Design and Implementation of PHM System Framework for Unmanned Surface Vehicles

Yiling Zhou[1]
Department of Management Engineering and Equipment Economics
Naval University of Engineering
Wuhan, China
521124808@qq.com

Tao Hu[2]
Department of Management Engineering and Equipment Economics
Naval University of Engineering
Wuhan, China
13871161071@139.com

Jianjun Yang[3]
Key Laboratory of Modern Manufacturing Quality Engineering
Hubei University of Technology
Wuhan, China
Yang791204@163.com

***Abstract*—Unmanned surface vehicles (USVs) often execute missions in highly dangerous and complex environments, making it difficult to maintain once critical failure occurs. Therefore, this paper aims to propose a prognostics and health management (PHM) system framework for USVs to satisfy the requirements for real-time fault monitoring, health-state evaluation, and preventive maintenance. A functional structure framework is proposed on the basis of USVs PHM system requirement analysis. The method of implementing the real-time health-state evaluation of the USVs is summarized through the case study of navigation radar. Thereafter, the multi-method modeling is used to simulate the failure of key components of the USVs system, and the mission capability simulation model is constructed, which lays a foundation for the realization of the USVs PHM system.**

Keywords-unmanned surface vehicles (USVs); prognostics and health management (PHM); multi-method modeling

I. Introduction

Unmanned surface vehicles (USVs) are autonomous marine craft that operate on the surface of water without any personnel onboard [1]. It is based on innovations in high-payload, high-speed small craft design and unmanned systems technology to provide a highly capable unmanned surface vehicle meeting the strenuous demands of multiple missions [2]. Executing missions in complex and dangerous waters without effective maintenance approach, may easily cause economic losses or even fatal consequences in combat if any critical failure occurs. Issues of fault detection and diagnosis (FDD) in USVs have attracted increasing attention in a wide range of research communities [3]. However, traditional maintenance methods could not meet the requirements of USVs during special mission.

Therefore, USVs prognostics and health management system is developed to achieve the real-time critical failure monitoring over their key equipment and scientific prediction of maintenance requirement which are significant to improving the operational readiness, mission availability and lowering life cycle cost of USVs.

Prognostics and health management (PHM) is an enabling discipline that uses sensors to assess the health of systems, diagnoses anomalous behavior, and predicts the remaining useful performance over the life of the asset [4]. At the end of the 20th century, PHM was officially established with the major U.S. military F-35 Joint Strike Fighter (JSF) project and now becomes the indispensable constituent part in the fields of airplane, ships and warships or vehicle system [5].

II. Function Requirement Analysis of PHM System

With its basic functions of critical fault early warning and intelligent failure diagnosis assistant, USVs prognostics and health management (PHM) system should be able to realize the real-time health-state monitoring and evaluation, mission capability simulation, maintenance strategy optimization, and automatically generation of maintenance resources requirement lists. Thus, the PHM system for USVs is mainly designed to achieve the following purposes:

A. Real-time Health-state Monitoring and Evaluation and Critical Fault Early Warning

The USVs should be able to transmit relevant health-state parameters to the shore base in real time, based on the technique condition data collected by sensors.

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The PHM system should be able to achieve critical fault monitoring and early warning during the mission, based on real-time status data and pre-set rules, through comparison with health status standards of equipment.

The monitoring terminal on shore can visually monitor the health status of the whole vessel and give real-time health-state assessment of the key equipment.

B. Intelligent Failure Diagnosis Assistant

Integrating historical information on law of equipment fault and real-time information on technique condition, the probability of occurrence of critical faults can be calculated and its risk can be assessed by means of intelligent fault tree analysis (FTA) and control chart analysis. The fault diagnosis tree and multi-signal flow graphs are used to intelligently assist the fault diagnosis and provide feasible maintenance plan.

C. Real-time Mission Capability Assessment

On the basis of health-state evaluation, the mission success probability of USVs can be simulated by establishing a correlation model between the USVs equipment system and mission system. So that, the goal of real-time evaluation of USVs mission execution capability can be achieved, thereby assisting the decision-making.

