estimate some data, they can share the procedure data from each other on the black board. That means that when the estimation begins, each estimation agent puts its own development in the black board; at the same time it tries to find the development of other estimation agents to see if their developments are useful for its own estimation. When its own estimation has useful development, this agent will go on putting the results on the black board for the reference of other agents. Finally, each estimation agent will get the most reliable and precise estimation results it can.

4. Development of a composite health monitoring system

In order to validate the possibility to develop a distributed health monitoring system based on a smart wireless sensor and multi-agent technology, a composite health monitoring system to monitor the applied concentrated load position and loose bolt is developed using Mica wireless sensor and multi-agent technology.

4.1. System setup

The setup of the composite health monitoring system based on wireless sensors and a multi-agent system is shown in figure 5. The composite is an 800 mm × 800 mm glass-fiber epoxy plate 4 mm thick fastened to a steel frame by 20 bolts. Two kinds of sensor network are incorporated in the composite, including four electric resistance wires of 80 mm length each, four piezoelectric ceramic sensors of 10 mm diameter and one piezoelectric ceramic actuator with a rectangular shape of 20 mm × 5 mm. Four electric resistance wires are adopted to monitor the position of concentrated load applied to the structure. There are in total nine areas to which the load may be applied. The four electric resistance wires are incorporated in area 1, area 3, area 7 and area 9, respectively. The piezoelectric ceramic sensors and the piezoelectric ceramic actuator are adopted to monitor the loose bolt. There are in total 20 bolts on the plate. If one bolt is loose, the system detects its position. Besides the sensors, eight Mica MTS101 board and MPR boards are also adopted. As shown in figures 2 and 3, the eight sensors are connected with Mica MTS101 and MPR board forming eight sensing agents, including four load monitoring agents and four bolt monitoring agents. Each kind of sensing agent forms a sensing agent network. A computer system and a signal generator are also included in the setup.

4.2. Multi-agent system

Since the structure size researched herein is not big and the objectives monitored by the system are not complicated, the multi-agent based health monitoring system only adopts one layer structure and some agents are not adopted here, such as the fusion agent, the communication agent and the database. There are in totally eight kinds and 20 agents in this system.

Load monitoring agent (LMA): implemented by the electric resistance wires together with Mica, used to monitoring load position applied to the composite plate. There are four LMAs in the developed system.

Bolt monitoring agent (BMA): implemented by the piezoelectric ceramic sensors and the piezoelectric actuator, adopted to monitor the loose bolt position. There are four BMAs in the system.

Load signal processing agent (LSPA) implemented by hardware and software together. The hardware parts including the designed amplifier circuits and the low-pass filter. The software parts including moving average and zero point compensation implemented in the Mica. There are four LSPAs in the system.

