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Structural health monitoring system based on multi-agent coordination and fusion for large structure

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ABSTRACT

In practical applications of structural health monitoring technology, a large number of distributed sensors are usually adopted to monitor the big dimension structures and different kinds of damage. The monitored structures are usually divided into different sub-structures and monitored by different sensor sets. Under this situation, how to manage the distributed sensor set and fuse different methods to obtain a fast and accurate evaluation result is an important problem to be addressed deeply. In the paper, a multi-agent fusion and coordination system is presented to deal with the damage identification for the strain distribution and joint failure in the large structure. Firstly, the monitoring system is adopted to distributedly monitor two kinds of damages, and it self-judges whether the static load happens in the monitored sub-region, and focuses on the static load on the sub-region boundary to obtain the sensor network information with blackboard model. Then, the improved contract net protocol is used to dynamically distribute the damage evaluation module for monitoring two kinds of damage uninterruptedly. Lastly, a reliable assessment for the whole structure is given by combing various heterogeneous classifiers strengths with voting-based fusion. The proposed multi-agent system is illustrated through a large aerospace aluminum plate structure experiment. The result shows that the method can significantly improve the monitoring performance for the large-scale structure.

1. Introduction

In recent years, there has been an increasing awareness of structural health monitoring (SHM) of the large infrastructures including aircraft structure, long-span bridges and high-rise buildings, since structure damage resulting from loading, joint failure and, etc. may cause the tremendous disaster [1,2]. However, for the actual large-scale structure monitoring, there are a number of sensors and various ones, which are distributed and dispersed, and the various evaluation methods, which are appropriate for different situations. For the application, the integration of a wide range of sensors and different evaluation methods must be done. Using the SHM technology on the large complicated practical structures, it is a critical problem that how to effectively manage the distributed sensor network, and coordinate and fusion different evaluation methods. Now multi-agent system (MAS) in artificial intelligence (AI) has been a natural model for developing a large-scale, complex, distributed system, which is loosely coupled and heterogeneous. It is an effective way for solving large-scale distributed problem [3]. Hence, multi-agent technology can be used to solve the SHM problem for the large structure.

At present, the MAS is researched in fault diagnosis and health monitoring, and there are some reports on MAS, related to mechanical fault diagnosis and health monitoring, etc.

In fault diagnosis domain, Stephen et al. worked at the research and the application of multi-agent power system condition monitoring [4]. NASA's Lyell et al. analyzed and designed the International Space Station's electric power system health monitoring using agent-based methods, and gave the simulation [5]. For fault detection and identification in chemical processes, Ng and Srinivasan utilized MAS to fusion different FDI methods for eliminating the results conflict and improving the diagnosis performance [6]. Their research focused on the construction of a single monitoring agent, the design and the functional verification of MAS for their fields.

In SHM domain, it is being in the initial stages of research on the MAS technology. Since 2002 NASA's Science and Technology Information Program (STI) was a research on non-life aerial vehicles using self-agent theory, and the work focused on the coordinate research of MAS [7]. Esterline et al. put forward the MAS

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model for the vehicle health management system, and their research was the distributed problem-solving based on contract net protocol [8]. Subsequently, Esterline et al. improved the above work and implemented MAS using JADE platform [9]. Yuan et al. initially proposed the distributed SHM system based wireless sensors and MAS which gave the agent's basic definition and implementation [10]. Then, Zhao et al. presented a complete design method for SHM based on MAS (SHM MAS) including ontology design, distributed database realization, facilitator design, and introduced the validation work of the case study in a large aviation aluminum plate in detail [11,12]. On the basis of Zhao's work, Sun et al. put forward the case-based reasoning and rule-based reasoning to coordinate obtaining the damage evaluation method for the accurate identification [13]. Bosse and Lechleiter present a hybrid data processing approach of on-line sensing and off-line inverse problem soluting for SHM systems by using self-organizing mobile multi-agent systems (MAS) [14].

In our past work [11–13], SHM MAS is also used to monitor the static distribution and joint failure on the structure. There, a strain sensor is an agent, and they are self-organized to monitor the strain load. Nevertheless, the system is complicated and every sensor agent has less autonomous. Meanwhile, the agent social ability is not studied intensively in the resource distribution for monitoring two types of damage uninterruptedly, and in the fusion of kinds of evaluation methods for the damage identification accuracy. Hence, this paper presents a MAS fusion and coordination framework for the damage accurately and real-time identification in the large structure, and gives the system implementation and experimental verification.

