Design of the Power Supply System and the PHM Architecture for Unmanned Surface Vehicle

Liqiang Zhang, Zhipeng Ji, Xiao Wang, Rui Yang, Lanjun Liu
College of Engineering
Ocean University of China
Qingdao, China
hdliulj@ouc.edu.cn

Jiucai Jin
The First Institute of Oceanography Ministry of Natural Resources
Qingdao, China
jinjiucai@fio.org.cn

***Abstract*—Unmanned Surface Vehicle (USV) has been widely used in the marine environment monitoring. The safety and reliability of the USV, especially the power supply systems, is very important. In this paper, a power supply system with PHM is proposed for USV, Field Programmable Gate Array (FPGA) is used as the main controller. Fault diagnosis, fault location and fault isolation can be implemented by acquiring the voltage and current information of all power equipment. At the same time, the fault prediction and health management of the whole ship is carried out by collecting the temperature, humidity, vibration and other information of every part of the USV. The power supply system and the Prognostics and Health Management (PHM) architecture proposed in this paper can be used for USV maintenance decision in the future.**

Keywords- unmanned surface vehicle; power supply system; PHM; design and implementation

I. INTRODUCTION

Intelligent ocean observation technology attracts more and more attention of researchers, Unmanned Surface Vehicle (USV) has become a research hotspot as a novel platform [1,2]. It can be applied to shipping service, surface rescue, surface environmental observation, scientific research, and provides new approaches for national defense, marine resource development. So the research of USV is significant and important. Due to the complex of the electrical loads in USV, it is particularly important to monitor, manage and protect the power supply system, and the PHM technology is necessary.

PHM is a new technology developed with the change of maintenance concept and the change of maintenance methods. It turns the traditional posterior maintenance into Condition Based Maintenance (CBM). Many model-based fault prediction methods, data-driven methods and statistical reliability-based methods are existing [3,4] and have been widely used in the aeronautics, astronautics and transportation area [5,6]. Many different types of PHM systems, such as the Health and Usage Monitoring System (HUMS), and the Integrated Vehicle Health Management System (IVHMS), Aircraft Condition Monitoring System (ACMS) has been proposed [7]. However, the PHM of the USV power supply system is rarely reported.

This paper proposes a design scheme of the power supply system with PHM architecture for USV. The remain part of this paper is divided into three parts: Section II provides the design of the USV power supply system. Section III gives the whole architecture of the PHM for USV. Finally, some conclusions are drawn in Section IV.

II. DESIGN OF THE POWER SUPPLY SYSTEM

The diesel engine is used as the main power of the USV, and the generator output voltage is 12V. An individually power supply system with the battery pack should be designed to guarantee the stability, the general block diagram is shown in Fig. 1. The existing components of the engine are shown in the virtual frame. The output voltage of the rectifier is 12V, which directly supplies power to the starter battery. This battery is used for starting, and supplies power to those existing facilities such as the console and instrument panel on the USV. The Li-ion battery pack is used for feed all other load with the power supply system, and it can be charged by a DC-DC converter if necessary.