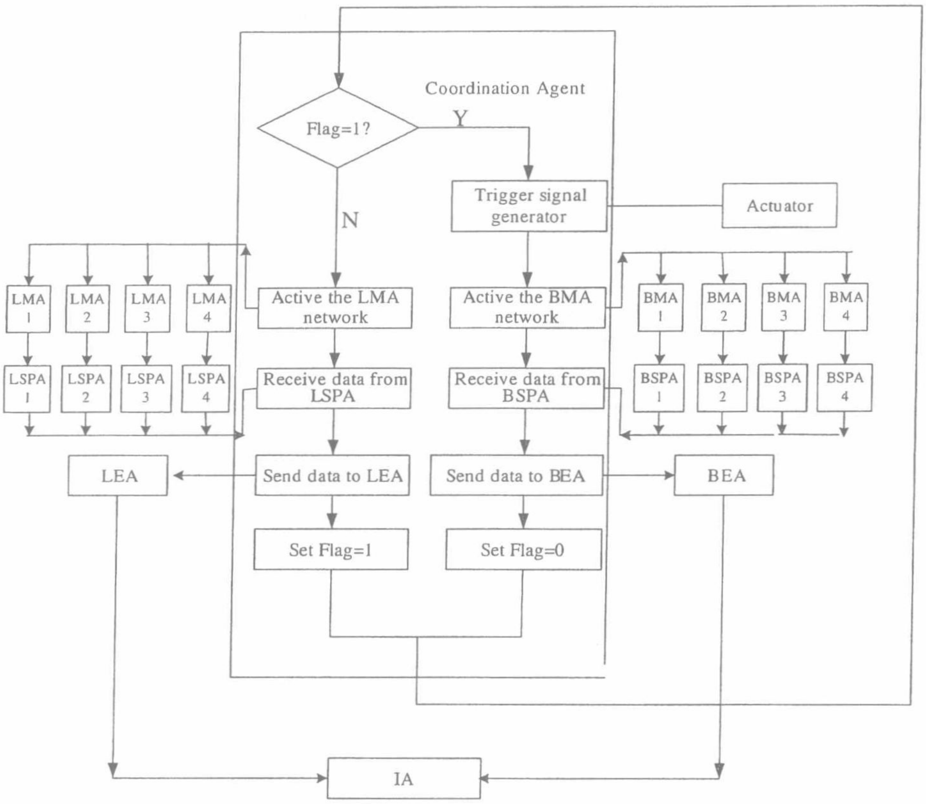

Figure 6. Multi-agent system and the working flow of the composite health monitoring process.

Bolt signal processing agent (BSPA): implemented by software in the Mica on-board software system. It extracts the peak value of each response monitored by BMA. There are four BSPAs in the system.

Load estimation agent (LEA): implemented by pattern recognition software based on Euclidean distance in the computer system to recognize the pattern outputs by the LMA network when load is applied at different positions on the composite plate. There is one LEA in the system.

Bolt estimation agent (BEA): implemented by BP neural network software in the computer system to distinguish which bolt is loose from the pattern outputs by the BMAs and BSPAs. There is one BEA in the system

Interface agent (IA): implemented by software in the computer system and the monitor of the computer system to accept commands from the user and show the monitoring results. There is one IA in the system.

Coordination agent (CA): implemented by software in the computer system. The CA coordinates the whole monitoring process. It decides when to communicate with the LMAs and LSPAs to input data using wireless links and when to give a control signal to the piezoelectric actuator to begin the loose bolt monitoring process.

Figure 6 shows the working procedure of the whole multi-agent based system and also the main coordination work the CA does.

4.3. Theory

The load position monitoring is based on the strain distribution change monitored by the LMA network. The four outputs of the LMA network form a mode to represent the strain distribution of the composite structure. When there is

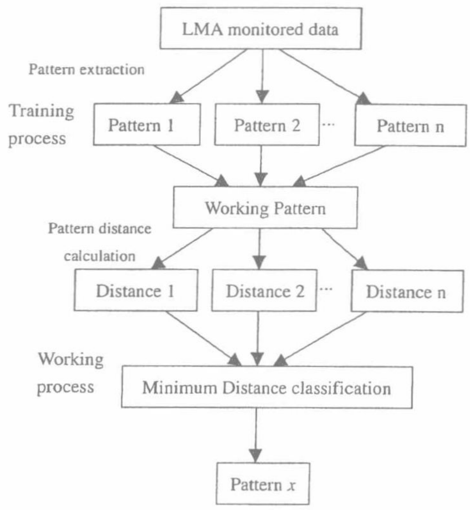

Figure 7. Pattern recognition process of LEA.

a concentrated load applied on the composite or the applied position changes, the strain distribution changes correspondingly, and the output mode of the LMA network changes too. The pattern recognition LEA classifies the different mode to decide different load positions [11, 12]. The pattern recognition method the LEA adopted is the minimum-distance classification. The distance between two patterns is calculated using the Euclidean distance, shown in equation (1).

$$d(x, y) = \left[\sum_{i=1}^{n} |x_i - y_i|2\right]^{1/2} \quad (1)$$

Table 1. Modes output from LSPAs.

Load applied area	LMA1 (mA)	LMA2 (mA)	LMA3 (mA)	LMA4 (mA)
No load	210	26	104	171
Area no. 1	246	35	103	174
Area no. 2	211	47	107	180
Area no. 3	211	63	108	179
Area no. 4	216	31	106	180
Area no. 5	212	34	109	186
Area no. 6	208	30	108	183
Area no. 7	204	27	109	210
Area no. 8	202	27	127	198
Area no. 9	211	29	162	185

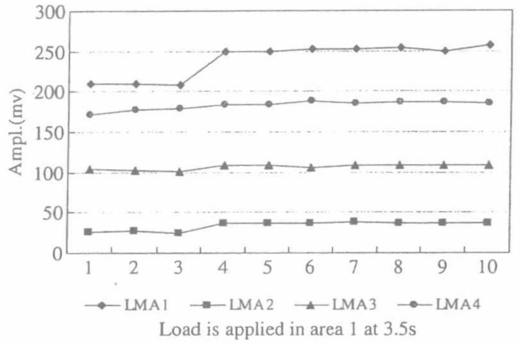

Figure 8. Typical waveforms monitored by the LMA network when a load applied.

