

## A Knowledge-based Structural Health Management System Design

Qi CHANG<sup>\*</sup>, He-Ming GAO, Xiao-Juan WANG, Qian-Ni FU

Faculty of Mechanical and Precision Instrument Engineering, Xi'an university of technology, NO.5  
South Jinhua Road, Xi'an, Shannxi, China

*cqhardrocker@163.com*

<sup>\*</sup>Corresponding author

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**Abstract.** Health Management System as a methodology can contribute safety and economics to the modern complex system. According to the OSA-CBM architecture, an open and configurable knowledge management system is proposed in this paper. Through the ontology modeling of the domain knowledge, building the related reasoning rules and with the help of reasoner, the structural health management system domain knowledge involved in health management can be inferred. The related functional agent can be organized into a multi-agent system to achieve the health management task based on the knowledge. A voting mechanism is proposed in data fusion to improve the veracity and reliability of diagnosis. A case study of structural impact detection is shown to verify the system and its efficiency.

### Introduction

With the ability to maintain system health and performance over the life of a system, complex system health management system has become a methodological tendency treating the modern complex system in terms of safety and economics in industries and aviations[1][2][5]. US DOD proposed the Prognostic and Health Management(PHM) system and Autonomic Logistics in the Joint Strike Fighter(F-35) Program gives the aircraft a thorough AI-based condition analysis and evaluation [3][4]. NASA developed the Integrated Vehicle Health Management (IVHM) system on the space vehicles X-33, X-34 and X-37, etc[1][3][4]. Yet the Open System Architecture for Condition-Based Maintenance (OSA-CBM) has been widely accepted as the standardized framework of the complex system health management system [1]. Based on the 5 functional layers defined in OSA-CBM, we defined a two-level health management system adopting a knowledge-based management mechanism to manage sensors, signal processing algorithm, reasoning rules and diagnostic tools, etc. All the information in the OSA-CBM is mapped within an ontology semantically describing the knowledge of each functional layer[6]. According to health management task, the knowledge can be reasoned through domain rule and new task knowledge about health management can be achieved[7]. A multi-agent system is organized to fulfill the health management task. A case study of structural impact detection in vehicle structure is shown to verify the system and its efficiency.

### Knowledge-based health management system architecture

Complex systems have interacting subsystems that operate in multiple physical domains, which demand the health management to manage various kinds of knowledge from the data acquisition to decision support. It requires self-contained and sophisticated knowledge configuration architecture for the health management to flexibly manipulate the knowledge configuration process. In figure 1, the knowledge-based health management system architecture is composed of different modules including knowledge base, data base, rule base, reasoner, multi-agent system[6][7]. Knowledge base consists of health management domain knowledge and the task knowledge accordingly. Through modeling the ontology of domain knowledge, the knowledge can be expressed flexible, sharable and reusable. Data base saves the raw data and the process information of the object so that

health management can be ensured. The health management system accesses the data base through a dynamic link, putting the data and information into it. By building productive rules of reasoning, the health management task is saved as the rule into the rule base. With the knowledge in knowledge base and rules in rule base, reasoner can reason with the task needed for current health management task. Multi-agent system can be configured with each relevant agent[8][9]. With the corporation between the agents, health management task of a certain object system can be realized.

**Health Management Domain Ontology.** An ontology is an explicit, formal specification of a shared conceptualization of a domain of interest[10][11]. According to OSA-CBM health management system function architecture, main concepts and relations of health management domain knowledge can be expressed as in figure 1[12].

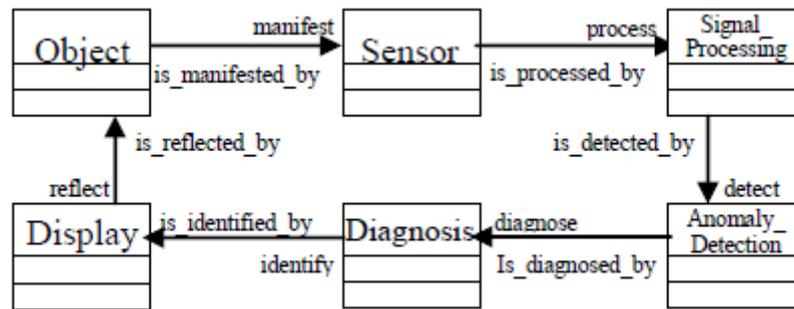


Fig. 1 Main concepts and relations involved in health management

The main concepts involved in health management knowledge are Sensors, Signal Processing, Anomaly Detection, Diagnosis and Display. Their relation between each other is just shown in figure 3. And the relation is symmetrical.