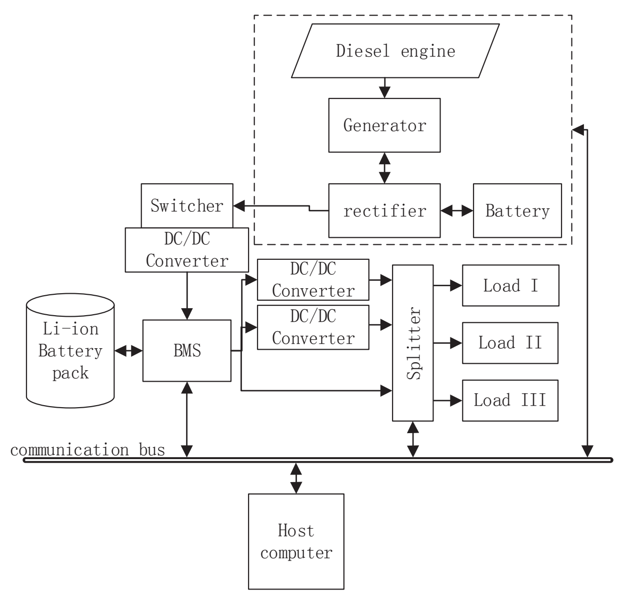

Figure 1. General block diagram of the power supply system

978-1-7281-0860-5/19/$31.00 ©2019 IEEE

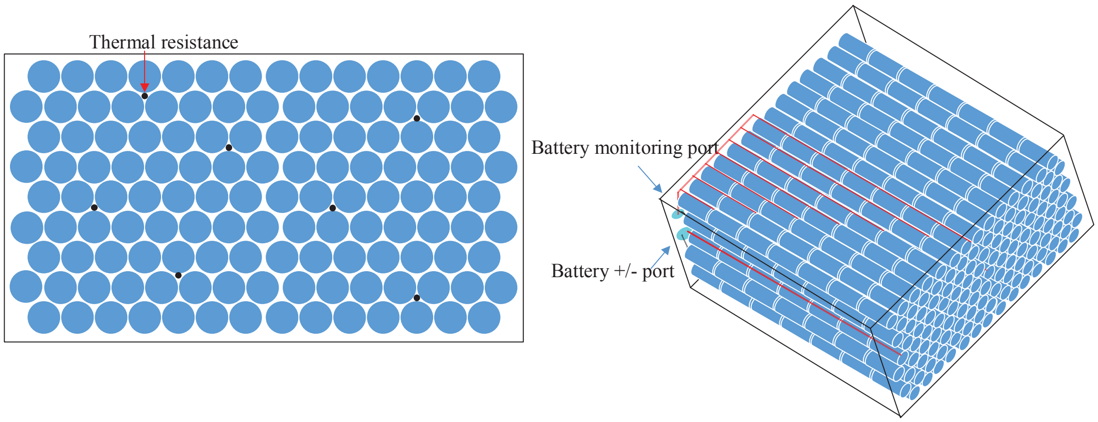

Figure 2. The schematic of the Li-ion battery pack.

The power supply system contains four parts: the Li-ion battery pack, the battery management system (BMS), various DC-DC converters and the splitter. The battery pack is an independent sealed box, and the BMS, DC-DC converters and the splitter share one sealed box.

A. Design of the Li-ion battery pack

The load in the USV includes radar, AIS, radio, and various measuring instruments. Most of them can directly use the DC power in the range of 9V~36V, and a few devices can only use 12V DC. Therefore, The DC bus voltage of the power supply system is determined to 24V, which is composed of 7 series Li-ion batteries (rated voltage 25.9V, working voltage 19.6V~ 29.4V). Some wide-range devices can be directly connected to the DC bus. Meanwhile, regulated 12V and 24V power supply is also designed for other DC loads.

The battery pack is composed of 3000mAh 18650 batteries. The required 10kWh battery packs is composed of 130 batteries (3000mAh 18650 type) in parallel and 7 cells in series, shown in Fig. 2. The phase change material is filled in the battery pack to absorb the heat of the battery. At the same time, seven PT100 thermal resistors are deployed in the battery pack to measure the temperature. And the measuring lines of temperature and the voltage for every single cell are connected to the multi-pin plug. The positive and negative electrode are also taken out by a 2-pin plug. The two plugs are connected to the BMS box.

B. Design of the BMS

The structure diagram of li-ion battery pack and BMS is shown in Fig. 3. The positive and negative electrodes, and the voltage of the single cell is connected to the relays. They are directly connected to the battery protection and balance module when the relays stays. When battery packs self-diagnosis is required, the battery pack is switched to the Electrochemical Impedance Spectroscopy (EIS) tester by relays.

The 12V DC output of the engine rectifier can be converted to charge the battery pack via a unidirectional DC-DC converter. When the battery pack needs to be charged, the FPGA enables the converter , then the battery pack can be charged through the battery protection and balance module. The DC-DC converter works in CC-CV mode, the constant current is 20A and the voltage is 29.4V. The total output power of the DC-DC converter exceeds 500W. The converter will stop working when the input voltage lower than 12V.

The battery protection and balance module can protect the battery pack from overcharging and over discharging. The maximum charging voltage is limited to 29.75V and the discharge protection voltage is 19.6V. And a parallel 60F supercapacitor is used to stabilize the output voltage. It can protect the battery pack at the moment when a high-power load (e.g. the radio) is connected.