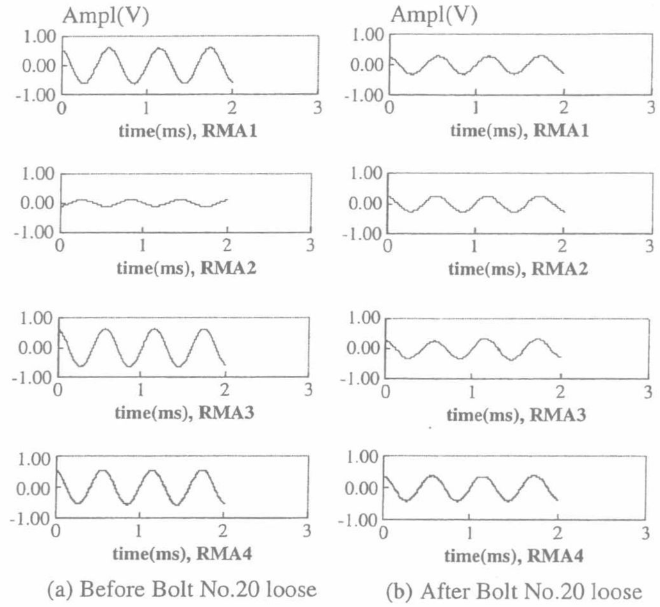

Figure 9. Typical waveforms monitored by the RMA network when there is a bolt loose.

where x, y indicate two different patterns, x_i are the elements of x, and y_i are elements of y. Figure 7 shows the recognition process.

The loose bolt monitoring is based on the structural vibration response [13]. A piezoelectric ceramic is adopted here to give a sine wave excitation signal to the structure at 1.7 kHz. One reason to choose 1.7 kHz excitation here is because this excitation is acceptable for the Mica board to sample data and transmit data. Another reason is because the vibration response of the structure under this excitation is sensitive to the loose bolt. The BMA network monitors the response of the structure under excitation and the BSPA extracts the peak values of each BMA to form a signature mode. When there is one bolt loose in the structure, the vibration response changes, causing the signature mode to change. Using the BP neural network, the mode can be shown to correspond to a certain loose bolt situation.

The system monitoring results are shown on the user interface. If there is a load concentrated on a certain area of the composite, the system will mark this area with a red color. If there exists a loose bolt, the system will diagnose its position and make a shining sign of the position on the user interface. Thus the user can find easily what is wrong with the structure.

4.4. Experimental results

Figure 8 is the typical waveforms monitored by the LMA network when a load is applied to the composite structure. Here, to show the changes clearly, the zero point of each LMA is adjusted to be different from each other. Table 1 shows the modes output from the LSPAs when a concentrated load which is 5 kg is applied to different areas on the structure. Figure 9 shows the typical waveforms monitored by the RMA network when there is a bolt loose. The peak values of these waveforms form a mode to represent the structure response under vibration excitation. Table 2 shows the mode outputs from the BSPAs when a different bolt is loose on the structure.

Experiments show that the developed system can successfully detect the position of the applied load and the position of the loose bolt. The advantage of the developed system is that by adopting a parallel distributed system structure based on the wireless smart sensor and multi-agent system, portions of the signal processing work are done in the Mica on-board processor which reduces the data that needs to be transferred to the computer system. Since each sensing agent has its own signal processing agent, all the local signal processing work is done in parallel, thus the system speed is improved.

5. Conclusion

This paper presents a new parallel distributed structural health monitoring technology based on a smart wireless sensor network and multi-agent system for large scale engineering

Table 2. Modes output from BSPAs.