D. Optimization of Preventive Maintenance Strategy

Reliability-centered maintenance (RCM) or risk-based maintenance (RBM) will be intelligently selected to analyze proactive maintenance strategies through simulation calculation models and to periodically optimize preventive maintenance strategies.

E. Automated Generation of Maintenance Resource List

Through the health-state evaluation, simulation of failure and mission capability and optimization of preventive maintenance decisions, the demand for maintenance resources such as device and personnel can be reasonably predicted, and automatically generated a maintenance resources list.

III. FUNCTION FRAMEWORK DESIGN FOR PHM SYSTEM

Integrate the available reliability information of equipment, and based on the operation of equipment, the historical outage data and the real-time perception of technique condition, use the fault tree analysis (FTA) and control chart model to perform early warning management of critical faults. Fault decision tree, multi-signal flow graphs, and other models are used to perform intelligent fault diagnosis. RCM or RBM analysis is carried out to perform active maintenance analysis and periodically optimize preventive maintenance. Failure and mission capability simulation could be performed to generate maintenance resource list and assess the mission capability of USVs. The functional structure of USVs PHM system is as shown in Fig. 1:

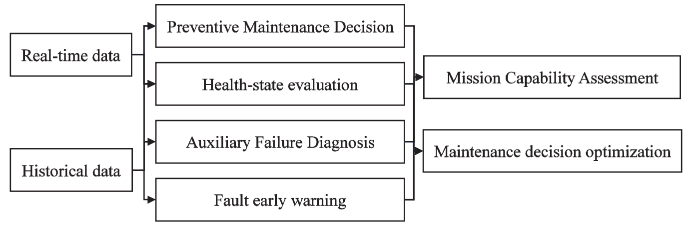

Figure 1. Functional structure of USVs PHM system

IV. KEY METHOD OF IMPLEMENTATION

In order to prevent the critical failure of USVs, several applicable methods are summarized for the characteristics of the equipment, and a monitoring and health management implementation plan is formed. A key electronic equipment that would cause the failure of the control system —— navigation radar is taken as an example.

A. FMECA Analysis of Key Equipment

The FMECA is composed of two separate analyses, the Failure Mode and Effects Analysis (FMEA) identifies different failure modes and their effects on the system while the Criticality Analysis (CA) classifies or prioritizes their level of importance based on failure rate and severity of the effect of failure. It is a technique used for identifying critical failure modes [6], which can help us find critical single point failures and identify the parts most likely to fail.

According to the analysis, the transmitter subsystem is one of key parts in navigation radar system, while klystron is a key element of transmitter. The state of transmitter is directly affected by the performance of transmitter. The tube and collector of klystron have the current tolerance of ±20%. If exceeding it, klystron is abnormal, which affects the power output of transmitter.

B. Analysis on Monitoring Techniques for Health-State of Key Parts

After checking a large amount of data from sensors, suitable technique is selected to monitor technique condition of each part according to its features.

For instance, current varies slightly at the collector and cathode of klystron, but the power output of transmitter fluctuates significantly. It is therefore necessary to select the cathode current that best reflects the state of klystron for monitoring. However, it is unreliable to perform the state monitoring and health management of transmitter accurately using the current measured at the cathode of klystron alone, since slight change of current arising from early fault is often inundated by numerous external interferences. Moreover, the current measured fast at the cathode is distorted rectangular pulse signal, which is not suitable for direct use in state monitoring. Consequently, wavelet technique is taken into account for feature extraction and used to train hidden Markov chain model, so as to achieve transmitter state monitoring indirectly. Current transformer and digital multimeter can be used to monitor the current at the cathode of klystron, while wavelet analysis model for signal feature extraction could be embedded in PHM system.

C. *Health Assessment of Key Parts*

Hidden Markov model is a class of probabilistic graphical model able to capture the dynamic properties of ordered observations [7].

