OPTIMAL SENSOR NETWORKS SYSTEM RELIABILITY ALLOCATION USING IMPROVED AGREE METHOD

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ABSTRACT

Reliability of sensor networks system plays an important role in monitoring the operational health conditions of any critical engineering system. In this paper, a methodology is proposed to improve an initial optimal allocation of sensor system by considering fault acceptance degree (FAD), fault influence degree (FID), importance factor (α), and the actual operational data of the critical system with initial allocated sensors for a small initial period. The paper has also proposed a method for estimation of expected life of the sensor network based on the above factors. A hypothetical case of the sensor system of an electric motor is presented to illustrate the proposed approach.

KEYWORDS: sensor reliability; fault acceptance degree (FAD); fault influence degree (FID); importance factor; optimal allocation.

1 INTRODUCTION

Reliability of sensor used for monitoring various parameters of critical systems is very important for timely assessment of their health and to take appropriate measures for fault diagnosis at incipient stages in order to prevent any catastrophic failures. This paper focuses on modelling of reliability of sensor under multiple load conditions and optimization of sensor networks system reliability. This type of modelling can be useful in applications such as: propulsion systems of a satellite, nuclear power plants, and aircraft systems etc. Such systems require continuous reliable monitoring system to avoid unexpected failures which might result in huge economic loses apart from ill effects on environment, health & safety of human beings and other species. Instead of spending huge amounts on replacement/repair of industrial systems due to unreliable sensors it may be better to have a highly reliable sensor networks system with adequate redundancies. An attempt is made in this paper to optimally allocate sensor networks system reliabilities and update the same by utilizing additional information on factors such as fault acceptance degree (FAD), fault influence degree (FID), importance factor, and the actual operational data of the critical systems. A method is also proposed for estimation of expected life of the sensor networks. This can be useful for taking proactive maintenance and replacement measures for achieving high sensor reliability over long operational period of the critical systems.

The rest of the paper is organized as follows:

In Section-2, the objectives of this paper are presented. In Section-3, proposed methodology to improve an initial optimal allocation of sensor networks system by considering a fault acceptance degree (FAD), fault influence degree (FID), and importance factor of the critical systems is presented. Mathematical models for the expected mean life & reliability of sensor system are presented in section 4. Redesign modelling approach for sensor networks system is presented in section 5. In section 6, an illustrative example for the proposed methodology is presented. Discussions on the results obtained in section 6 are presented in section 7. Conclusions are presented in section 8 followed by selected references in section 9.

2 OBJECTIVE

Swajeeth et al. [1] developed a model for evaluation of sensor reliability under multiple load conditions. An algorithm is also proposed for optimal allocation of number of sensors of different types such as current, temperature, and vibration sensors for achieving specified sensor networks system reliability with minimum cost. See [6, 7, and 10] for reliability optimization algorithms. Reliability of these sensors used for monitoring various parameters of critical systems is very important for timely assessment of their health and to take appropriate measures for fault diagnosis at incipient stages in order to prevent any catastrophic failures. The reliability of a sensor network decreases as time of operation progress continuously. Therefore, the actual reliability of sensor network after 'T' hours may be low/ very low compared to the designed system target reliability.

The objective of the present paper is to effectively remodel the sensor network configuration [1] to provide improved reliability at 'T' hours compared to initial allocation. This paper also deals in meeting the objectives of decision making in ambiguity situations arising from sensor networks used in [1], to improve the expected mean life of each sensor network. To fulfil the above mentioned objectives, it is essential to evaluate the following three critical values of sensor networks of a system.

a) Importance factor (α) of each sensor network in contributing to damage of operational system.
b) Expected mean life ('θ' in hours) of each sensor network.
c) Reliability of each sensor network ($R_i(T)$) after 'T' hours of operation.

Following methodology is used to evaluate the critical factors.

3 METHODOLOGY

Sensors are electronic elements. So, the failure distributions of sensors follow exponential distribution [4], [5], [9]. Refer [1, 8] for distribution used in sensor modelling. The sensor networks system presented in [1] used for operational health monitoring of an electric motor is as shown in fig.1. It is clear that the three sensors are in series configuration. The mathematical models suggested by Wang et al. [2] are used for evaluating the critical values mentioned in section 2 to fulfil the objectives. Suitably, Improved AGREE method [2] (including new parameter-FAD) is used in this work to meet the objectives mentioned in section 2.

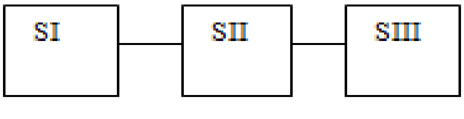

Fig.1. Functional wise series configuration of three sensors for motor monitoring

SI: current sensor
SII: Temperature sensor
SIII: Vibration sensor

4 EVALUATION OF CRITICAL VALUES OF A SENSOR NETWORK

4.1 Defining sensor network failure

A sensor network is considered as failed if it gives false alarms about the operational health condition of the main system.