Mode	RMA1 (mV)	RMA2 (mV)	RMA3 (mV)	RMA4 (mV)
System normal	1248	262	131	112
Bolt no. 1 loose	1127	770	639	801
Bolt no. 2 loose	692	689	440	614
Bolt no. 3 loose	1202	265	559	546
Bolt no. 4 loose	1670	888	462	770
Bolt no. 5 loose	1056	916	449	492
Bolt no. 6 loose	856	326	970	1168
Bolt no. 7 loose	659	354	1626	208
Bolt no. 8 loose	1301	526	537	638
Bolt no. 9 loose	1186	384	644	1054
Bolt no. 10 loose	1063	182	610	588
Bolt no. 11 loose	1033	314	840	652
Bolt no. 12 loose	1111	590	183	304
Bolt no. 13 loose	956	516	912	876
Bolt no. 14 loose	1058	420	1538	1152
Bolt no. 15 loose	509	186	824	946
Bolt no. 16 loose	857	632	994	787
Bolt no. 17 loose	1318	1413	1283	987
Bolt no. 18 loose	572	372	722	819
Bolt no. 19 loose	466	428	809	1251
Bolt no. 20 loose	627	542	717	813

structures. Using this technology, the health monitoring system becomes a distributing parallel system instead of a serial system. The functions, the reliability, the flexibility and the speed of the whole system will be greatly improved. This demonstration system is a small size structural health monitoring system. There are a number of important issues that need to be addressed for this new technology which has great potential. Some are listed as follows.

(I) The hardware and software of the smart wireless sensor platform need to be improved. The Mica Mote smart wireless sensor platform still has some limitations, such as limited sampling rate, limited memory, limited processing speed and limited data transmission ability, making it only able to be adopted to solve simple structural health monitoring problems at present.

(II) The development of an appropriate hardware and software framework to support the building of multi-agent based structural health monitoring system.

(III) The development of the appropriate communication, coordination and negotiation methods for the agents in the structural health monitoring system.

(IV) The development of methods to scale up to agent societies in a multi-agent based structural health monitoring system.

Acknowledgments

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Distributed Structural Health Monitoring Technology for Large Engineering Structure

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Abstract

This paper discusses the distributed structural health monitoring technology for large scale engineering structures. A hybrid wing box health monitoring system developed is first presented. Piezoelectric sensor array based active Lamb wave diagnostic method and Bragg gating sensor based structural strain monitoring method are adopted. The distributed health monitoring technology realized by multi-agent technology is discussed, including the individual agent design, the design of the whole multi-agent system (MAS) and three important aspects in designing MAS. Finally, the paper explains the motivation of the agents realized by wireless sensor network and the wireless sensor node developed.

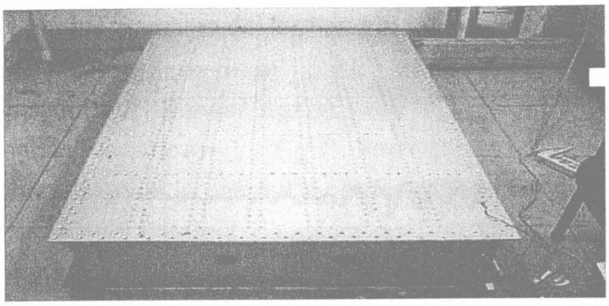
KEYWORDS : structural health monitoring, multi-agent technology, wireless sensor network, distributed system

1. Introduction

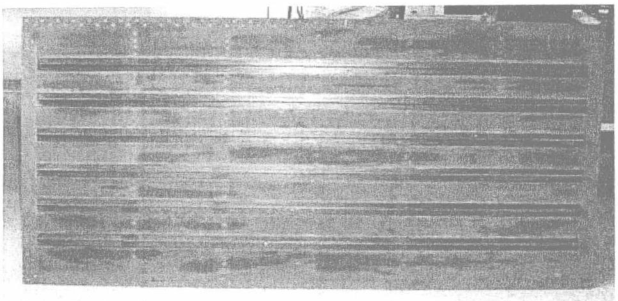
For structural health monitoring system applied on large scale structure, different kinds of density sensor networks are required to be adopted and monitor different structure parameters, such as stress, stain, displacement, acoustic, pressure, temperature and etc. Among the density sensors, the sensors use different theories and have different functions. The information each sensor get is limited, so does its local signal processing ability. Besides, real large scale engineering structures are very complicated systems to be estimated. Hence to reduce the weight of the sensor networks, to coordinate and manage the density sensor networks, to fuse the information from different kinds of sensors to take advantage of different estimation methods to make a reliable estimation of the whole structure in an acceptable speed is still a challenge [1-4].

