Decomposition versus Minimal Path and Cuts Methods for Reliability Evaluation of an Advanced Robotic Production System

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Abstract:
As complex systems have become global and essential in today's society, their reliable design and the determination of their availability have turned into a very important task for managers and engineers. Industrial robots are examples of these complex systems that are being increasingly used for intelligent transportation, production and distribution of materials in warehouses and automated production lines. In this paper, two techniques of reliability evaluation are developed for a complex system of robots. Decomposition method and minimal path and cuts method are adapted for the proposed complex system. For practical implementation, a particular robot system is first modeled. Then, reliability block diagram is adopted to model the complex system for reliability evaluation purpose. Finally, the methods are implemented and their properties are discussed.

Keywords: *complex system reliability, industrial robots, decomposition method (DM), minimal paths and cuts method (MPCM) cone*

1. Introduction

In the past few years a considerable amount of work has been devoted to improve the efficiency of methodologies applied to reliability and safety analyses of industrial plants. In particular, the need for a more detailed analysis of the system under study is growing, whereby the plants structures as well as its working conditions were taken into account. This implies the evaluation of the interaction of several elements, namely physical transient, control system intervention and operator tasks, which are very important during operational or abnormal situations [3]. Much effort has been devoted to fill the gap between deterministic dynamic analyses of plants, i.e. engineering simulations particularly useful to study small configurations, and classical reliability methods, such as logical methodologies like Fault Trees (FTs) and Event Trees (ETs), necessary to study complex system as a whole [3]. New approaches have been embarked on: as an example Jeong [16] introduced the Markov chain in the FT analysis to permit the evaluation of the probabilistic behavior of system unavailability versus time, when the plant is decomposed into a reasonable number of super components; other studies have been developed to assess the system reliability by a dynamic and qualitative approach based on Petri Nets theory and Markov chains [6, 21]. The GO FLOW method has been realized to enhance the GO characteristics with the introduction of a time-ordered analysis [31, 23]. All these methodologies show very interesting approaches to system analysis, but they present two main problems:

- The effort needed for system decomposition into supercomponents or the construction of charts;
- The adequacy of the process model used in the probabilistic analysis of the system to represent the actual interaction between the process physics and component behavior.

The first issue is related to the need to study the reliability of a complex system in detail and it does not seem to be avoidable. On the contrary, the second problem can be tackled by a more accurate study of the physical and dynamic behavior of the system; a number of methods are being developed with the particular attention to this problem. As an example the approach proposed by Hassan and Aldemir [13] separated the physical and probabilistic analysis and realizes a suitable method to assess top event sensitivity to uncertainty on the component failure data. Other methods are the Markov Failure Modelling [2] and the Continuous Event Tree method [27] which link the system model to probabilistic treatment using Markovian or semi-Markovian chains in a complete theoretical analysis, but seem to be very difficult to apply on large configurations; the DYLAM attainment and the possible recovery of "top" methodology, which uses a quantitative dynamic process model for probabilistic analysis; and finally the Dynamic Event Tree method [26] which is similar to DYLAM approach, but deals with the system at a lower level of detail in order to reduce the computation efforts.

There is extensive literature on reliability characteristics of repairable systems with two or three components under varying assumptions on the failures and repairs. In most of these papers, exponential distributions are assumed for mathematical convenience. The concept of reliability can also be applied in other fields using different techniques. Mahajan and Singh [22] discussed the reliability analysis of utensils manufacturing plant. Goel and Singh [11] presented reliability analysis of a standby complex system having imperfect switch over device and availability analysis of butter manufacturing system in a dairy plant. Singh [25] suggested some applications of reliability technology such as fertilizer industry, sugar industry and biogas plant. Dhillon and Natesan [8] discussed power system in fluctuating environment. Dayal and

Singh [7] studied reliability analysis of a system in a fluctuating environment. Kumar *et al.* (1988) discussed feeding systems in the sugar industry.

Traditional system reliability analysis methodologies are based on "bottom up" relationships between system and component reliabilities, such as the methodologies explained by Hoyland and Rausand [15], Kumamoto and Henley [18], and the Nuclear Regulatory Committee (NRC) Probability Risk Assessment Guide (1983). This approach drives reliability analysis towards understanding component reliability characteristics, which then allows system level reliability prediction. Recent techniques allow reliability analysis to be conducted at sub-system or system levels (which is referred to as higher level as it appears "higher" in many visualization methodologies). The parameters that describe the reliability characteristics of components define the reliability characteristics of the system. Accordingly, these parameters will always be the unknowns of interest in any system reliability analysis, and, correspondingly, reliability analysis inherently involves the "downwards" propagation of information. Conversely, reliability prediction is an "upwards" expression of information.