The organization of this paper is as follows: Section 2 provides the multi-agent coordination framework for the SHM. In Section 3, the proposed multi-agent system for the static distribution and joint failure monitoring is described in a case evaluation for damage identification. Then, Section 4 gives a discussion and a brief comment.

2. Development of SHM based on MAS

Considering a typical SHM system, a large-scale structure can be divided into several subareas monitored. The sensors are placed in or on the structure to acquire the data on the structural status parameters. The appropriate signal or information processing methods are adopted to analyze and extract the damage-sensitive features from the sensing data. The corresponding damage evaluation methods can obtain the structure health status using the key feature. Thus, according to the three typical parts, the data monitoring layer, data interpretation and damage diagnostic layer can be defined to form SHM MAS. Considering a large scale structure divided into some subareas, an information layer is needed to collaborate and fuse the damage information from the local subareas and provide the whole information to the user. Hence, according to the various functional components of the large SHM system, and considering the management and the coordination function, the agent in the system can be divided into 9 categories as follows:

(1) Sensing agent (SA) is to monitor the structure specific parameters.
(2) Signal processing agent (SPA) extracts the structural key features from the sensing signal.
(3) Damage evaluation agent (DEA) assesses the structural state in the light of structural features.
(4) In every subsystem, facilitator (agent) provides ‘‘yellow pages’’ services to every kind of agent. It is in charge of registering every agent services, such as feature extraction, damages assessment. Thus this is convenient for the agent to search the services and resources to achieve interaction and collaboration.
(5) District monitor agent (DMA) manages several sensing agents, and obtains the important (valid) damage data in local area.
(6) Central coordination agent (CCR) is responsible for the coordination among subsystems, such as conflict solving, time synchronization, resource distribution, and negotiation strategy.
(7) Central information fusion agent (CIFA) is in charge of fusing the damage information from different subareas to give a global estimation of the whole structure.
(8) User interface agent (UIA) provides information to the user and accepts the user's instruction.
(9) In every subsystem, sharing information management agent (SIMA) is designed. It is a distributed database, and it allows the agent to publish its identity (ID) and address in order that other agents can easily find it, and it is beneficial to exchange the information between different DEAs in the same or different subsystems. Meanwhile, it saves and provides the DEA's parameter.

The data monitoring layer includes (1) and (5) agents. The data interpretation and damage diagnostic layer separately corresponds to (2) and (3) agents. The information fusion layer is realized by (4), (6), (7), (8) and (9) agents.

The whole structure's damage evaluation work can be realized through agent's coordination and cooperation, in which consists of the coordination between the adjacent sensors and the cooperation of the DEAs between subsystems, and the one of the agents between different layers of a subsystems for the distributed problem studied by the paper. The SHM architecture based on MAS presented is shown in Fig. 1. The detail design of this architecture has been consideration in our work [11].

3. Evaluation of SHM based on MAS

3.1. System setup

In order to verify the effectiveness of multi-agent system, in this paper, a large aerospace aluminum plate structure is studied as the experimental object. In Fig. 2 it gives the flat structure and the sensor distribution diagram, and the photo of the structure and the monitoring system, as shown in Fig. 3. The plate structural material is the aviation-specific hard aluminum LY12, whose basic dimensions and thickness are 120 cm $\times$ 200 cm $\times$ 0.25 cm. Around the structure there are 64 M6-bolts which are used to fix the plate with bracket, and the bolt space is 10 cm. The bracket is put on the ground vertically, supporting the aluminum structure. The structure is divided into eight sub-regions, each of which is 49 cm $\times$ 45 cm except its edge. PZT (Lead Zirconate Titanate) sensors are laid on the vertices of each sub-region. In the 3th sub-region, FBG sensors are arranged, and in other sub-regions, the strain gauge sensors are arranged. In addition, each sub-area is divided into nine regional units.

SHM MAS has been developed by Zhao et al. [11]. In the paper, the presented improved multi-agent system is described in detail for the strain distribution and joint failure monitoring as follows. It should demonstrate the following advantages: the system can manage different sensor networks to monitor two kinds of damage, and focus on the static load on its boundary, and choose the idle damage evaluation method in different subsystems to improve the efficiency, and fusion different evaluation methods to