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Reliability analysis of waste clean-up manipulator using genetic algorithms and fuzzy methodology

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ABSTRACT

In this paper, the reliability analysis of waste clean-up manipulator has been performed using Real Coded Genetic Algorithms and Fuzzy Lambda Tau Methodology. The optimal values of mean time between failures and mean time to repair are obtained using genetic algorithms. Petri Net tool is applied to represent the interactions among the working components of the system. To enhance the relevance of the reliability study, triangular fuzzy numbers are developed from the computed data, using possibility theory. The use of fuzzy arithmetic in the Petri Net model increases the flexibility for application to various systems and conditions. Various reliability parameters (failure rate, repair time, mean time between failures, expected no. of failures, reliability and availability) are computed using Fuzzy Lambda Tau Methodology. Sensitivity analysis has also been performed and the effects on system mean time between failures are addressed. The adopted methodology improves the shortcomings/drawbacks of the existing probabilistic approaches and gives a better understanding of the system behavior through its graphical representation.

1. Introduction

The subject of robot reliability is very complex and there are numerous interlocking variables in evaluating and accomplishing various reliability levels [1]. 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 problem becomes more important for robots, which are used in hazardous environments for removing, treating and disposing of the wastes stored in underground tanks at nuclear sites. 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 complex robotic systems, it is required to develop a suitable methodology so that timely 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 (RSR) [2]. Jin et al. [3] carefully analyzed the behavior of two robots in a combination of arrangements. Operations are represented with a Petri Net (PN) model and analysis of probabilistic behavior and reliability is performed with introducing Markov renewal process. Dhillion and Singh [4] and Dhillon and Yang [5] used the established techniques and presented the safety, reliability and availability analysis of various robotic systems. Khodabandehloo [6] presented the use of systematic techniques such as fault tree analysis (FTA) and event tree analysis (ETA) to examine the safety and reliability of a given robotic system. Walker and Cavallaro [7] described the application of FTA to the design phase of a robot manipulator for hazardous waste retrieval. Dhillon and Fashandi [8] presented probabilistic analysis of a system consisting of a robot and its associated safety mechanism. Expressions along with plots for the robot system availability and state probabilities are presented. Leuschen et al. [9,10] introduced and extended the technique for analyzing fault tolerant designs under considerable uncertainty by introducing a logical extension of the underlying concepts of fuzzy sets and Markov models. Carreras et al. [11] and Carreras and Walker [12] used interval method to chalk out the reliability analysis of robot. Carlson and Murphy [13] proposed a new approach and studied the reliability analysis of mobile robots. Sharma et al. [1] analyzed the reliability of multi-robotic system and computed various reliability parameters using fuzzy approach. The results obtained using Markov process, fault tree were compared with the defuzzified values and found that the results obtained by fuzzy methodology are better. Based on the obtained results, they also gave recommendations to enhance the system reliability.

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For the parameterizations of system availability, it is difficult to obtain the optimal solutions within a limited range of parameters using conventional methods. In such case, it is possible to approach optimal solution within a limited time frame by using the features of generational evolution and parallel search of genetic algorithms (GA). GA was applied to a wide variety of fields in recent decades. GA can efficiently solve the reliability and/or availability optimization problem of any industrial system, as it is suitable to the domain of feasible solution with nonlinearity or discontinuity. When the solution space to be searched is relatively large, noisy, nonlinear and complicated, the GA has higher opportunity for obtaining near-optimal solutions [14]. Yokota et al. [15] utilized GA to successfully solve the reliability optimization problem of series–parallel system with parallel components and several failure modes, which were formerly solved by Tillman [16]. Coit and Smith [17] used GA to solve the reliability optimization problem of series–parallel system meeting the cost and weight constraints. The results proved that GA offered more time-saving solution than the method proposed by Bulfin and Liu [18]. Taguchi and Yokota [19] formulated reliability optimization problem as nonlinear goal programming with interval coefficients and used GA to solve it. Hsieh et al. [20] used GAs for solving various reliability design problems, which include series systems, series–parallel systems and complex bridge systems with respect to three nonlinear constraints, namely cost, volume and weight constraints. Levitin and Lisnianski [21] solved the joint redundancy and replacement schedule optimization problem generalized to multi-state system using GA. Yamada and Takata [22] proposed a novel method for improving reliability of manufacturing facilities by optimizing operating conditions. The method is applied to an industrial robot. The effectiveness of the method has been verified by applying the method to assembly robots. Elegbede and Adjallah [23] employed weighted average for transforming a problem of multiple objective to single objective and solved it with GA. Martorell et al. [24] proposed a general framework for multiple-objective optimization problem based on reliability, availability, maintainability, safety and resource criteria. Two GA-based methods, single-objective GA and multi-objective GA, were used to solve the optimization problem. Marquez and Coit [25] formulated a redundancy allocation problem with the objective of minimizing design cost. The heuristic offers more efficient and straightforward analysis. Solutions to three different problem types are obtained illustrating the simplicity and ease of application of the heuristic without compromising the intended optimization needs. Yun and Kim [26] addressed the problem in which redundancy is available at all levels in a series system and a mixed integer programming problem is constructed. A heuristic algorithm and a genetic algorithm are proposed to solve the problem and the procedure is explained by examples. You and Chen [27] presented a novel algorithm for solving a series–parallel redundancy allocation problem with separable constraints. Numerical results for the 33 test problems from previous research are reported and compared. As reported in the study, the solutions found by the approach are better than the well-known best solutions obtained earlier. Azaron et al. [28] solved a multi-objective discrete reliability optimization problem in a *k*-dissimilar-unit non-repairable cold-standby redundant system using genetic algorithm approach. Each unit is composed of a number of independent components with generalized Erlang distributions arranged in a series–parallel configuration. The results are compared against the results of a discrete-time approximation technique to show the efficiency of the proposed GA approach. Sharma et al. [29] modeled and chalked out the performance measures of repairable system using RCGA.