The EIS tester is connected to each single cell of the battery pack via relays, and the electrochemical impedance spectroscopy test is performed during the battery pack rest period. The obtained data will be transmitted to the host computer through the FPGA for the PHM analysis of the battery pack.

The voltage and current of the battery protection and balance module output is measured, as the supercapacitor. These data of voltage and current are transmitted to the FPGA for status monitoring and diagnostics of the power system.

The BMS contain an auxiliary power which consisted of a

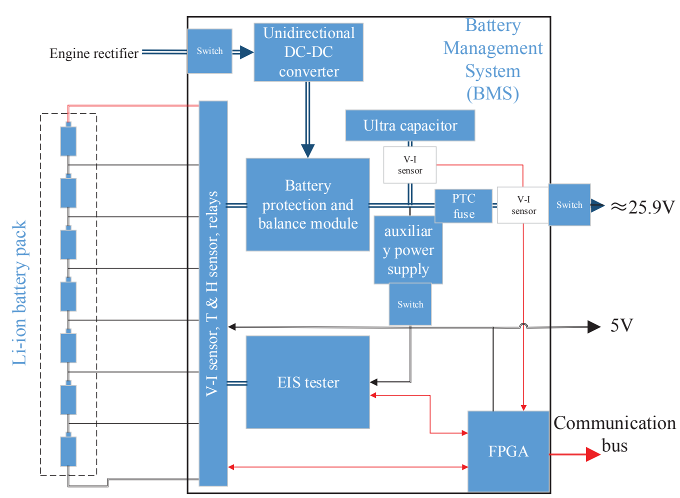

Figure 3. The Block Diagram of BMS

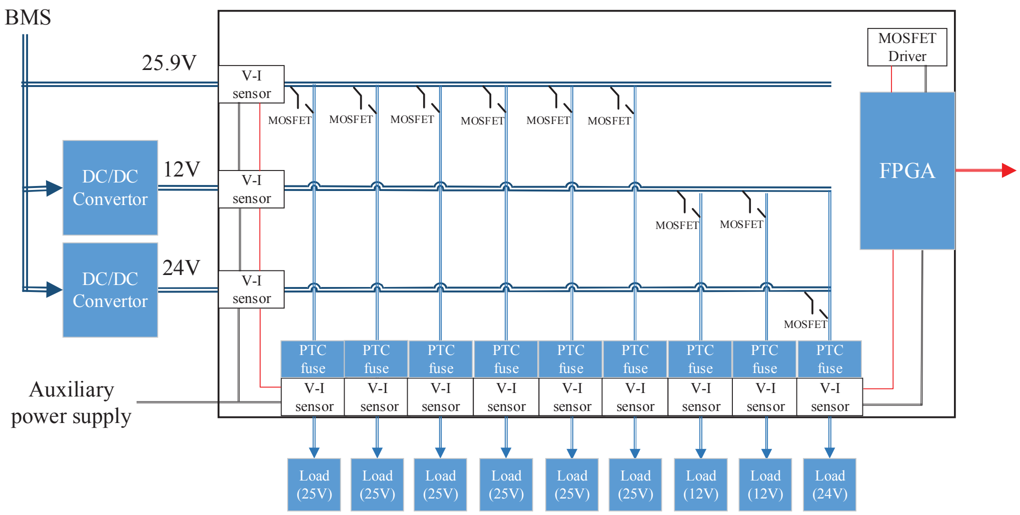

Figure 4. Block diagram of DC-DC converter and the splitter

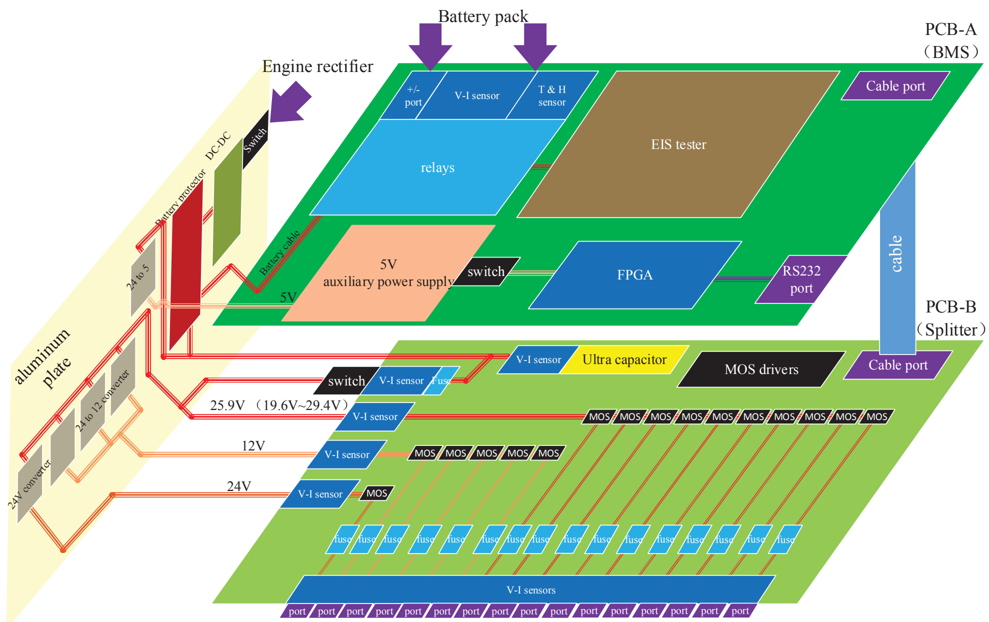

Figure 5. Internal design of the power supply system

small li-ion battery. It is charged by a DC-DC module on the DC bus. The FPGA, various sensors and MOSFETs in the power supply system are powered by the auxiliary power. So the monitoring and diagnostics parts in the power supply system can work independently of the main power supply.

C. Design of the Splitter

The structure of the DC-DC converter and the splitter is shown in Fig. 4. According to the demand of electrical load, it is necessary to design a 12V regulated power in addition to the 25.9V DC bus. It is composed of three 24V to 12V DC-DC converters in parallel. The maximum power of each converter are 360W, and their output is paralleled uses ideal diodes for anti-backflow. And the 24V regulated power supply is designed as the same way.

