Health Monitoring Strategies for Multifunctional Vessels with Modular Mission-Oriented Architecture

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Abstract. Intelligent transport systems (ITS) are today one of the main stream for development of high reliable smart transport means. Health and usage monitoring systems (HUMS) is one of the type of ITS for collection of diagnostics data and processing to help ensure dependability and safety of transport means. The maritime industry faces more stringent requirements for the efficient use of ship technologies. Modular construction is one of the effective methods used for this purpose. Periodical operation for different type of modules are typical for modular mission-oriented multifunctional vessels (MMOMV). The active periods of operation during mission for such ships is combined with long pauses in operation. In the case of module's failure during pause of its active operation, there is the probability of mission failure during relatively short mission sessions. The article analyses the dependability of the MMOMV module for different methods of testing with integrated health and usage monitoring system. The diagnostic procedures proposed and the optimal value of the periodicity of monitoring is determined that minimize the unavailability of the mission operation for MMOMV.

Keywords: Modular ships · Diagnostics · Test system · Reliability

1 Introduction

Intelligent transport systems (ITS) are today one of the main stream for development of high reliable smart transport means. Health and usage monitoring systems (HUMS) is one of the type of ITS for the collection of diagnostics data and processing to help ensure dependability and safety of transport means. The maritime industry faces more stringent requirements for the efficient use of ship technologies. In this situation, there is a need to increase the level of automation of all operational processes to improve the dependability, safety and cost-effectiveness of the use of sea vessels by incorporated of multi-functional diagnostic system for condition-based maintenance (CBM) purposes.

The HUMS can be used for both maintenance and mission operation cost efficiency. They cover all types of subsystems from mechanical systems to electrical energy and electronics systems. HUMS can be designed as embedded systems for all subsystems of modern ships.

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Most automation systems used in ships are still developed individually for each type of vessel, which makes them very inflexible. A new system that combines modular architecture with a new smart solution designed specifically for ship operation opens up new possibilities for shipbuilders [1].

Periodical operation for different type of modules are typical for modular mission-oriented multifunctional vessels (MMOMV). The active periods of operation t_{ms} during mission for such ships is combined with quite long periods of non-operation T_{ms} (Fig. 1). In the case of module's failure during periods of non-operation, there is the probability of mission failure when the need for such a mission appears. The article analyzes the dependability of the MMOMV module with integrated HUMS for different diagnostics algorithms. The test strategy is proposed and the optimal value of the periodicity of monitoring operations is determined that minimize the unavailability of the mission operation in the vessels with ITS.

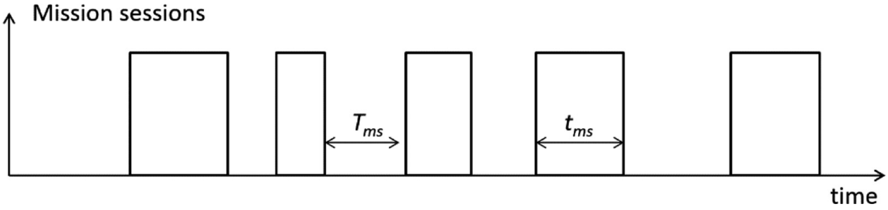

Fig. 1. Operation of mission module during life cycle.

The rest of this paper is organized as follows. In Sect. 2 some important works in the discussed area are reviewed. In Sect. 3 the main definitions and assumptions are introduced. In Sect. 4 a dependability models of MMOMV with HUMS and different test methods are proposed and optimal solution is designed. In Sect. 5 the conclusions are presented.

2 Related Works

The questions concerning ship construction optimization were discussed in [2]. Cost reduction during the design phase of ship lifecycle was discussed in [3–5]. Aspects of sustainability today are an important factor for competitive production of the sea ships and there effective operation. In the project [6] the questions of sustainability for decision support of vessel production are studied. Different approaches have been proposed for optimization of system development planning. In the paper [7] a multi objective optimization model to simultaneously optimize the maturity of the system's selected functions or capabilities and the consumption of development resources are discussed. In the paper an evolutionary algorithm is used to obtain a Pareto set of optimal solutions, where each solution represents a development plan informing which system components should be advanced to which maturity levels without exceeding a certain amount of resource consumption with correlation to typical system development lifecycle. In [8] the problem of optimal design for ship universal platform is discussed and genetic algorithm to find the optimal solutions is used.

Modularity is one of the effective tools to increase vessel operation efficiency in ship building today [1, 9]. Models of design, maintenance and functionality cost efficiency for modular ship architecture are discussed in [10]. Multi-criteria decision support models for various modules of multifunctional special ships are discussed in [11].