Definition 2. A health management issue is defined as:

$$HM = \{C, P, Cr, R\} \tag{1}$$

where

*C* — a set of components may constitute a health management task;

*P* — a set of properties of components ;

*Cr* — a set of constraints imposed on components;

*R* — a set of requirements, which are usually specified in the forms of constraints;

Definition 3. A health management task is defined as:

$$HT = \{I, V, B\} \tag{2}$$

where

*I* — a set of individuals, which are instances of components.

*V* — a set of values, which are assigned to properties of individuals.

*B* — a Boolean function,  $B: \{Cr, R\} \rightarrow \{T, F\}$ . The assignment of *I* and *V* makes the expressions *Cr* and *R* true.

Definition 3. A health management task configuration engine (*TC*) is a function that maps a configuration problem *HM* to a set of configuration solutions *HT*:

$$TC: \{HM\} \rightarrow \{a \text{ finite set of } HT\}. \tag{3}$$

**Health Management Multi-agent System Design.** In a health management system, task configuration can be achieved through reasoning about the present task in knowledge base. From this task configuration, a multi-agent system can be organized. Then through the corporation between multi-agent [10][11], the full task which is impossible for a single agent can be accomplished.

Agent designing depends on the domain knowledge. Based on the health management domain knowledge and the main concept listed in figure 3, the following types of agents are designed:

SA (Sensing Agent): data sampling, signal modulation and A/D converting;

SPA (Signal Processing Agent): signal processing, analysis and feature extraction;

ADA (Anomaly Detection Agent): to compare the feature value with threshold value to monitor anomaly affairs;

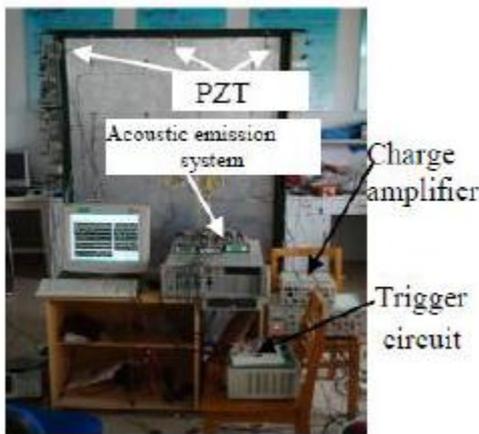
DA (Diagnosis Agent): if there's an anomaly detected, the failure is to be diagnosed and the failure report to be made;

DPA (DisPlay Agent): human machine interface, raw data display and accessing, history data preservation;

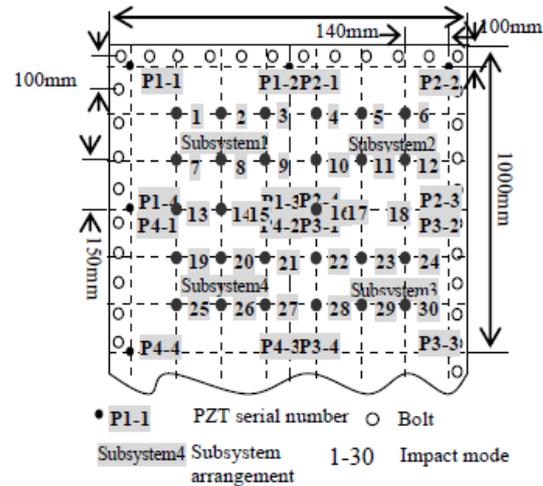
CMA (Central Management Agent): management of all agents, task allocation, task dispatch, coordination between agents.