Hidden Markov chain model is employed to calculate the KL distance, which is used to judge the health of key parts. The health assessment model for transmitter is developed in the following steps:

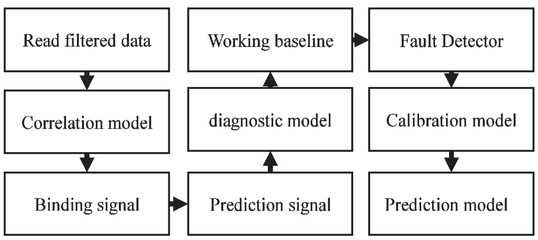

Figure 2. Construction of health assessment model for transmitter

- Import calibration and evaluation data. Verify the correctness of calibration data, and delete corrupted data. Calibration data must be able to correctly reflect the normal operation of the tested system. Calibration data and assessment data should be similar operation data. Calibration data are used to calibrate the model, while assessment data could verify the detection sensitivity of the calibrated model.
- Construct a relevant model, and identify the work phase of the tested system. For different work states, different relevant models can be defined to identify.
- Connect input signal with the relevant mode.
- Configure data filter to eliminate abnormal data.
- Add the prediction model for assessment signal in each phase. Select the input signal suitable for each prediction mode.
- Define the prediction model for each relevant model, and obtain the work baseline of the tested system in a work state.
- Add and place signal fault detector.
- Use calibration data to calibrate the model. Use assessment data to test the model. Adjust the prediction model and fault detector, and set as necessary to optimize performance.
- Assess and test the setting of fault detection carefully, modify the settings of prediction model and fault detector to eliminate false alarms and improve detection sensitivity.

V. Simulation Framework for PHM System Based on Multi-Method Modling

Multi-method modeling refers to the simulation modeling scheme that applies multiple simulation methods to the same model. It can combine the advantages of various modeling techniques, including system dynamics, discrete event modeling and multi-agent modeling, and adopt appropriate modeling methods for elements of different features, which can effectively solve the problems of diverse elements and behaviors in the health management simulation evaluation model. The system dynamics method assumes a high abstraction level, which we use to simulate the degradation of key equipment. Discrete event modeling is mainly used at operational and tactical levels. Multi-agent models are used at all levels, with the agents possibly being any active entity. Multi-method modeling technology can simulate complex systems and is suitable for simulation of PHM systems.

A. *Simulation of Complex System Based on Multi-agent modeling*

Multi-agent modeling technology appears in the development of distributed application systems, mainly used in artificial intelligence and computer fields [8]. Agent has the characteristics of autonomy, interactivity, reactivity, initiative, etc [9][10]. It is a flexible modeling technology. The use of multi-agent technology to simulate the USVs PHM system requires modular modeling ideas, and the tasks, equipment systems, equipment components, faults and other elements in the USVs PHM system are regarded as an agent type. The internal state change mechanism of various elements is made into a highly versatile simulation module. The state diagrams of various simulation modules are as follows:

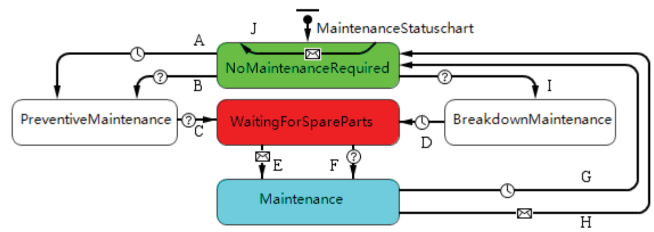

Figure 3. Maintenance status chart of component modules

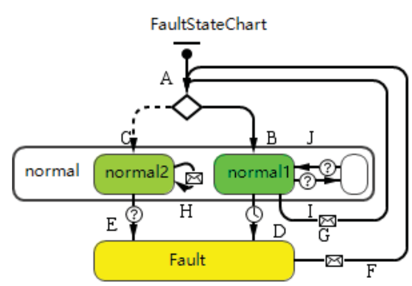

Figure 4. Fault status chart of component modules

According to the USVs equipment system and mission system structure, these simulation modules are used to construct the USVs mission simulation model as shown in the following figure:

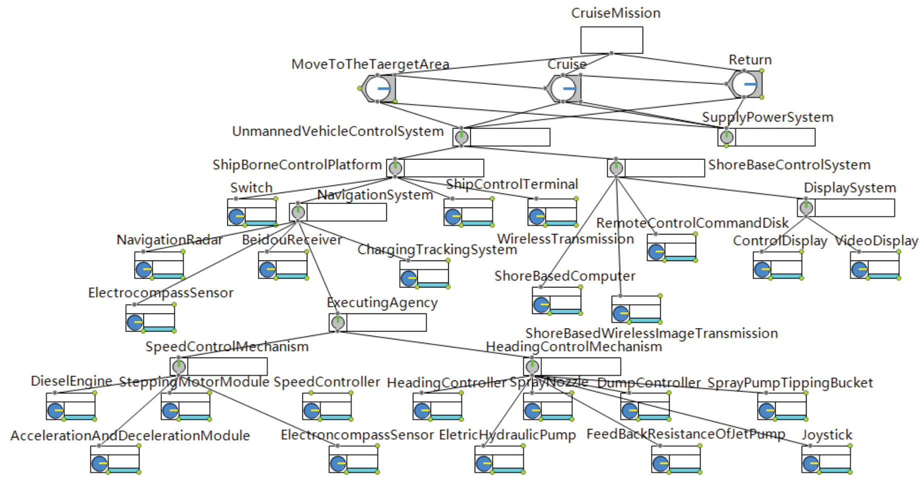

Figure 5. Mission simulation model of unmanned surface vehicle

According to this simulation model, the equipment fault condition, technical state, health state, and task execution state can be fully simulated, and the maintenance and mission strategies can be optimized based on this.

As shown in Figure 5, the control system and supply power system are two important part of the entire USVs PHM system. They are in series relationship which means one of them breaks down will cause the USVs system failure. Using the control system as an example: the fault time interval data can be collected and fitted into an appropriate distribution, and the state diagram technology in the multi-agent modeling is used to simulate the generation of the fault, thereby the reliability of the control system is simulated and its results are integrated into the entire PHM system simulation model.

B. *Simulation of Key Equipment Based on System Dynamics*

System dynamics is a technique that uses a differential equation composed of several state variables and its relationship to describe the relationship between quantities. System dynamics is used to simulate the changes of various physical quantities in the device, and the table function technology is used to correlate physical quantities and failure rates, which is very suitable for the calculation of related quantities in actual engineering. To this end, a related system dynamics model can be constructed to reflect the changing relationship between the physical quantities of the devices. If using the theory of impact degradation, a critical equipment wear quantity model constructed using system dynamics technology.

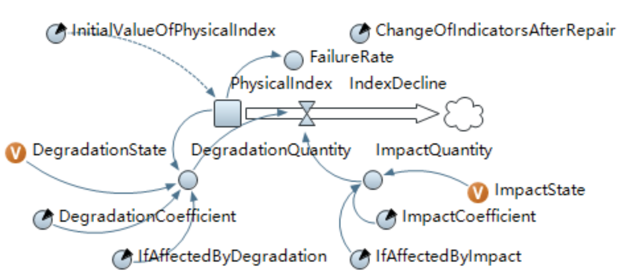

Figure 6. System dynamics model of wear amount of a key equipment based on impact degradation theory

CONCLUSION

After fully considering the adverse environment for USVs in mission execution, functional requirement analysis is first carried out on prognostics and health management (PHM) system to define a general functional framework. By presenting a case study on navigation radar, a monitoring and health management system design for key equipment is given, and how to realize the design is also discussed. After that, multi-method modeling technique is employed to simulate the failure of key component and successful mission of parts, and present the simulation model.

Above all, there is still much room for the application of PHM technique in USVs. Based on functional requirement, this paper presents a preliminary PHM system architecture, which should be further improved in details. Multi-method modeling technique can be effectively used in implementation of PHM system to effectively perform state monitoring and support fault prediction and maintenance decision by building equipment fault simulation model. Moreover, mission simulation model is constructed to assess mission availability. More technical details should be further studied.

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