Various types of electrical load are connected to the three DC busses by low conduction resistance MOSFET, and the voltage and current of the three DC busses are measured separately.

According to the control signal or the fault diagnosis result from the host computer, the MOSFET is controlled by the FPGA to switch the loads. The current and voltage of each electrical load is measured separately. Their working conditions can be obtained, and used for fault diagnosis research.

D. Implementation of the power supply system

The BMS, DC-DC converters, and the splitters are placed in the same sealed box. The internal design is shown in Fig. 5.

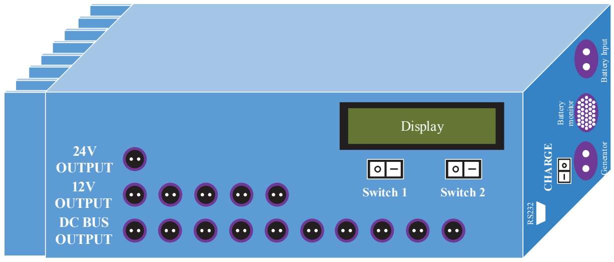

Figure 6. Appearance of the power supply system

The DC-DC converters, battery protection and balance modules are fixed to an aluminum plate with screws and thermal silica. The BMS and the splitter are implemented on the PCB-A board and the PCB-B board, respectively. The voltage, current, and MOSFET control signals on PCB-B are connected to the FPGA via a cable.

The above power supply system is integrated into a metal sealed box, and its appearance is shown in Fig. 6

III. ARCHITECTURE OF THE PHM SYSTEM

The PHM system of the USV can be divided into three parts: The first one is the engine part, the second one is various electronic loads, and the third one is the power supply part based on the battery pack and BMS. It is proposed to use Open System Architecture for Condition Based Maintenance (OSA-CBM) [7] to establish a entire PHM system. Fig. 7 shows the PHM system architecture of USV.