**Structural impact detection health management system**

Impact is one of the major hazards that aviations concerning. The detection of impact on aviation structure is critical to the safety of the aircraft[13][14][15]. Figure 4a shows a typical aviation plate structure. Structural material is LV-26 aluminum. The plate is clamped all round by bolts. The upper half of the plate is chosen for this study. Nine PZT sensors are placed on the plate to sample the acoustic emission signals when impact occurs.



(a) Impact detection system configuration



(b) Sensor location and impact mode

Fig. 2 Experiment system

**Impact Detection Health Management Knowledge**

**Impact Detection Domain Knowledge.** The object in this task is impact events in the plate. The sensor is PZT sensors. Wavelet transforming is chosen for signal processing. In Anomaly Detection the threshold value test is adopted. If the amplitude exceeds the threshold value, an anomaly is reported. In Diagnosis, the Euclid Distance algorithm is adopted for impact mode recognition. In Display, the impact Display is chosen for position of the impact is displaying. The Protégé ontology modeling tool and the OWL modeling language are adopted in domain knowledge modeling.

**Domain Rule and Reasoned.** Domain rule defines the constitute of health management task. As can be seen in the following, the impact detection health management task is constituted by PZT, Amplitude (Differential Unitary\_PZT), Limit Detection (Impact\_Anomaly), Euclid Distance and Impact Display. The main rule in rule base is:

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SWRL:Task(?x) ^
PZT) ^ have_signal_processing(?x,
Impact_Task(?x)
DifferentialUnitary_PZT) ^ have_anomaly_detection(?x,
Task(?x) ^ have_sensors(?x,
Impact_Anomaly) ^ have_diagnosis_algorithm(?x, Euclid_Distance) ^ have_display(?x,
Impact_Display)

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JESS: (Task(name,?x)) (Impact_Task(name,?x)) → (Task(name,?x)) (have_sensors(?x, PZT))
(have_signal_processing(?x, DifferentialUnitary_PZT)) (have_anomaly_detection(?x,
Impact_Anomaly)) (have_diagnosis_algorithm(?x, Euclid_Distance)) (have_display(?x,
Impact_Display)))

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From the above, the productive rule is written in SWRL (Semantic Web Rule Language) language. The reasoner is made up of the JESS (Java Expert Shell System) reasoning engine. JESS turns the OWL ontology into facts with OWL2JESS, and the SWRL rule into JESS rule with SWRL2JESS. Then JESS reasons with the facts and rule to get new facts about the health management task.

**Impact Detection Health Management Agent System Configuration.** To make impact detection for large structure, the nine PZT sensors are divided into 4 subsystems in this paper. Each subsystem includes 4 PZTs, and we name it a SubSystem Agent (SSA). For the whole structure, each SSA has a certain degree cognition of the impact event. Since each single SSA itself can't tell the whole story, the integration of all the 4 SSAs' cognition of the impact can make possible a more accurate cognition of the impact health. In this way, the mode aliasing can be eliminated and failure rate of monitoring can be reduced.

SA: In each subsystem, 4 PZT sensors form a Sensor Agent. As showed in figure 3, each PZT sample the acoustic emission signal propagated in plate.

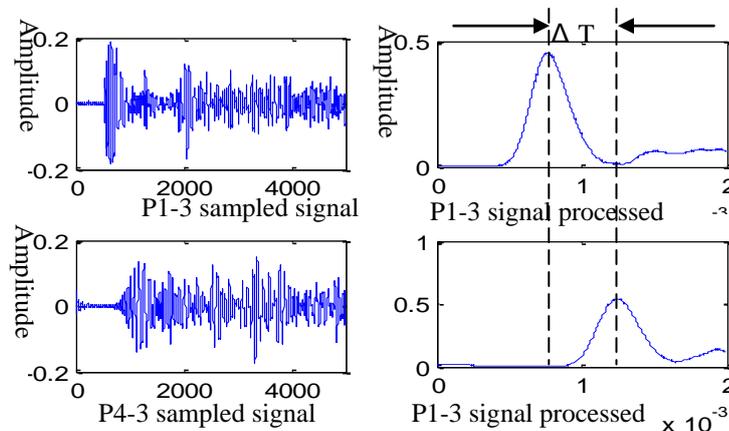


Fig. 3 SA sampled signals and SPA processed signals

*SPA*: The signal sampled by *SA* is processed by wavelet transforming, the Gabor wavelet is used in this paper. As showed in figure 3, the time according to the max value of the signal after wavelet transforming is adopted as the characteristic parameter.