The modular architecture of vessels requires a special product testing [10]. In this situation the HUMS is an important tool of product quality assurance and increase cost efficiency for all types of CBM applications. HUMS define the technical condition of construction by diagnostics of various critical parameters and can be used both for increase efficiency of vessel production and operation [12].

There are a lot of HUMS for monitoring of different ship systems: mechanical stressed state of a vessel hull [13], propulsion and ship guidance monitoring systems [14], fluid system [15] and a ship engine shaft average torque, power and rotational speed monitoring system [16]. Different technics are used for collection of diagnostics information [17]. For example in [18] authors describe a wireless shipboard diagnostics subsystem, called Intelligent Components Health Monitor as part of vessel ITS.

The present paper analyzes the dependability of the mission modules for multifunctional vessels with module-oriented construction and with periodical sessions of operation (Fig. 1) for different diagnostics methods of integrated HUMS. The test algorithm is proposed and the optimal value of the periodicity for test operations is determined that minimize the unavailability of the ship missions.

3 The Definitions and Assumptions

The following symbols have been used to develop equations for the models:

λ	Failure Rate
μ	Repair Rate
A	Availability
$MTBF$	Mean Time Between Failures, $MTBF = 1/\lambda$
P_i	Probability of being in state H_i
T_m	Periodicity of test operations with parameter of flow $\omega = 1/T_m$
t_m	Time of test operations
τ	Parameter of exponential distribution of t_m
t_f	Mean time of failure fixation by automatic test system
$v_1 = 1/t_f$	Parameter of exponential distribution of t_f
T_{ms}	Periodicity of demand on active use of module with parameter of Poisson's flow $\varphi = 1/T_{ms}$
t_{ms}	Mean time of mission's session for module
$\psi = 1/t_{ms}$	Parameter of exponential distribution of t_{ms}
t_{ti}	Mean time of test interruption in the case of active use of module
$v_2 = 1/t_{ti}$	Parameter of exponential distribution of t_{ti}

4 Model Formulation and Solution

For modular mission-oriented multifunctional vessels with periodical operation of modules (Fig. 1) there are two possible methods of their dependability monitoring: modules with testing only during ship mission's sessions (monitoring method 1), modules with additional test during the module non-operation time (monitoring method 2). In this session reliability of modules for both of these monitoring methods is analyzed.

4.1 Module with Monitoring Actions During Mission's Sessions

The reliability of the analyzed system can be described by the Markov Chain state transition diagram (Fig. 2), where: H_1 – initial state of the module equipment without failures; H_2 – active use of module without failure; H_3 – failure of the module; H_4 – mission with module under failure; H_5 – detection of the module failure.

We can write the system of Chapman–Kolmogorov's equations which describe the state transition diagram for a Markov's process shown in Fig. 2, as follows:

$$\begin{aligned}
P_1^{'}(t) &= \psi P_2(t) - (\varphi + \lambda)P_1(t) + \mu P_5(t)\\
P_2^{'}(t) &= \varphi P_1(t) - (\psi + \lambda)P_2(t)\\
P_3^{'}(t) &= \lambda P_1(t) - \varphi P_3(t)\\
P_4^{'}(t) &= \lambda P_2(t) + \varphi P_3(t) - \upsilon_1 P_4(t)\\
P_5^{'}(t) &= \upsilon_1 P_4(t) - \mu P_5(t)
\end{aligned}$$

In this equations $P_i(t)$ is the probability of the state $H_i(t), i = \overline{1,5}$.

The normalizing condition is

$$\sum_{i=1}^{5} P_i(t) = 1$$

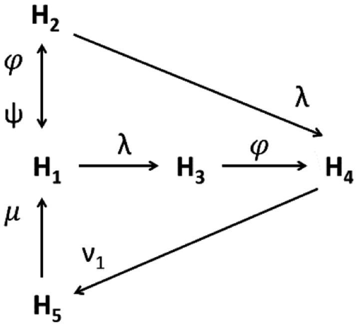

Fig. 2. Markov chain for the monitoring method 1.

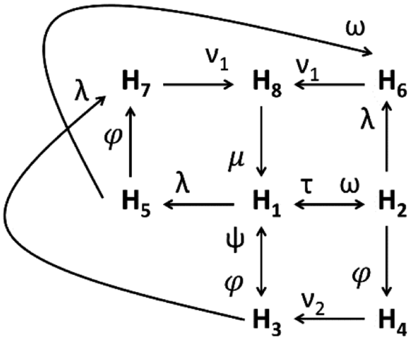

Fig. 3. Markov chain for the monitoring method 2.