4.2 Improved AGREE method for sensor network

AGREE (Advisory Group on Reliability of Electronic Equipment) method [2], allocates reliability to the components and possibly subcomponents in a manner that will support the system reliability goals defined. This method assumes that the components are in series, independent, and have constant failure rates.

4.3 Introduction to parameters:

4.3.1 Fault acceptance degree (FAD)

We define a term known as fault acceptance degree which is the degree of acceptance of faults in a sensor network based on severity of damages caused to the operational system. It is denoted by $\beta_{i\,(j)}$. The fault acceptance degree lies between 0 and 1. Generally, when a sensor network failure causes catastrophic, critical, marginal, and negligible damages to the operational system we assign acceptance degrees of 0.1, 0.5, 0.8, and 1 respectively. FAD is discussed in detail with an illustrative example in section 4.

4.3.2 Fault influence degree (FID)

Fault influence degree [2] is a probability that the failure of a sensor network will lead to the operational system failure. It is often marked by $\omega_{i\,(j)}$, which denotes the probability that the fault of sensor network ‘i’ (number of failure is ‘j’) will lead the system to fail. Sensors are very crucial in critical systems like rocket propulsion systems, aircrafts, nuclear power plants etc. So, we consider fault influence degree as unity in all sensor applications.

4.4 Calculation of Importance factor (α)

The Fault acceptance degree of sensor network ‘i’ can be expressed by row vector (β_{i1}, β_{i2},…..β_{in}), while the fault influence degree can be expressed by columns vector (ω_{i1}, ω_{i2},…. ω_{in}), Then the importance factor of a sensor network ‘i’ can be denoted as follows:

$$\alpha_i = \frac{1}{n}[\beta_{i1}, \beta_{i2}, \ldots, \beta_{in}]\, [\omega_{i1}, \omega_{i2}, \ldots \omega_{in}]^T \qquad (1)$$

Sensor network with high importance factor should be given first priority in decision making during ambiguity situations.

4.5 Calculation of mean life of sensor network

Notations

N : Total number of sensors in a system

n_i : Number of sensors in a network 'i' of a system
R_s : Sensor networks system reliability
T_i : Time (in Hours) for which a sensor network 'i' is operated continuously.
R_i : Reliability of a sensor network 'i'

The expected mean life of a sensor network 'i' can be expressed as [2]:

$$\theta_i^* = \frac{N\, \alpha_i\, T_i}{-n_i\, \ln(R_S(T))} \tag{2}$$

Note: For static reliability $R_S(T) = R_S$. As if all the sensor networks are operated continuously for 'T' hours, then $T_i = T$.

4.6 Calculation of a sensor network reliability at 'T' hours

Reliability of each sensor network follows exponential distribution while operating for 'T' hours continuously. The reliability at 'T' hours can be expressed as [3], [4]:

$$R_i(T) = e^{\frac{-T}{\theta_i^*}} \tag{3}$$

The reliability logic diagram (RLD) of a sensor networks used in monitoring operational health of an electric motor [1] is as shown in fig.2.

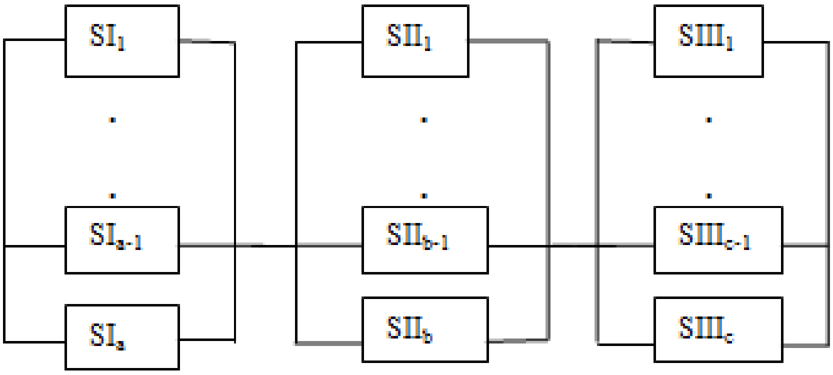

Fig.2. RLD of sensor networks monitoring operational health of an electric motor

a, b, & c are allocations for current, temperature, and vibration sensor networks.
For the sensor networks system shown in fig.2, the reliability is expressed as follows:

$$R_S(T) = e^{\frac{-T}{\sum_{i=1}^{3} \theta_i^*}} \tag{4}$$

The assessment of motor's operating health condition [1] is done based on the feedback from all three types of sensor networks shown in fig.2. From equation (4), it is clear that the reliability of senor networks system shown in fig.2, decreases exponentially with time of operation. Therefore, at time 'T' which is less than actual mission time, the reliability of system may be low/very low compared to designed target reliability. Many times this may leads to ambiguity in sensor network's feedback. All possible cases of ambiguities are shown in table I.

