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Reliability analysis of complex robotic system using Petri nets and fuzzy lambda-tau methodology

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Abstract

Purpose – The purpose of this paper is to evaluate various reliability parameters of a multi-robot system, arranged in a complex configuration. The effects of failures and course of action on the system performance have also been investigated.

Design/methodology/approach – The present work is based on a multi-robotic system, in which two robots are working independently with a conveyer unit. Petri net (PN) tool is applied to represent the asynchronous and concurrent processing of the system. To enhance the relevance of the reliability study, fuzzy numbers are developed from available data of the components, using fuzzy possibility theory to define membership functions. The use of fuzzy arithmetic in the PN model increases the flexibility for application to various systems and conditions. Various reliability parameters (such as mean time between failures, ENOF, reliability, availability, etc.) are computed using fuzzy lambda-tau methodology. As the available data are imprecise, incomplete, vague and conflicting, the fuzzy methodology can deal easily with approximations.

Findings – The adopted methodology in the present work improves the shortcomings/drawbacks of the existing probabilistic approaches and gives a better understanding of the system behavior through its graphical representation.

Originality/value – In an earlier study failure behavior of a single robot was analyzed. This paper is an extension of the previous work, in which failure behavior of multi-robotic system is analyzed. Also, the interactions among the working units of multi-robotic system are deeply studied. The paper contains a new idea about the reliability analysis of robotic system. Fuzzy lambda-tau methodology, a fuzzy PROBIST technique, is used for the proposed robotic system and the results obtained are compared with crisp results. Reliability analysis of a multi-robotic system is presented in this paper, which may help the system analysts to analyze and predict the system behavior and to reallocate the required resources.

Keywords Reliability management, Robotics, Failure modes and effects analysis, Systems analysis

Paper type Research paper

1. Introduction

During recent decades, a wide use of robotic systems has increased the importance of robot reliability and quality. The problem becomes more important for robots which are used in hazardous environments. Reliability is an important factor for industrial and medical robots. The subject of robot reliability is very complex and there are numerous interlocking variables in evaluating and accomplishing various reliability levels. A successful robot installation has to be safe and reliable. A robot with poor reliability leads to many problems such as high maintenance cost, unsafe conditions and inconvenience.

The reliability of a robotic system can be maintained at a higher level using the structural design of the system or components of higher reliability, or both of them may be performed simultaneously (Henley and Kumampto, 1985). If, components of higher

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reliability are used, the associated cost of components also increases. This is an important issue to be considered for industrial application purpose. Thus, decision-makers have to consider both the profit and the quality requirements. Reliability and performance of robotic systems may be improved if failure analysis techniques are used during the design process. An industrial robotic system consists of numerous components, and the probability that the system survives depends directly on each of its constituent components. For analyzing the performance of a complex robotic system, it is required to develop a suitable methodology so that timely repair or replacement actions may be initiated for achieving the goal of high production. Despite the existence of a vast amount of literature on robotic research, not much work has been done on robot system reliability.

Dhillon and Yang (1996) used the established techniques and performed a safety, reliability and availability analysis of robotic systems. Carreras *et al.* (1999), Carreras and Walker (2000) used interval method to chalk out the reliability analysis of a robot. Different strategies were evaluated in order to gain a more complete understanding of the potential benefits of the approach. Khodabandehloo (1996) presented the use of systematic techniques such as fault tree analysis (FTA) and event tree analysis to examine the safety and reliability of the considered robotic system. Walker and Cavallero (1996a, b) described the application of FTA in the design phase of a robot manipulator for hazardous waste retrieval. Analysis of the trees revealed a number of ways to improve the safety and reliability of the manipulator design. Walker Leuschen *et al.* (2001) introduced a new technique for analyzing fault-tolerant designs under considerable uncertainty using fuzzy Markov modeling. The technique was a logical extension of the underlying concepts of fuzzy sets and Markov models. Carlson *et al.* (2004) proposed a new approach, which was extended in 2004. The reliability analysis of mobile robots was studied and suggestions based on mean time between failures (MTBF), mean time to repair and downtime, for system performance, were given. Stancliff *et al.* (2006) estimated mission reliability for a repairable robotic system and then extended the approach to multi-robot system design and presented the first quantitative support for the argument that larger teams of less-reliable robots can perform certain missions more reliably than smaller teams of more-reliable robots. Kumar *et al.* (2007) analyzed the reliability of a non-redundant robot using fuzzy lambda-tau methodology. Savsar and Aldaihani (2008) developed a stochastic model to analyze performance measures of a flexible manufacturing cell (FMC), consisting of two machines, served by a robot for loading and unloading purposes, and a pallet handling system, under different operational conditions, including machine failures and repairs. Using Markov processes, the closed-form solutions for the probabilities of system states were obtained to calculate system performance measures, such as production output rate and utilizations of system components. Aldaihani and Savsar (2008) extended the previous approach for FMC, consisting of two machines served by two robots. Korayem and Iravani (2008) applied failure mode and effect analysis and Quality function deployment approach to improve the reliability and quality of 3P and 6R mechanical robots.