The above three types of PHM are studied in seven levels, respectively: (1) Data Acquisition, (2) Data Manipulation, (3) Condition Monitor, (4) Health Assessment, (5) Fault Prognostics, (6) Decision Support, (7) Human Interface. According to different monitoring objects and their characteristics, research programs at all level are determined. The methods of Condition Monitoring, Decision Support and Human Interface are universal. While, the vibration, temperature and humidity data are collected by various types of sensors in the data acquisition part. The data manipulation will be performed on the FPGA and the data will be transmitted to the host computer. Condition monitor, health assessment, fault prognostics and decision support will be run in software on the host computer.

A. PHM of the cabins

PHM of the cabin includes the monitoring and fault diagnosis of the stern drive engine and the various cabin conditions. For stern drive engine, the engine speed, pressure, temperature, cylinder vibration and remaining fuel should be measured. The data provided with the engine CAN bus should be preferred used. While the temperature and vibration of the engine shell can be measured at the same time. Temperature, humidity and vibration sensors are installed in each cabin. All data will be uploaded to the host computer via an ARM-based acquisition system, which shown in Fig 8.

The wavelet transform is used to detect the singular signal

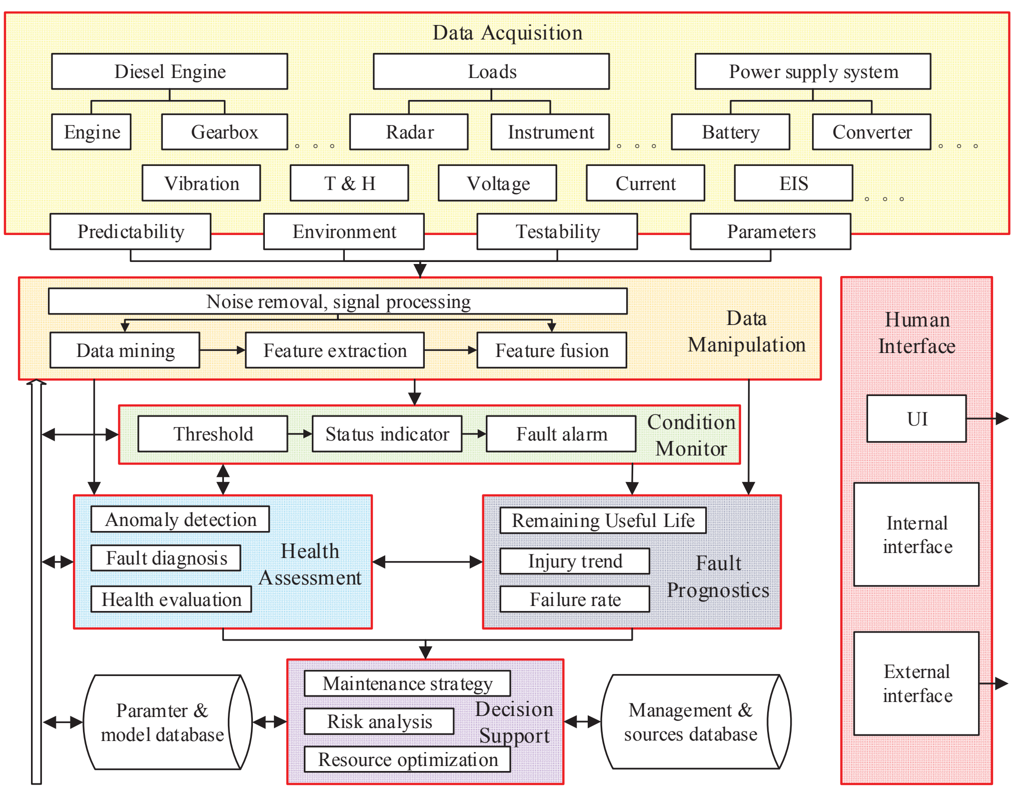

Figure 7. Architecture of the USV PHM system

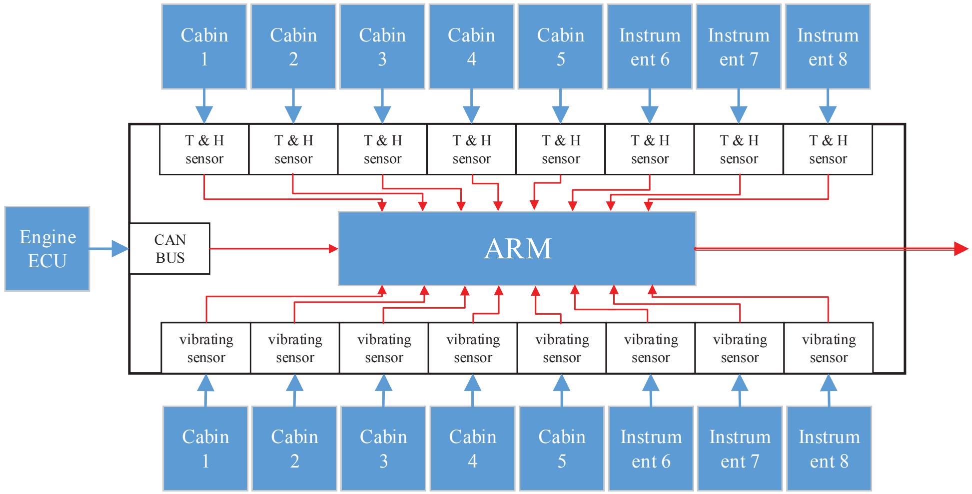

Figure 8. Cabin data acquisition system

in data manipulation layer, the fuzzy C-means clustering method can classify the fault type, and the fault will be diagnosed and located in the condition assessment layer. Meanwhile, abnormal vibration and temperature and humidity changes of each cabin are diagnosed. The cumulative damage is used to quantify with the Miner's rule, then the cumulative damage model can be obtained for diagnosis and prediction of the host fault, vibration abnormality and water leakage accident.

B. *PHM of the loads*

All electrical loads are integrated electronic systems. According to the power supply system designed in the previous section, only the voltage and current of each load and module inside the power supply system can be measured. Statistical analysis is performed on those data to obtain the signal features, and the features can be optimized by the particle swarm optimization, so the feature dimensions will be reduced. The failure of electrical load caused by high temperature, high humidity and salt fog can be diagnosed and located by Bayesian network in the condition assessment layer. The autoregressive moving average (ARMA) is used to establish a time series model of observation data to predict the fault of the loads.