*ADA*: to compare the stamp with the normal operating parameter of the system and decide whether there is a impact event.

$$ada = \begin{cases} 0, & |spa - \overline{spa}| < sv \\ 1, & |spa - \overline{spa}| \geq sv \end{cases} \quad (4)$$

where *ada* is anomaly detecting result; *spa* is signal stamp;  $\overline{spa}$  is system normally operating parameter; *sv* is the valve value, determined by experience.

*DA*: when there's an anomaly report, *DA* starts the diagnosis about the impac. Using the Euclid Distance algorithm, the position of impact can be figured out.

$$da_i = \underset{i=1}{\overset{n}{\text{MIN}}}(|\overrightarrow{ada} - \overrightarrow{ada}_i|), i=1 \dots n \quad (5)$$

where  $\overrightarrow{ada}_i$  is the stamp vector when the impact  $i$  mode is happened;  $da_i$  is DA diagnosis result is the impact  $I$  mode is happening.

**DPA:** to display the impact mode state and raw data sampled, providing the access to history data base and parameter configuration.

**Data Fusion Agent (DFA):** to fuse each SSA's diagnosis result and get the integrated diagnosis result of the whole system. As shown in figure 4, when there's an impact event, each SSA will have its own judgement of the position of impact. Yet, for a certain impact mode, each SSA may have different credibility for its diagnosis. As can be seen, if the distance between impact position and the subsystem is relatively small, the relevant SSA may have a high credibility in diagnosing. On the other hand, the relevant SSA may have a low credibility in diagnosing. To illustrate the relation between SSA credibility and the impact position, the following formula is obtained after times of experiments, showing the credibility weightings of the SSAs' diagnosis on impact.

$$r_i = \frac{\frac{1}{\sum_{j=1}^4 l_{i,j}}}{\sum_{i=1}^4 \frac{1}{\sum_{j=1}^4 l_{i,j}}}, i = 1 \dots 4 \quad (6)$$

Where  $l_{i,j}$  is the distance between the  $j$  sensor of  $SSA_i$  and the impact position.

When every SSA has its own diagnosis result, it sends the result to CMA, CMA computes the weighting sum according to each SSA's result. And the maximum of the sum is the fusion diagnosis result. The process is as follows: given  $SSA_i$  diagnosed that the impact mode  $t$  of subsystem  $m_i$  is failure(loose), then the voting process is:

$$vote_{i,j} = \begin{cases} 0, & SSA_j \text{ result isn't the same with } SSA_i \\ 1, & SSA_j \text{ result is the same with } SSA_i \end{cases} \quad i=1 \dots 4, j=1 \dots 4 \quad (7)$$

$$ma_i = \max_{j=1}^4 \left( \sum_{j=1}^4 r_{i,j} \times vote_{i,j} \right) \quad (8)$$

where  $vote_{i,j}$  is the vote from other  $SSA_j$  when  $SSA_i$ 's result is in consider;  $r_{i,j}$  is the credibility weight that  $SSA_j$  diagnosis for impact of subsystem  $m_i$ ;  $ma_i$  is the voting result, means that impact mode  $t$  is happening.

**Impact detection health management system working flow.** Figure 8 shows how the system works. CMA gets the knowledge about the health management and decomposes the task to each SSA. Each SSA organizes each SA, SPA, ADA, and DA. Through the corporation between these agents, the functions including data exchange, data sampling, signal processing, anomaly detection, failure diagnosis can be realized. When no anomaly is detected, the normal report is sent to DPA directly. And DPA displays the normal state. When there's an anomaly detected, each SSA sends its DA result to DFA fusing. After data fusion, DFA sends the fusion result to DPA to report the position of the impact.

