Applied Soft Computing 12 (2012) 405–415

Contents lists available at SciVerse ScienceDirect

Applied Soft Computing

journal homepage: www.elsevier.com/locate/asoc

Reliability analysis of complex multi-robotic system using GA and fuzzy methodology

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ARTICLE INFO

Article history:
Received 8 December 2009
Received in revised form 9 June 2011
Accepted 14 August 2011
Available online 10 September 2011

Keywords:
Reliability
MTBF
Petri Nets
Linguistic variables
Genetic algorithms
Optimization

ABSTRACT

The objective of the study is to compute various reliability parameters for multi-robotic system, using Real Coded Genetic Algorithms (RCGAs) and Fuzzy Lambda-Tau Methodology (FLTM). The paper contains a new idea about the reliability analysis of robotic system. The optimal values of mean time between failures (MTBF) and mean time to repair (MTTR) are obtained using GAs. Petri Net (PN) tool is applied to represent the interactions among the working components of multi-robotic system. To enhance the relevance of the reliability study, triangular fuzzy numbers (TFNs) are developed from the computed data, using possibility theory. The use of fuzzy arithmetic in the PN model increases the flexibility for application to various systems and conditions. Various reliability parameters, namely failure rate, repair time, MTBF, expected number of failures (ENOF), reliability and availability, are computed using FLTM. Sensitivity analysis has also been performed and the effects on system MTBF 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. The analysis presented, may be helpful for the system analyst to analyze and predict the system behavior and to reallocate the required resources.

1. Introduction

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 robotic system can be maintained to a higher level using the structural design of the system/components of higher reliability or both of them may be performed simultaneously [1]. When the components of higher reliability are used, the associated cost of components also increases. This is an important issue to be considered for industrial application purpose. Thus, the 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 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.

The present work is an extension of the work, earlier done by Sharma et al. [2,3], in which the cost factor was not considered in mathematical modeling. In this study, various reliability parameters have been evaluated for a multi-robotic system, arranged in a complex configuration. 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 MTBF and 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 [4]. The computed parameters have been used to calculate various fuzzy reliability parameters (failure rate, repair time, MTBF, expected number of failures, 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 PN model of the system is drawn and the system

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doi:10.1016/j.asoc.2011.08.031

failure rates and repair times are computed from the optimal MTBF and 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 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 $t = 100$ h. To study the failure behavior of the system, crisp and defuzzified values are obtained at ±15%, ±25% and ±50% spreads. The effects of failures and course of action on the system performance have also been investigated.

2. Review of literature

In this section, a brief literature review regarding reliability/availability evaluation and optimization is given. The gaps found from literature review are addressed in the next section.

2.1. Performance analysis of robotic system

Despite the existence of a vast amount of literature on robotic research, not much work has been done on robot system reliability (RSR) [5,6].

Jin et al. [7] carefully analyzed the behavior of two robots in a combination of arrangements. The robots operate independently and in coordination with each other and then each of them operates in conjunction with a conveyer incorporated in the system. Operations are then represented in a PN model and analysis of probabilistic behavior and reliability is performed with introducing of Markov renewal process. Dhillion and Singh [8] and Dhillon and Yang [9] used the established techniques and presented the safety, reliability and availability analysis of various robotic systems. Khodabandehloo [10] 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 [11] described the application of FTA to the design phase of a robot manipulator for hazardous waste retrieval. Dhillon and Fashandi [12] presented probabilistic analysis of a system comprised 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. [13,14] introduced and extended the technique for analyzing fault tolerant designs under considerable uncertainty. The technique introduced was a logical extension of the underlying concepts of fuzzy sets and Markov models. Carreras et al. [15] and Carreras and Walker [16] used interval method to chalk out the reliability analysis of robot. Different strategies were evaluated in order to gain a more complete understanding of the potential benefits of the approach. Carlson and Murphy [17] proposed a new approach and studied the reliability analysis of mobile robots. The previous approach was extended by Carlson et al. [18]. Using statistical analysis they showed that the MTBF, MTTR and downtime vary widely. McIntyre et al. [19] considered fault identification for robot manipulators. The proposed method did not require acceleration measurement and was independent of the controller. Stancliff et al. [20] estimated mission reliability for repairable robotic system and then extended the approach for 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. [21], Sharma et al. [2,3,22] 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. Savsar and Aldaihani [23] developed a stochastic model to analyze performance measures of a flexible manufacturing cell (FMC) consisting of two machines served by a robot, under different operational conditions, including machine failures and repairs. The model was based on Markov processes and determined closed-form solutions for the probabilities of system states to calculate system performance measures, such as production output rate and utilizations of system components under different parametric conditions and equipment failures and repairs. Again Aldaihani and Savsar [24] extended the approach for flexible manufacturing cell (FMC) consisting of two machines served by two robots. Korayem and Iravani [25] applied failure mode and effect analysis (FMEA) and quality function deployment (QFD) approach to improve the reliability and quality of 3P and 6R mechanical robots.

2.2. Reliability/availability optimization using genetic algorithms

Under repairable series–parallel system framework, there are many methods to determine the optimal parameters of components, such as dynamic programming, integer programming, non-linear integer programming and heuristic or meta-heuristic algorithms. 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 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 non-linearity or discontinuity. When the solution space to be searched is relatively large, noisy, non-linear and complicated, the GA has higher opportunity for obtaining near-optimal solutions [26]. Yokota et al. [27–29] 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 [30]. Coit and Smith [31,32] 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 [33]. Taguchi et al. [34,35], Taguchi and Yokota [36] formulated reliability optimization problem as nonlinear goal programming with interval coefficients and used GA to solve it. Hsieh et al. [37] 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 [38] solved the joint redundancy and replacement schedule optimization problem generalized to multi-state system using GA. Yamada and Takata [39] 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 [40] employed weighted average for transforming a problem of multiple objective to single objective and solved it with GA. Martorell et al. [41] 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 [42] 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