Table 1. Possible ambiguity cases in sensor networks under consideration

SI Network	SII Network	SIII Network
H	H	U
H	U	H
.	.	.
.	.	.
U	U	H

H: sensor network showing motor is in healthy condition.
U: sensor network showing motor is in unhealthy condition.

Suppose, consider the first row of table I i.e., H, H, and U. Here, current and temperature sensor networks are showing motor is in healthy condition. However, vibration sensor network is showing motor operating in unhealthy condition. In this situation, the user monitoring the sensor networks cannot make a proper decision. Therefore, in this ambiguous case, the decision from a sensor network with highest importance factor should be considered by the user for confident decision making.

In the following section, a redesign modelling approach steps which improves the reliability of sensor networks system at 'T' hours compared to initial allocation are presented.

5 REDESIGN MODELLING APPROACH FOR SENSOR NETWORKS

Steps

i. Obtain initial design configuration for sensor network to meet given target reliability with minimum cost using the procedure followed in [1].
ii. Evaluate importance factor and expected mean life of each sensor network shown in fig.2. using Eqs. (1) & (2) respectively.
iii. Evaluate reliability of each sensor network and the total sensor networks system reliability using Eqs. (3) & (4) respectively.
iv. Based on current sensor's network reliability value obtained, evaluate each current sensor's reliability present in the network.
v. Repeat step iv for temperature and vibration sensor networks.
vi. Put the new reliability values of current, temperature, and vibration sensors in the algorithm [1] with the same initial costs and obtain the new allocation to achieve the initially assigned sensor networks system target reliability.
vii. Update the number of redundancies for each type of sensor based on step vi.

6 ILLUSTRATIVE EXAMPLE

The proposed redesign modelling approach has been illustrated by considering an electric motor which is used as a prime mover of a centrifugal pump. As discussed earlier three types of sensors (current, temperature, and vibration) are used for monitoring the parameters of this motor. The data required for this illustration are presented in the tables 2, 3, & 4. The desired target reliability of sensor network system is 0.9892. It is proposed that the system (motor & sensor networks) be observed for 12 hours continuous operation and the information thus collected be used for further improved reliability design. Develop solutions to fulfil the following objectives:

a) Evaluate the expected mean life of each sensor network using the data collected on FAD, FID, & importance factors during 12 hours of operation.
b) Reliabilities of each sensor network at 12 hours.
c) Develop a new allocation that improves the reliabilities of each sensor network at 12 hours than the reliabilities obtained in (b).
d) Evaluate expected mean life and reliability of each new allocated sensor network and compare the same with the values obtained for (a) & (b).

The data required for this illustrative example are given in [1].

Table 2. Reliabilities & costs of sensors

Sensor type	**Reliability**	**Cost ($)**
Current	0.84393	15
Temperature	0.94690	22
Vibration	0.63580	30

Table 3. Threshold levels at normal load condition

S. No	**Sensor type**	**Threshold**		**Units**
		LL	***UL***	
1	Current	3	6	amps
2	Temperature	30	90	^{0}C
3	Vibration	2	5	g

Table 4. Threshold levels at full load condition

S. No	**Sensor type**	**Threshold**		**Units**
		LL	***UL***	
1	Current	6	9	amps
2	Temperature	90	150	^{0}C
3	Vibration	5	8	g

UL: upper limit; *LL*: Lower limit

Solution: - (a) The FAD for the system is defined as follows:

0.1: for any one or more of the following situations:

- Motor current consumption > 9 amperes but current sensor network readings are showing 3 to 6 amperes.
- Motor temperature >150^{0}C, but temperature sensor network readings are showing 30 to 90^{0}C.
- Motor vibration > 8 g, but vibration sensor network readings are showing 2 to 5 g.

Due to above reasons, significant system failure occurs that can result in injury, or major damage

0.5: Motor operating in full load region, but all sensor networks' readings are showing motor is in healthy region. Due to this reason, complete loss of system (motor) may occur; performance is unacceptable.

0.8: for any one or more of the following situations:

- Motor current consumption is 3 to 6 amperes, but current sensor network readings are showing > 9 amperes.
- Motor temperature is 30 to 90^0 C, but temperature sensor network readings are showing $>150^0$ C.
- Motor vibration is 2 to 5 g, but vibration sensor network readings are showing > 8 g.

Due to these reasons, user turns off the motor which causes no output from centrifugal pump. This leads to partial economical losses and impede progress of work.

1: Motor operating in healthy region, but all sensor network's readings are showing motor is in full load region. Due to this reason, minor economical losses occur, with no effect on acceptable system performance.