According to the current mission requirements, fault diagnosis and prediction results, the mission risk model will be established. The load power will be cut off in time if faults occurred, so the power supply system and other electrical devices could work safely.

C. *PHM of the power supply system*

The PHM of the power supply system is mainly aimed at the battery pack. The voltage, current, temperature and EIS of the battery pack are measured, and the sample entropy can be extracted. Then the battery pack model can be established. The measured voltage and current can be used in EKF or UKF to estimate the State Of Charge (SOC). Meanwhile, the Failure Mode Effects and Criticality Analysis (FMECA) is used to analyze the influence of parameter anomalies in the system, then the comprehensive evaluation of the health status can be obtained. The sample entropy of the tested data is used as the eigenvalue in the particle filtering algorithm to predict the remaining useful life of the battery pack. The rapid EIS test is performed during the task pause and maintenance period, to assist the estimation of SOC. And the EIS results can be used to indicate the battery degradation status, to predict and locate the faults occurred inside the battery pack. The estimation result of the battery pack health could be finally obtained.

All mentioned methods in the three parts are listed in Table I. The host computer will obtain the PHM results of each subsystem and component according to the above method. And the current health states of the USV will be graphically represented in the monitor, a sketch is shown in Fig. 9.

TABLE I. THE MENTIONED METHODS IN THE USV PHM SYSTEM

	Cabins	**Loads**	**Power supply system**
Data Acquisition	temperature, humidity vibration, engine speed, pressure, remaining fuel	Voltage, current, temperature	Voltage, current, temperature, EIS
Data Manipulation	wavelet transform	statistical analysis, particle swarm optimization	sample entropy
Condition Monitor	SCADA, threshold value comparison, failure detection, outlier alarm		
Health Assessment	fuzzy C-means clustering	Bayesian network	FMECA
Fault Prognostics	cumulative damage	ARMA	particle filtering
Decision Support	expert system, rule-based reasoning, FMADM		
Human Interface	Wired / wireless data transmission, host computer monitoring		