From the above literature, it is observed that the traditional approaches of reliability analysis rely on probabilistic assumptions, which is often inappropriate for this task, as probability theory cannot deal with uncertainty due to vagueness in data (Walker and Cavallero, 1996a,b; Cai, 1996, Verma *et al.*, 2007). Further, the data obtained from the past history of any industrial system are imprecise, incomplete, vague and conflicting. If the data are used as such in the calculations, the results will be highly uncertain. On the other hand, Fuzzy methodology can deal with imprecise, uncertain dependent information related to system performance and provides a better, consistent and mathematically more sound method for handling uncertainties in data than conventional methods, such as Bayesian statistics, Markov process, etc. Singer (1990) developed a new methodology to find out various reliability parameters using fuzzy set approach and fault tree. The failure rate and repair time were represented using triangular fuzzy numbers (TFN). Cheng and Mon (1993) used confidence interval for analyzing the fuzzy system reliability. Through theoretical analysis and computational results, it was shown that the proposed approach was more general and straightforward compared to Singer's. Chen (1994) presented a new method for analyzing system reliability using a fuzzy number arithmetic operations. Knezevic and Odoom (2001) proposed a new methodology by making use of Petri nets (PNs) instead of fault trees. Fuzzy set theory was used to represent failure and repair data. The method was able to calculate the reliability indices more efficiently.

PN, introduced by Carl Adam Petri (1962), is a powerful technique, widely used in modeling and analysis of complex manufacturing systems and process due to its ability to model the dynamics of the system. Desrochers and Al-Jaar (1995), Baccelli *et al.* (1996) and Liu and Chiou (1997) demonstrated that PN modeling was superior to traditional Markov chain modeling and FTA, as they provide a powerful formalism to model various classes of discrete events and may be used for qualitative and quantitative purposes simultaneously. Adamyan and He (2002a,b) showed that PN modeling provides the ability to assess the quality and reliability impacts of unplanned failures and the sequence of these failures. Keeping these points in view, interactions among the working units of the robotic system are modeled using PNs. Different cut sets are obtained using matrix method (Liu and Chiou, 1997). The motive of this study is to evaluate various reliability parameters of a multi-robotic system, arranged in a complex configuration. The effects of failures and course of action on the system performance have been analyzed. To remove the uncertainty in the available data, fuzzy numbers are developed using fuzzy possibility theory. The use of fuzzy methodology increases the flexibility for application to various systems and conditions. Various reliability parameters such as fuzzy failure rate, repair time, MTBF, ENOF, reliability and availability are calculated using fuzzy lambda-tau methodology, which improves the shortcomings/drawbacks of the existing probabilistic approaches and gives a better understanding of the system behavior through its graphical representation. The basic expressions for fuzzy lambda-tau methodology and some reliability parameters are given in Tables I and II for ready reference.

2. System description and methodology

The present work is based on evaluating the reliability of multi-robot system with a conveyer unit. The system cosists of two robots and one conveyor unit between them. There are three joints in each robot, each joint has one motor (M_i, $1 \leq i \leq 6$) and one sensor (S_i, $1 \leq i \leq 6$), whereas the conveyor unit has a bearing (*Br*) and a roller (*Rl*) as its components. The PN model of the robot is depicted in Figure 1. $\{M_i,\ 1 \leq i \leq 6\}$, $\{S_i,\ 1 \leq i \leq 6\}$, $\{Br\}$ and $\{Rl\}$ are minimal cut sets, obtained using the matrix method. The following assumptions were taken while modeling the system:

Table I.
Basic expressions of fuzzy $\lambda - \tau$ methodology

Gate	λ_{AND}	τ_{AND}	λ_{OR}	τ_{OR}
Expressions	$\prod_{j=1}^{n} \lambda_j \left[\sum_{i=1}^{n} \prod_{\substack{j=1 \\ i \neq j}}^{n} \tau_j\right]$	$\dfrac{\prod_{i=1}^{n} \tau_i}{\sum_{j=1}^{n} \left[\prod_{\substack{i=1 \\ i \neq j}}^{n} \tau_i\right]}$	$\sum_{i=1}^{n} \lambda_i$	$\dfrac{\sum_{i=1}^{n} \lambda_i \tau_i}{\sum_{i=1}^{n} \lambda_i}$

- Component failures as well as repairs are statistically independent, constant and obey an exponential distribution.
- After repairs, the repaired component is considered as good as new.
- $\lambda_i \ll \mu_i$.
- Separate maintenance facility is available for each component.

Parameters	Expressions
Mean time to failure	$MTTF_s = \frac{1}{\lambda_s}$
Mean time to repair	$MTTR_s = \frac{1}{\mu_s} = \tau_s$
Mean time between failures	$MTBF_s = MTTF_s + MTTR_s$
Availability	$A_s = \frac{\mu_s}{\lambda_s + \mu_s} + \frac{\lambda_s}{\lambda_s + \mu_s} e^{-(\lambda_s + \mu_s)t}$
Reliability	$R_s = e^{-\lambda_s t}$
Expected number of failures	$W_s = \frac{\lambda_s \mu_s t}{\lambda_s + \mu_s} + \frac{\lambda_s^2}{(\lambda_s + \mu_s)^2}[1 - e^{-(\lambda_s + \mu_s)t}]$

Table II.
Expressions for reliability parameters

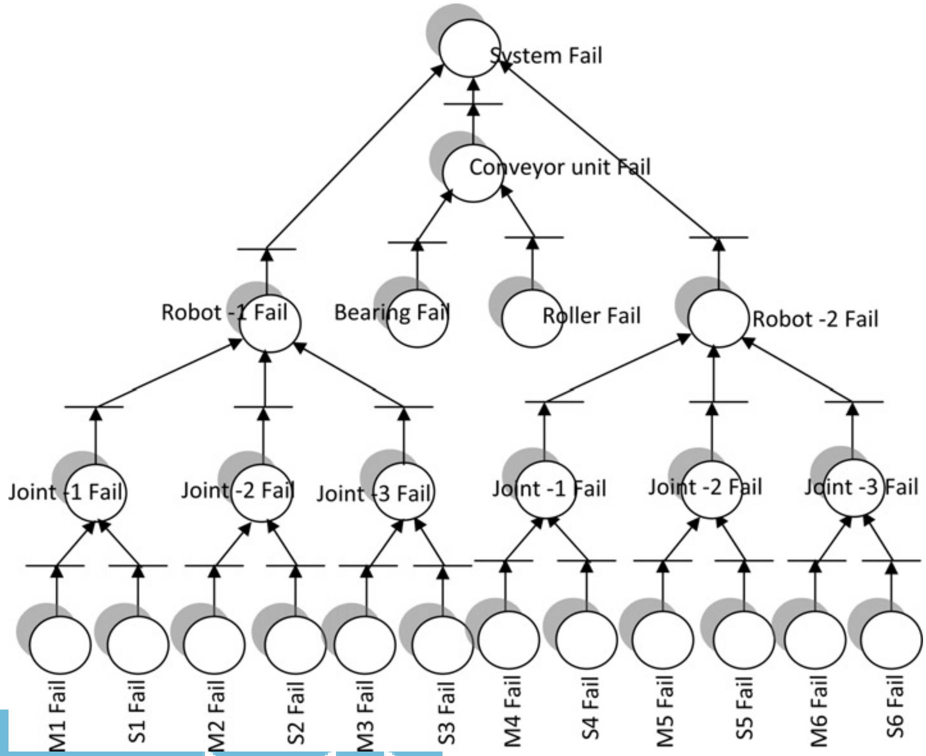


Figure 1.
PN model of the proposed robotic system

The procedural steps of the methodology are given below:

Step 1: The data related to failure rates λ_i and repair times τ_i of the components are collected from the historical/present records of the system and are given in Table III. The mission time for calculation of the reliability parameters is taken to be 100 h.