During the recent years, the requirement of modern technology, especially the complex systems used in the industry, leads to a growth in the amount of researches about the design for reliability. Avontuur and van der Werff [5] and Avontuur [4] emphasized the importance of reliability analysis in the conceptual design phase. It is demonstrated that it is possible to improve a design by applying reliability analysis techniques in the conceptual design phase. The aim is to quantify the cost of failure and unavailability and compare them with investment cost to improve the reliability [1].

In following the increase of using automatic systems, the problem of performance reliability in such equipment and regarding to it, some indexes such accessibility, rate of fault and etc. are suggested. Since the most automatic systems are designed for continuous missions and the destruction during the mission can make high expenses for utilizers, so evaluating the assurance on equipment must be considered in different steps and also in the phase of planning, to prevent such unwanted destructions (faults) during the work [10]. In this field Korayem and Iravani [17] have promoted the reliability and improvement of robot 3P and robot 6R by tools FMEA and QFD.

Structural design *via* deterministic mathematical programming techniques has been widely accepted as a viable tool for engineering design [12]. However, in most structural engineering applications response predictions are based on models involving uncertain parameters. This is due to a lack of information about the value of system parameters external to the structure such as environmental loads or internal such as system behavior. Under uncertain conditions the field of reliability – based optimization provides a realistic and rational framework for structural optimization which explicitly accounts for the uncertainties [9, 20, 24].

Although risk assessment evaluation of complex dependable systems can be performed through the use of dynamic stochastic modeling, in the real industrial world the well-known combinatorial techniques, such as Reliability Block Diagram (RBD) and Static Fault Tree (SFT), are still the most widely used [28].

This paper is organized as follows: The problem is stated and formulated in Section 2. An implementation study is conducted in Section 3. Section 4 contains conclusion and some recommendations for future works.

2. Proposed Problem and Methods

Consider a complex production system including automated processes and multiple robots. In this system, appropriate functioning of the facilities is guaranteed by functioning of its vital equipment. The question is how to evaluate and analyze the performance of the system defined by the availability of the whole system. In this regard, the reliability evaluation comes to the picture as an effective instrument. While the system under consideration is complex due to having many material handling robots, developing an efficient approach to compute and analyze the system reliability has a significant benefit. For instance, this helps to determine proper arrangements of robots and machine layout as well as specifying an adequate process plan. Note that all these factors influence the reliability of the whole system. In addition, as the robots are assumed to operate in two states of working and not working, in what comes in the next subsection some techniques that are capable of determining the reliability of a complex system are explained.

2.1. Decomposition Method

One way to determine the reliability of complex system is decomposition method (DM). According to DM, a component is chosen close to the left or to the right end of the system block diagram. This component is called "keystone". Then, the conditional reliability of the system given that the "keystone" survives, and the conditional system reliability given that the "keystone" fails is computed. The reliability of the whole system is then determined as a weighted average of these two conditional reliabilities, where the weights are the reliability of the "keystone", R and 1-R, respectively.

Lets' consider the "keystone" by C_X and the corresponding reliability by R_X, then,

$$R_{SYS} = R_X . R_{SYS|C_X} + (1-R) . R_{SYS|\bar{C}_X}, \tag{1}$$

where $R_{SYS|C_X}$ is the conditional reliability when the "keystone" survives and $R_{SYS|\bar{C}_X}$ is the conditional reliability when the "keystone" fails.

2.2. Minimal Paths and Cuts Method

Minimal path and cuts method (MPCM) is a technique for reliability computation in complex systems specifically network systems. Let $\psi(x_1, \dots, x_n)$ be a function of n variables, $0 \leq x_i \leq 1$ for all $i = 1, \dots, n$. this function is called a "structure function" if $\psi(I_1, \dots, I_n) = 1$ when the system survives and is equal to zero otherwise, where $I_1, \dots, I_n$ are survival indicators of the components.

Consider a system S of n components, represented by a given structure function. Let $P=\{C_{i1},...,C_{im}\}$ be a set of m components of S. P is called a "path set" if the system S survives whenever all the elements of P are survive. A path set, P, is called minimal if the set is not a path set following the exclusion of any of its members, i.e., no proper subset of P is a path set. Having the block diagram of a system all the minimal paths can be listed.

A "cut set" is a set of components of a system such that if all the components belonging to the set fail then the system fails, too. A cut set is called minimal if the survival of any of its elements entails system survival.