In this paper, the distributed structural health monitoring technology for large scale engineering structures is discussed. First, a hybrid wing box health monitoring demonstration system is developed based on hybrid piezoelectric sensor array and Bragg gating sensor array. This is still a central computer base serial system. For more complicated engineering structure, the distributed parallel structural health monitoring concept based on smart sensor and multi-agent technology is discussed. By adopting smart sensor with embedded microprocessors, portion of signal processing and computation can be done locally and simultaneously. Multi-agent technology is adopted to organize and coordinate the density sensor networks and the information they obtained[5-6] Thus the whole structural health monitoring system turns out to be a parallel system instead of the traditional serial system. With such a kind of parallel computation structure, the amount of information needs to be transmitted over the network will be greatly reduced and the system speed will be improved. Besides, if the smart sensor adopts the wireless communication links, information can be communicated in a wireless way which will reduce the weight of the sensor network, thus facilitate densely distributed sensing[7-8]

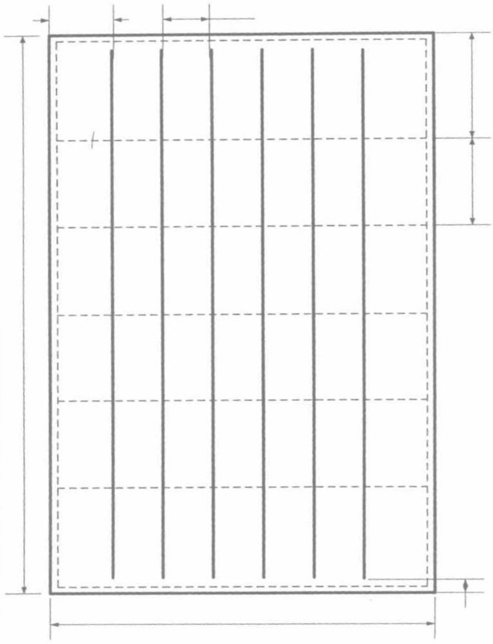
2 Hybrid Piezoelectric and optic fiber sensor based wing box health monitoring system



(a) Aluminum wing box skin



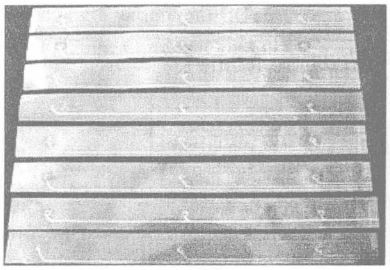
(b) Carbon fiber composite skin



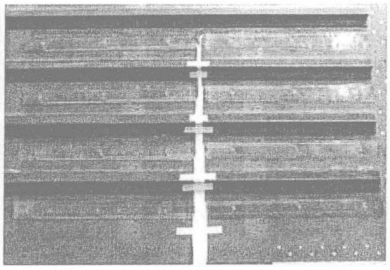
(c) Skin dimension

Fig.1 Wing box specimen

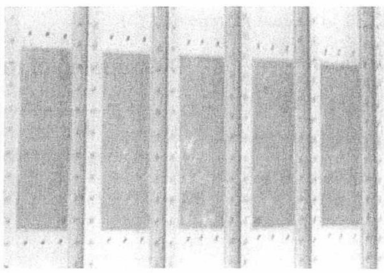
Wing box is an important part of the aircraft structure[9]. The wing box researched is shown in Fig.1. The dimension is 1000×1800×200mm. The top skin is made of carbon fiber composite material and the bottom skin is made of metal aluminum. The skin is fastened to the steel box frame. There are totally six T shape stiffeners with a distance of 130mm between each other. Vertical to the stiffeners there are totally five lines of bolt hole. The distance between lines is 280mm. On the wing box specimen, a hybrid health monitoring demonstration system is developed. Piezoelectric sensor array based active Lamb wave diagnostic method[10]and Bragg gating sensor based structural strain monitoring method are adopted. The PZT sensors are arranged on the carbon fiber skin and the optic fiber sensors are arranged on the aluminum skin. To make it easy to arrange the sensor array and ensure the arrangement process of each element to be the same, the smart layers are manufactured. The arrangement of the smart layer is shown in Fig.2.



(a) PZT smart layer



(b) Distribution of smart layer on the wing box skin



(c) Optic fiber smart layer and their distribution on the wing box

Fig.2 Smart layer and their arrangement on the wing box skin