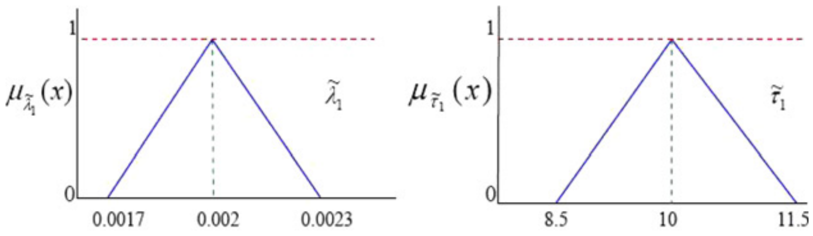
Step 2: To handle the vagueness and uncertainty in data, the crisp data related to λ_i and τ_i are converted into TFN (Zimmermann, 2000) with ±15 percent (±25 percent, ±50 percent) spreads, as depicted in Figure 2. As soon as the input TFN for failure rates and repair times for each of the components are known, the corresponding fuzzy value ($\tilde{\lambda}$ and $\tilde{\tau}$) for the uppermost (System Fail) node can be obtained using the extension principle coupled with α-cut and interval arithmetic operations on fuzzy triangular numbers (Dhillon and Singh, 1991). The basic expressions of fuzzy lambda-tau methodology are given in Table I. The interval expressions for the fuzzy triangular number, for the failure rate $\tilde{\lambda}$ and repair time $\tilde{\tau}$, for AND/OR-transitions are as follows:

Expressions for AND-transitions:

$$\lambda^{(\alpha)} = \left[\prod_{i=1}^{n}\{(\lambda_{i2}-\lambda_{i1})\alpha+\lambda_{i1}\}\cdot\sum_{j=1}^{n}\left[\prod_{\substack{n\\ i=1\\ i\neq j}}\{(\tau_{i2}-\tau_{i1})\alpha+\tau_{i1}\}\right]\right.$$
$$\left.\times\prod_{i=1}^{n}\{-(\lambda_{i3}-\lambda_{i2})\alpha+\lambda_{i3}\}\cdot\sum_{j=1}^{n}\left[\prod_{\substack{n\\ i=1\\ i\neq j}}\{-(\tau_{i3}-\lambda_{i2})\alpha+\tau_{i3}\}\right]\right] \quad (1)$$

Table III.
Failure rates and repair times of the components

Components Parameters	Motors (M_i, $1 \le i \le 6$)	Sensors (S_i, $1 \le i \le 6$)	Bearing *Br*	Roller *Rl*
Failure rates λ (h^{-1})	1.85×10^{-5}	2.35×10^{-5}	1.55×10^{-5}	1.50×10^{-5}
Repair times τ (h)	2	2	1	2



(a) (b)

Figure 2.
Input fuzzy triangular numbers

Notes: (a) Failure rate and (b) repair time

$$\tau^{(\alpha)} = \left[\frac{\prod_{i=1}^{n} \{(\tau_{i2} - \tau_{i1})\alpha + \tau_{i1}\}}{\sum_{j=1}^{n} \left[\prod_{\substack{i=1 \\ i \neq j}}^{n} \{-(\tau_{i3} - \tau_{i2})\alpha + \tau_{i3}\} \right]}, \frac{\prod_{i=1}^{n} \{-(\tau_{i3} - \tau_{i2})\alpha + \tau_{i3}\}}{\sum_{j=1}^{n} \left[\prod_{\substack{i=1 \\ i \neq j}}^{n} \{(\tau_{i2} - \tau_{i1})\alpha + \tau_{i1}\} \right]} \right] \tag{2}$$

Expressions for OR-transitions:

$$\lambda^{(\alpha)} = \left[\sum_{i=1}^{n} \{(\lambda_{i2} - \lambda_{i1})\alpha + \lambda_{i1}\}, \sum_{i=1}^{n} \{-(\lambda_{i3} - \lambda_{i2})\alpha + \lambda_{i3}\} \right] \tag{3}$$

$$\begin{aligned} \tau^{(\alpha)} = & \left[\frac{\sum_{i=1}^{n} [\{(\lambda_{i2} - \lambda_{i1})\alpha + \lambda_{i1}\} \cdot \{(\tau_{i2} - \tau_{i1})\alpha + \tau_{i1}\}]}{\sum_{i=1}^{n} \{-(\lambda_{i3} - \lambda_{i2})\alpha + \lambda_{i3}\}} \right. \\ & \times \left. \frac{\sum_{i=1}^{n} [\{-(\lambda_{i3} - \lambda_{i2})\alpha + \lambda_{i3}\} \cdot \{-(\tau_{i3} - \tau_{i2})\alpha + \tau_{i3}\}]}{\sum_{i=1}^{n} \{(\lambda_{i2} - \lambda_{i1})\alpha + \lambda_{i1}\}} \right] \end{aligned} \tag{4}$$

Step 3: To analyze the system behavior qualitatively as well as quantitatively, various reliability parameters such as failure rate, repair time, availability, MTBF, reliability and expected number of failures, with left and right spreads, can be computed at various membership grades, as shown graphically in Figure 3. The expressions for various reliability parameters are given in Table II.