3. Numerical Example

Let's consider a numerical example to show the effectiveness of implementing the proposed methods for reliability evaluation of an advanced production system. Consider a production system having 9 robots for material handling which are either active or failed (binary state). The robots are unidirectional and move between stations S and T. a configuration of the system is drawn in Figure 1.

Using the decomposition method we need to determine a keystone robot first. Robot 6 is considered as keystone and using the equation below the reliability of the system is computed:

$$R_{sys} = R_6.R_{sys} \,/\, R_6 + (1-R_6)\, R_{sys} \,/\, R_{\bar{6}} \qquad (2)$$

Since the formula is conditional we need to compute the reliability based on the condition given separately. First, consider that robot 6 is active then all paths including robot 6 are functioning. Thus, the paths are:

1-2-6-8; 3-2-6-8; 1-2-6-7-9; 3-2-6-7-9.

The series/parallel structures in different paths are taken in to account for reliability evaluation of the system. Robots 1 and 2 are series and their integration is parallel with robot 3. Also, robots 7 and 9 are series and their integration is parallel with robot 8 and the integration is series with robot 6. Then, mathematically we have,

$$R_6.R_{sys} \,/\, R_6 =$$
$$= 1-[1-(R_1.R_2).(1-R_3)].R_6.[(1-(1-R_8))(1-(R_7.R_9))]. \quad (3)$$

The second case is when the system is conditionally not working so that robot 6 as keystone is failed. Then, paths should be selected in which robot 6 is not present. The paths are:

3-5-7-9; 4-7-9.

Then according to the decomposition main formula, we obtain:

$$(1-R_6).R_{sys} \mid R_{\bar{6}} =$$
$$= [1-((1-(R_3.R_5))(1-(R_4.R_7)].R_9.(1-R_6) \qquad (4)$$

The reliability of the system is the addition of the two preceding relations as given below,

$$R_{sys}=1-[1-(R_1.R_2).(1-R_3)].R_6.[(1-(1-R_8))(1-(R_7.R_9))]+$$
$$+[1-((1-(R_3.R_5))(1-(R_4.R_7))).R_9.(1-R_6)] \qquad (5)$$

Since robots are similar and homogenous ($R=0.845$), then the numerical result of the system reliability when robot 6 is the keystone is obtained to be 0.928.

The same computations are performed when other robots are considered as keystone. The results are summarized in Table 1.

Table 1. Different keystones and the corresponding reliability of the system

Keystone robot	Reliability of the system
1	0.701
2	0.776
3	0.891
4	0.7415
5	0.6528
7	0.815
8	0.8117
9	0.94

The results in Table 1 show that when robot 9 is considered as a keystone, the reliability of the system is increased. Then, maintenance department should concentrate more on this robot for more system availability.

The decomposition method is used when the system in in network configuration.