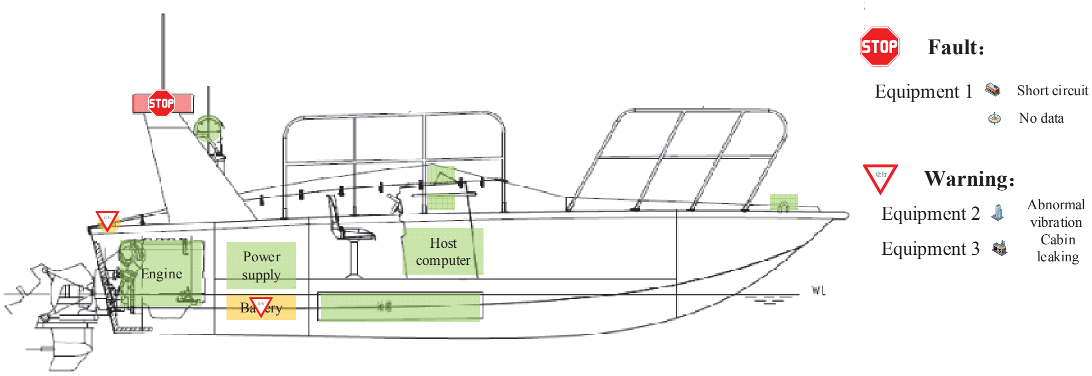

Figure 9. Sketch of the PHM monitor

IV. CONCLUSION

This paper proposes a design of the power supply system with PHM architecture for the USV. The power supply system uses 7 series Li-ion batteries for energy storage. There are three kinds of voltage output: the battery DC bus (19.6V~29.4V), 12V DC and 24V DC. The voltage and current of all loads and converters, as well as the voltage, current, temperature and EIS of the battery pack can be measured by sensors. Meanwhile, a PHM architecture is proposed, based on the monitoring data of the power supply system and the monitoring data of the temperature, humidity, vibration and water inflow information of various parts of the USV. Some key methods in the seven levels from Data Acquisition to Human Interface are discussed. The proposed design could make the USV power supply system more reliably. At the same time, the fault diagnosis and health assessment of all devices can be used for USV maintenance strategy decision.

ACKNOWLEDGMENT

This work was supported by the National Key R&D Program of China (2017YFC1405203). We are also grateful to all anonymous reviewers for providing useful comments and suggestions that resulted in the improved quality of this paper.

REFERENCES

[1] J. Alves, P. Oliveira, R. Oliveira, A. Pascoal, M. Rufino, L. Sebastiao, et al, "Vehicle and mission control of the DELFIM autonomous surface craft," 14th Mediterranean Conference on Control and Automation, pp.1-6, 2006.

[2] R. J. Yan, S. Pang, H. B. Sun, and Y. J. Pang, "Development and missions of unmanned surface vehicle," Journal of Marine Science & Application, vol. 9, pp. 451-457, 2010.

[3] J. Cai, H. Ferdowsi and J. Sarangapani, "Model-based fault detection, estimation, and prediction for a class of linear distributed parameter systems," Automatica, vol. 66, pp. 122-131, 2016.

[4] H. Wang, Y. Cai, G. Fu, M. Wu, and Z. Wei, "Data-driven fault prediction and anomaly measurement for complex systems using support vector probability density estimation," Engineering Applications of Artificial Intelligence, vol. 67, pp. 1-13, 2018.

[5] L. R. Rodrigues, J. P. P. Gomes, F. A. S. Ferri, I. P. Medeiros, R. K. H. Galvao, and C. L. Nascimento Junior, "Use of PHM information and system architecture for optimized aircraft maintenance planning," IEEE Systems Journal, vol. 9, pp. 1197-1207, 2015.

[6] L. Li and G. Xu, "Development status of the fault prediction and the Physical Health Management(PHM) and its application in China railway high-speed," 3rd Asian Conference on the Social Sciences(ACSS 2015), Paris,France, pp. 342-346., 2015.

[7] R. K. Sebastian, S. Perinpinayagam and R. Choudhary, "Health management design considerations for an all electric aircraft," Procedia CIRP, vol. 59, pp. 102-110, 2017.