Step 4: Defuzzification is necessary to convert the fuzzy output to a crisp value, as most of the actions or decisions implemented by humans or machines are binary or crisp. There exist many defuzzification techniques in the literature (Ross, 2004), which can be used, depending on the application. Herein, center of area (COA) method is used for this study, it being equivalent to mean of data, is very appropriate for reliability calculation. If the membership function $\mu_{\tilde{A}}(x)$ of the output fuzzy set $\tilde{A}$ is described on the interval $[x_1, x_2]$, then COA defuzzification $\bar{x}$ can be defined as

$$\bar{x} = \frac{\int_{x_1}^{x_2} x \cdot \mu_{\tilde{A}}(x)dx}{\int_{x_1}^{x_2} \mu_{\tilde{A}}(x)dx} \tag{5}$$

3. Results

From Figure 3, it is clear that the sides of membership functions of reliability parameters are parabolic, not linear, as were taken initially. The crisp and defuzzified values for various reliability parameters at ±15 percent, ±25 percent and ±50 percent spreads are calculated and depicted in Table IV, which clearly indicates that the defuzzified values of various reliability parameters change with change of spreads. It

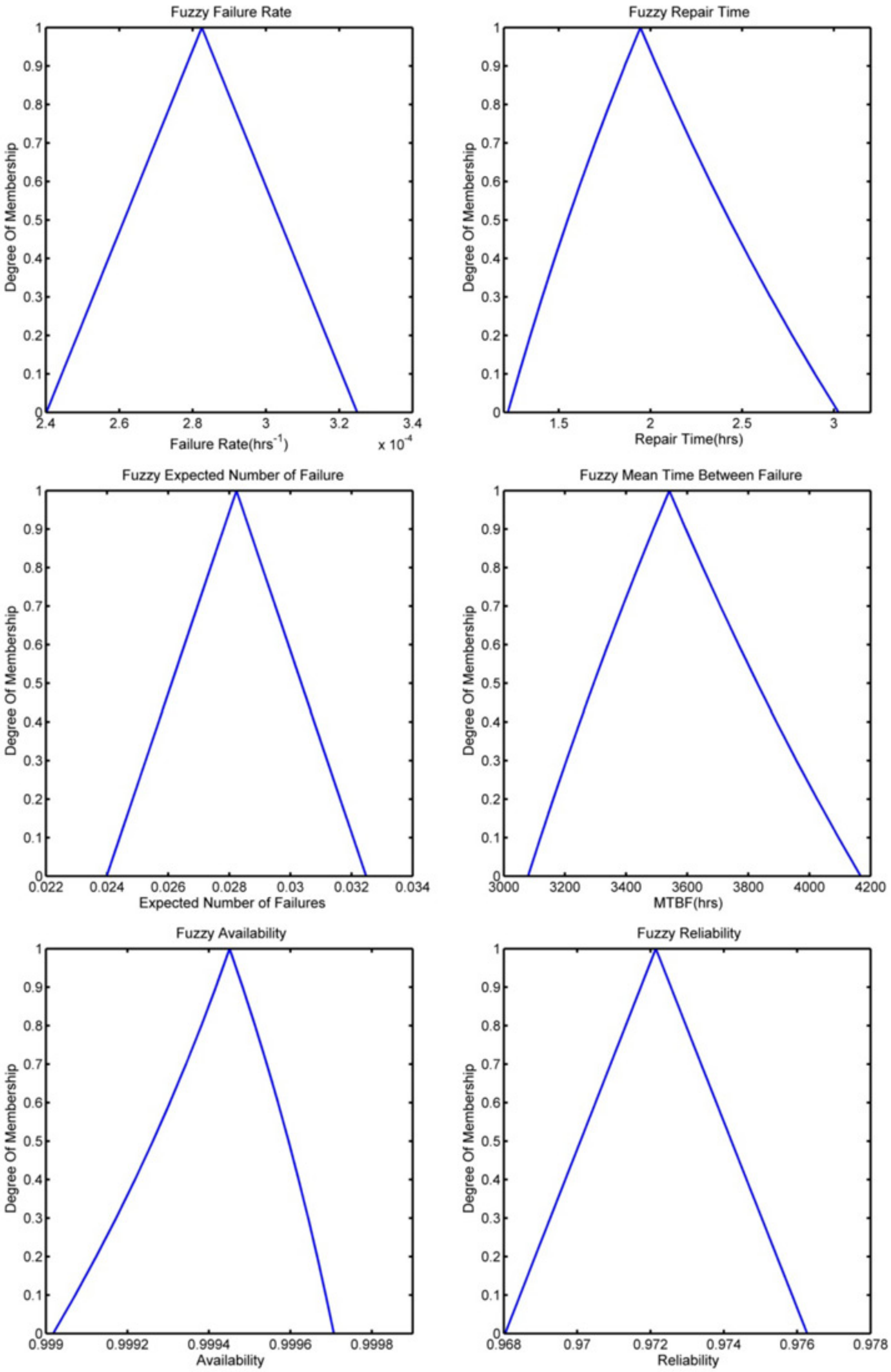


Figure 3.
Fuzzy reliability parameters at 15 percent spread

also shows that the defuzzified values of failure rate, repair time and expected number of failures, increase with the increase of spreads. On the other hand, the defuzzified values of MTBF, reliability and availability, decrease with increase of spreads. This means that the values obtained through fuzzy methodology are conservative in nature, which may be beneficial for the maintenance engineer in terms of performing maintenance. Thus, from the above analysis it is clear that maintenance should be based on defuzzified MTBF, rather than on crisp MTBF, because by using a defuzzified value of MTBF, a safe interval between times of maintenance can be established and inspections can be conducted to monitor the condition or status of various equipments of the system before it reaches the crisp value. Hence, selection of the spread on the crisp value for fuzzy input data should be used with great care, based on good knowledge of the system, its available data and the operating environment.

4. Conclusions

The development of fuzzy numbers from available data on components and using fuzzy possibility theory to define membership function can greatly increase the relevance of the reliability study. The use of fuzzy arithmetic in the PN model increases the versatility for application to various systems and conditions. Fuzzy reliability methodology has important implications for management with respect to plant maintenance and operation. The most important benefit is that the crisp, fuzzy and defuzzified values for even highly complex integrated system can be obtained all at once.