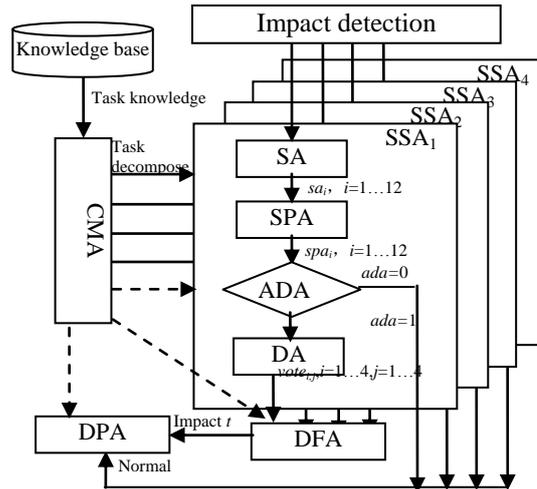


Figure 4 Multi-agent system working flow

**Case study**

A case study of impact detection has been down to verify the validity of the health management system design and effect of the multi-agent system . The impact mode 1-30 have been simulate on the plate and five sets of relevant data was sampled after five experiments. The impact energy is standardized by the 0.5mm pencil core broken. Four sets of the data were used in training the failure mode. The other set of data was used in testing the failure mode and diagnosing the impact. Part of the data, is shown in the table below.

Tab. 1 Data sampled by PZT sensors after the wavelet transforming

Impact mode	The time according to the max value of the signal obtained after the wavelet transforming(S)			
	Subsystem 1 (P1-1,P1-2,P1-3,P1-4)	Subsystem 2 (P2-1,P2-2,P2-3,P2-4)	Subsystem 3 (P3-1,P3-2,P3-3,P3-4)	Subsystem4 (P4-1,P4-2,P4-3,P4-4)
9	(0.00107,0.00085, 0.00072,0.00103)	(0.00085, 0.00131, 0.00072,0.00125)	(0.00103,0.00072, 0.00120,0.00128)	(0.00072,0.00125, 0.00172,0.00120)
16	(0.00165,0.00142, 0.00010,0.00152)	(0.00142,0.00169, 0.00011,0.00010)	(0.00152,0.00010, 0.00120,0.00142)	(0.00010,0.00011, 0.00120,0.00159)
20	(0.00083,0.00104, 0.00161,0.00045)	(0.00104,0.00120, 0.00089,0.00161)	(0.00045,0.00161, 0.00052,0.00051)	(0.00161,0.00089, 0.00091,0.00052)
29	(0.00188,0.00130, 0.00091,0.00129)	(0.00130,0.00131, 0.00092,0.00091)	(0.00129,0.00091, 0.00080,0.00123)	(0.00091,0.00092, 0.000850,0.00080)

For data in table 1, each SSA diagnosis result is shown in the table below:

Tab. 2 The diagnosis result by SSA and DFA

Impact mode	SSA diagnosis result				Fusion result (DFA)
	SSA <sub>1</sub>	SSA <sub>2</sub>	SSA <sub>3</sub>	SSA <sub>4</sub>	
9	9	9	10	9	9
16	17	16	16	17	16
20	21	24	20	20	20
29	24	28	29	29	29

It can be seen that a single SSA may diagnose falsely for its different acknowledgement of the impact detection. Yet considering their credibility weighting for different impact mode. Through DFA data fusion and voting for each SSA diagnosis, a more credible and correct diagnosis can be achieved. Diagnostic errors caused by mode aliasing can be further reduced.

## Conclusion

A knowledge-based health management system is proposed in this paper. Ontology modeling make the domain knowledge sharable, reusable, and configurable. Building the domain knowledge rule, knowledge can be reasoned in view of various tasks. According to the task knowledge reasoned, the relevant multi-agent system can be configured to fulfill the task to implement the health management task for an object system. A typical aviation structure is adopted as a case study to verify the health management system integration and its functional efficiency. A voting strategy is applied in agent data fusion to overcome the false diagnosis and increase the credibility and correctness.

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