As discussed in section 4, FID for the system under consideration is defined as unity.
The following tables show the values defined for FAD & FID for the system under consideration operating for 12 hours. Readings are observed for every 3 hours of interval.

Table 5. FDD & FID for sensor networks operated for 12 hours

	Fault acceptance degree				Fault influence degree			
Sensor type	**3 hr**	**6 hr**	**9 hr**	**12 hr**	**3 hr**	**6 hr**	**9 hr**	**12 hr**
SI	0.1	0.1	0.1	0.1	1	1	1	1
SII	NF	0.8	0.5	0.1	NF	1	1	1
SIII	NF	NF	0.8	0.8	NF	NF	1	1

NF: No fault

According to the Wang et al. [2], the importance factor (α) for each sensor network is evaluated as follows:

$$\alpha_{\text{SI}} = \frac{1}{4}[0.1, 0.1, 0.1, 0.1][1, 1, 1, 1]^T = 0.100$$

$$\alpha_{\text{SII}} = \frac{1}{3}[0.1, 0.8, 0.5][1, 1, 1]^T = 0.466$$

$$\alpha_{\text{SIII}} = \frac{1}{2}[0.8, 0.8][1, 1]^T = 0.800$$

Table 6. Initially allocation of importance factor & rankings

Sensor network type	(α)	Ranking
SI	0.100	3
SII	0.466	2
SIII	0.800	1

Then, using Eq. (2), we get the expected mean life of current sensor network as follows:

$$\theta^*_{\text{SI}} = \frac{12 \times 0.1 \times 12}{-4 \times \ln(0.989)} = 325.47 \text{ hours}$$

Similarly, for temperature and vibration sensor networks we get 2022.24, 2083.00 hours respectively.
The expected lives of sensor networks are tabulated in table 7.

Table 7. Expected mean life of each sensor network

Sensor network type	θ (in Hours)
Current	325.47
Temperature	2022.24
Vibration	2083.00

(b) Using Eq. (3), we get the reliabilities of each sensor network at 12 hours of operation. The reliabilities along with the initial allocation of each sensor network are presented in table 8.

Table 8. Reliability of each sensor network

Sensor network Type	Initial allocation	Initial network reliability	Network reliability at 12 hours
Current	4	0.99940	0.9638015
Temperature	3	0.99984	0.9940835
Vibration	5	0.99359	0.9900210

(c) Following the steps discussed in section 3, we get the following new allocation to each sensor network for achieving the target reliability of ≥ 0.9892.

New allocation: 7, 6, 8
New Cost: 477$

(d) The FAD & FID for new allocation of each sensor network are defined in table 9.

Table 9. FDD & FID for new allocated sensor networks for 12 hours

	Fault acceptance degree				Fault influence degree			
Sensor type	3 hr	6 hr	9 hr	12 hr	3 hr	6 hr	9 hr	12 hr
SI	NF	0.8	0.5	0.5	NF	1	1	1
SII	NF	NF	0.8	0.8	NF	NF	1	1
SIII	NF	1	1	1	NF	1	1	1

NF: No fault

For the data (given in table 9), the improved importance factor and expected mean life of each sensor network for new allocation are tabulated in table 10.

Table 10. Importance factors & expected mean life of sensor network

Sensor network Type	(α)	θ (in Hours)
Current	0.6	1952.81
Temperature	0.8	3037.71
Vibration	1	2847.85

Reliability of each sensor network (for new allocation) at 12 hours is as shown in table 11.

Table 11. Reliability of sensor network at 12 hours

Sensor network Type	**New allocation**	**Initial network reliability**	**Network reliability at 12 hours**
Current	7	0.997103	0.993873
Temperature	6	0.999994	0.996057
Vibration	8	0.998421	0.995795

Therefore, new allocation of sensor networks provides the improved reliabilities at 12 hours compared to initial allocation of sensor networks. The mean life of current, temperature and vibration sensor networks is also increased considerably.

7 DISCUSSION

If ambiguity cases like the one mentioned in table 1 arises, we give first priority to SIII network for confident decision making based on rankings mentioned in table 6. It is proposed to replace the sensor networks periodically at times given in table 7 for initial allocation. The improved expected life of each sensor network is also presented in table 9. This procedure can be repeated for further improvement of sensor configuration.

8 CONCLUSIONS

A methodology is proposed in this paper to improve the initial optimally allocated sensor networks reliabilities for critical systems. Additional information such as fault acceptance degree (FAD), fault influence degree (FID), importance factor, and the actual operational data of the critical system for an initial operational period are used for this purpose. The methodology proposed for estimation of expected life of sensor networks, can be effectively utilized for planning preventive replacements of sensor networks used for critical systems such as: propulsion systems of a satellite, nuclear power plants, aircraft systems, and turbines of thermal power plants etc.

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