In this paper a structured framework has been developed that may help maintenance engineers to analyze and predict system behavior. Attempts have also been made:

- to deal with imprecise, uncertain dependent information related to system performance as the fuzzy methodology provides a better, consistent and mathematically sound method for handling uncertainties in data than conventional methods, such as Bayesian statistics;
- to model and deal with highly complex robotic system using fuzzy sets, as these sets can deal easily with approximations; and
- various reliability parameters (such as failure rate, repair time, MTBF, availability, reliability and expected number of failures) were found to predict the system behavior in objective terms and it is concluded that in order to improve the availability and reliability aspects, it is necessary to enhance the maintainability requirement of the system.

Also, maintenance should be based on the defuzzified value of MTBF, rather than crisp MTBF, as a safe interval between maintenance is established and inspections may be conducted long before the crisp estimation is reached.

Values Reliability parameters	Crisp value	Defuzzified value at 15% spread	Defuzzified value at 25% spread	Defuzzified value at 50% spread
Failure rate ($\times 10^{-4}\,h^{-1}$)	2.825000	2.825013	2.835217	3.152798
Repair time (h)	1.945133	2.034763	2.203569	3.204719
ENOF ($\times 10^{-2}$)	2.823478	2.831527	2.971923	2.991524
MTBF ($\times 10^{3}$ h)	3.541768	3.522729	3.212815	2.998759
Reliability	0.972145	0.971501	0.968925	0.942509
Availability	0.999450	0.998406	0.988321	0.987799

Table IV.
Crisp and defuzzified values at different spreads

5. Future scope

The work done on the proposed robotic system may be extended for n-robots working in hybrid configuration, e.g. series, parallel, series-parallel, etc. The cost factor plays a key role in reliability analysis and its improvement. The costs include manufacturing cost, repair cost, failure cost, etc., may be considered in future study to find out the optimal value of various reliability indices, which give the optimum system performance. Also, prediction of system performance, considering different reliability indices, can be done using Bayesian statistics and/or soft computing techniques.

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