Petri Net (PN) tool is used to model the interactions among the working components as it is a powerful tool and widely used in modeling and analysis of complex manufacturing systems and process. The tool has the ability of assessing the quality and reliability impacts of unplanned failures and the sequence of these failures, and capacity in modeling the dynamics of the system [30–32]. The graphical depiction of the system (with PNs) enable the system analyst to quickly understand the various interactions amongst the components of the system. Petri Net (PN) based matrix method is used to achieve minimal cut sets as it takes lesser procedural steps in comparison to that of fault trees [30]. The other benefit on this method is that minimal cut and path sets can be obtained simultaneously, whereas it is not in the case of fault trees.

In this study, various reliability parameters have been evaluated for waste clean-up manipulator. Reliability Block Diagram (RBD) of the system is drawn and based on it, availability model is constructed by considering availability function, manufacturing cost and repair cost, and optimal values of mean time between failures (MTBF) and mean time to repair (MTTR) are obtained using GA. With reference to the availability and cost factors, it is possible to find out maximum overall efficiency of the entire system [33]. The computed parameters have been used to calculate various fuzzy reliability parameters (failure rate, repair time, mean time between failures (MTBF), expected number of failures (ENOF), reliability and availability). In the quantitative framework, the quantification of system parameters is important for effective managerial decision-making with respect to maintenance planning and it is done in terms of fuzzy, crisp and defuzzified values. First, the Petri Net (PN) model of the system is drawn and the system failure rates and repair times are computed from the optimal mean time between failures (MTBF) and mean time to repair (MTTR). To remove the uncertainty in data, the fuzzification of failure rate and repair time data is done using triangular fuzzy numbers (TFNs). After knowing the input triangular fuzzy numbers (TFNs) for all the components, the corresponding values for failure rate (λ) and repair time (τ) for the system at different confidence levels (α) are determined using fuzzy transition expressions. The mission time for the calculation of reliability parameters is taken to be 100 h. To study the failure behavior of the system, crisp and defuzzified values are obtained at $\pm 15\%$, $\pm 25\%$ and $\pm 50\%$ spreads. The effects of failures and course of action on the system performance have also been investigated.

The paper is organized as follows: in Section 2, the objective of the study is described. Methodology is presented in Section 3. In Section 4, system description and its modeling is presented. Results and discussions are presented in Section 5 followed by conclusion in Section 6.

2. Objectives

The following observations may be made after critically reviewing the literature:

(i) The empirical methods (dynamic programming, integer/mixed integer programming, etc.) do not provide global optimal solutions to the most of problems but they provide local optimal solution, and hence the design cost increases.
(ii) The costs, associated with system design, such as manufacturing cost, repairing cost, etc., are not well taken into account.
(iii) Most of the modeling tools, like FTA, are not capable of modeling the dynamics of the system, unplanned failures and the sequence of these failures. Also, the generation of minimal cut and path sets takes a lot of procedural steps and cannot be obtained simultaneously.
(iv) Most of the probabilistic techniques are not capable of modeling the non-exponential phenomena and dependent/subjective