The availability $A_1 = P_1 + P_2$ (P_i - stationary probability values of $P_i(t), i = \overline{1, n}$) of the modules with the first monitoring method may be defined by solution of the Kolmogorov's above mentioned system of equations:

$$A_1 = (1 + a_1)/(1 + a_1 + a_2), \tag{1}$$

Where $a_1 = \lambda\left[\gamma(1 + \beta) + \frac{1}{\varphi}\right], a_2 = \frac{\varphi}{\lambda + \psi}, \gamma = \frac{1}{\mu} + \frac{1}{\upsilon_1}$.

Comparing the equation for A_1 with the equation for the A_0 availability of the system with ideal failure detection and ideal switch [19], it is possible to get conclusion that $A_1 = A_0$ with increase of the intensity of communication φ and the reduction of the failure detection time $v_1 \to \infty$.

4.2 Modules with Monitoring Actions During Active Operation and Periodical Test Actions During Non-operational Time

In this case the reliability of module could be described by the following Markov chain diagram (Fig. 3), where: H_1 – initial state of the module equipment without failures; H_2 – monitoring of reliability in the non-operation module; H_3 – mission's session; H_4 – demand on mission during monitoring process; H_5 – failure of module during non-operation; H_6 – monitoring of module with failure; H_7 – demand on mission in the module with failure; H_8 – fixation of failure by HUMS.

The system of Chapman–Kolmogorov's equations can be writing on the base of the Markov chain state transition diagram shown in Fig. 3:

$$\begin{aligned}
&P_1'(t) = \tau P_2(t) - (\varphi + \lambda + \omega)P_1(t) + \psi P_3(t) + \mu P_8(t)\\
&P_2'(t) = \omega P_1(t) - (\varphi + \tau + \lambda)P_2(t)\\
&P_3'(t) = \varphi P_1(t) - (\lambda + \psi)P_2(t) + \upsilon_2 P_4(t)\\
&P_4'(t) = \varphi P_2(t) - \upsilon_2 P_4(t)\\
&P_5'(t) = \lambda P_1(t) - (\omega + \varphi)P_5(t)\\
&P_6'(t) = \lambda P_2(t) + \omega P_5(t) - \upsilon_1 P_6(t)\\
&P_7'(t) = \lambda P_3(t) + \varphi P_5(t) - \upsilon_1 P_7(t)\\
&P_8'(t) = \upsilon_1 P_6(t) + \upsilon_1 P_7(t) - \mu P_8(t)
\end{aligned}$$

The normalizing condition is

$$\sum_{i=1}^{8} P_i(t) = 1$$

The availability $A_2 = P_1 + P_2 + P_3$ of the module with the second monitoring method may be defined by solution of the Chapman–Kolmogorov's above mentioned system of equations:

$$A_2 = (1 + a_2)/(1 + a_1 + a_2) \tag{2}$$

where

$a_1 = \omega/(\lambda + \varphi + \tau)[\lambda(1/\mu + 1/\nu_1) + \varphi/\nu_2 + \lambda\varphi\ (1/\mu + 1/\nu_1)/(\lambda + \psi)] +$
$+ \lambda/(\omega+\varphi)[1 + \omega(1/\mu + 1/\nu_1) + \varphi(1/\mu + 1/\nu_1)] + \varphi\ (1 + \lambda/\nu_1)/(\lambda + \psi),$
$a_2 = (\lambda + \psi)^{-1}[\omega(\lambda + \varphi + \psi)/(\lambda + \varphi + \tau) + \varphi].$

The analysis of (2) shows that function $A_2(\omega)$ has extremum in the ω_{opt} point.

The expression for optimal periodicity of monitoring $T_{m\ opt} = 1/\omega_{opt}$ can be found from the condition $dA_2/d\omega = 0$. In general case the expression for the $T_{m\ opt}$ is quite complex. For the practical important case of the highly reliable systems ($\lambda \ll \mu$) with the short time of the failure fixation ($\mu \ll v_1,\ \mu \ll v_2$) the following approximate expression is justified for the definition of the optimal periodicity of monitoring sessions:

$$T_{mopt}^{-1} = \upsilon_2 \frac{\left[\lambda + \sqrt{\left(\lambda - \frac{\varphi^2}{\upsilon_2}\right)^2 + \frac{\lambda\varphi\tau}{\upsilon_2}}\right]}{\varphi} - \varphi$$

4.3 Numerical Example

Let's evaluate the mission availability of modular mission-oriented multifunctional vessel with operations in the random moments of time. The failures of the MMOMV modules could be fixed by the HUMS executing the periodical test. As example of such MMOMV we can use Small Waterplane Area Twin Hull (Fig. 4) with modules (Fig. 5): A - gun module, B - oil pollutions recovery module, C - diver chamber module [8, 11].

The typical reliability parameters of modules are shown in the Table 1 [8, 11].

Fig. 4. Small Waterplane Area Twin Hull with mission's module [8].

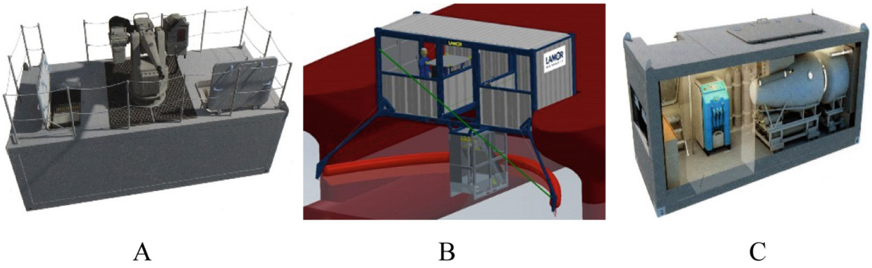

Fig. 5. Functional modules [8, 11].

Let us analyze of dependability decreasing in the real module in comparison with the ideal one with dependability degradation factor

Table 1. The reliability parameters of modules for the numerical example.

Modules	A	B	C
$\lambda 10^{-4}$, 1/h	13	26	38
$\mu 10^{-3}$, 1/h	10	6	6

$$V = (1 - A_i)/(1 - A_0), \qquad i = 1, 2$$

where A_0 is availability of the ideal system determined in [19].

At the Fig. 6 the dependability degradation factor

$$V = \frac{1 - A_1}{1 - A_0}$$

shown for the first monitoring method as function of average time between missions T_{ms}, where the value of A_1 is defined by the expression (1).

At the Fig. 7 the reliability degradation factor

$$V = \frac{1 - A_2}{1 - A_0}$$

shown for the second monitoring method as function of periodicity of monitoring operations T_m for various modules and typical average dependability parameters. The value of A_2 is determined in accordance with the expression (2).

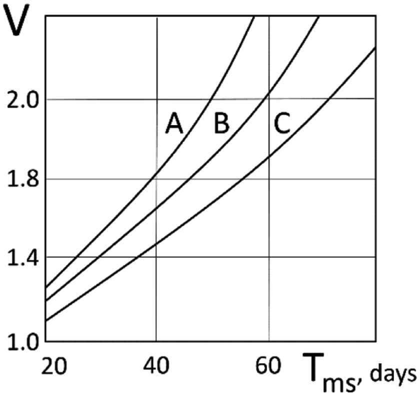

Fig. 6. The dependability degradation factor in the module with monitoring method 1.

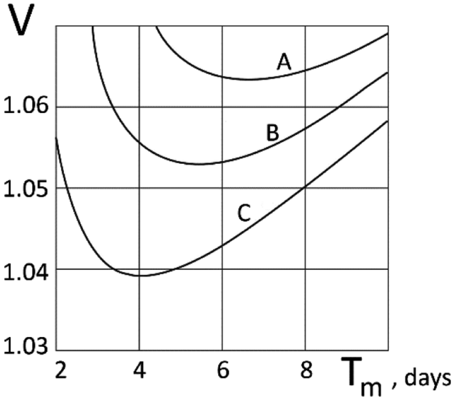

Fig. 7. The dependability degradation factor in the module with monitoring method 2.

5 Conclusions

Modularity is one of the effective tools to increase vessel operation efficiency in ship building. The modular architecture of vessels requires special monitoring procedures that can be provided with HUMS. Periodical sessions of operation for different type of mission modules are typical for modular mission oriented multifunctional vessels. The active periods of operation during mission for such ships interspersed with long periods of non-operation. The reliability of the MMOMV modules depends on different methods of monitoring its performance with integrated HUMS.

Comparison of two monitoring methods for analyse of modules reliability shows that modules with diagnosis during operation sessions and their periodical monitoring during non-operation of ship modules are about twice more reliable than modules with diagnosis only during mission sessions.

The availability of the modules with diagnosis during operation is unimodal function of monitoring period. The optimal periodicity of monitoring will increase with the increase of the duration of diagnostics, with the increase time of monitoring interruption and with the increase of MTBF. The optimal periodicity of monitoring will be reduced with the increase of the intensity of missions and is staying practically invariant to the duration of the mission sessions.

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