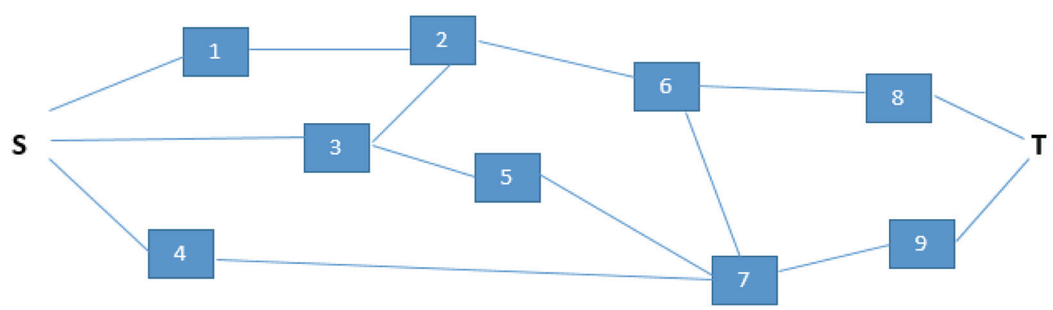

Fig. 1. Configuration of the system understudy

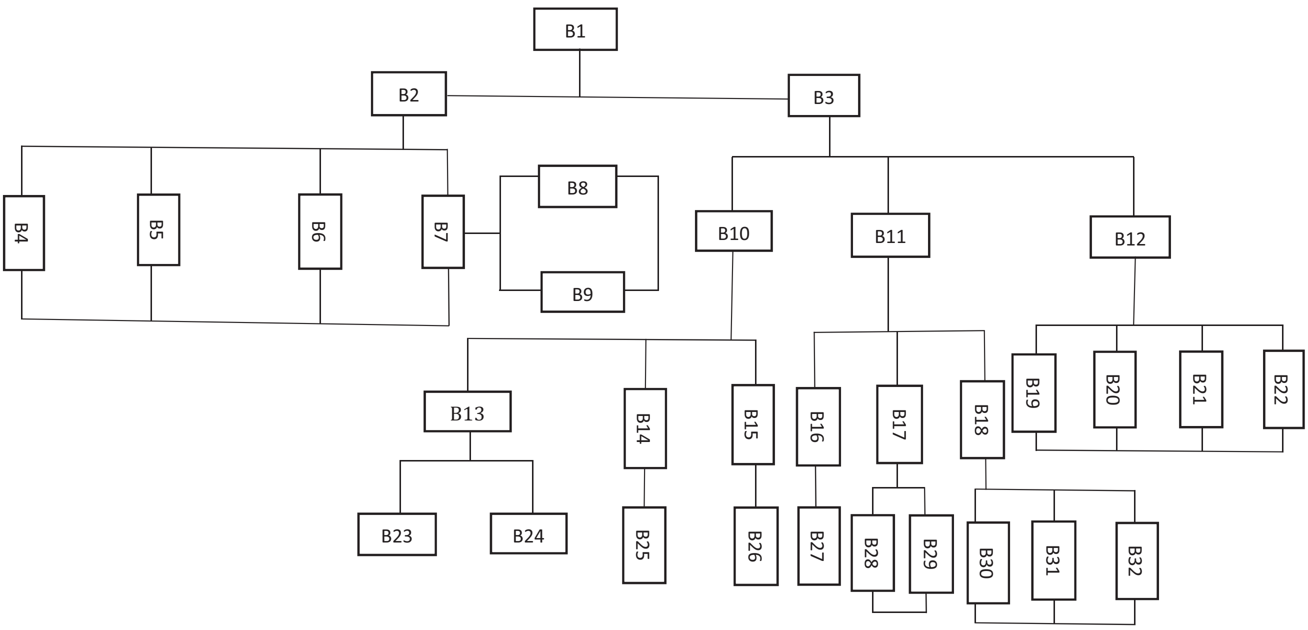

Figure 2. Reliability block diagram

Now, consider a system having the following reliability block diagram shown in Figure 2.

Also, the block diagram coding is presented in Table 2.

Table 2. Block diagram coding

B1	Fails in dispatching
B2	Failure in allocation
B3	Condition met for failure in dispatching
B4	Sending false command from system
B5	Failure of reflecting control system
B6	Failure of emergency stopping system
B7	Locking of the holding system
B8	Failure of the protecting system
B9	Failure of the electrical system
B10	Robot mechanical parts failure in dispatching
B11	Robot input and control failures in dispatching
B12	Loss of power supply
B13	Drive unite (brushless DC electric motor failure)
B14	Brake system failure
B15	Steering failure
B16	Laser navigation system failures
B17	Robot software control system failure
B18	Safety system failure
B19	Over heat
B20	Electrical charge
B21	Leakage
B22	Performance degeneration
B23	Motor temp
B24	Humidity
B25	Depreciation
B26	Failure of the network
B27	Failure in connections
B28	P.L.C connection to other components
B29	P.L.C control system fail
B30	Failure of the system processor hardware
B31	Failure of the communicating system
B32	Failure of the protecting system sensors

According to the block diagram of a 9 robot system, the reliability of the whole system is computed using minimal path and cut. Initially, the existing minimal paths are determined (according to definitions given in section 2.2). Note that L_j implies robot *j*th.

Path 1: $\{L_1, L_2, L_6, L_8\}$;
Path 2: $\{L_3, L_5, L_7, L_9\}$;
Path 3: $\{L_4, L_7, L_9\}$;
Path 4: $\{L_3, L_2, L_6, L_8\}$;
Path 5: $\{L_3, L_2, L_6, L_7, L_9\}$;
Path 6: $\{L_1, L_2, L_6, L_7, L_9\}$.

In identifying the minimal paths it should be noted that the robot movement is unidirectional. Then the proposed structure function is,

$$\begin{aligned} &\Phi(I_1,\ldots,I_9) = \\ &= \Phi(I_1I_2I_6I_8,\, I_3I_5I_7I_9,\, I_4I_7I_9,\, I_3I_2I_6I_8,\, I_3I_2I_6I_7I_9,\, I_1I_2I_6I_7I_9) = \\ &= I_1I_2I_6I_8 \cdot I_3I_5I_7I_9 \cdot I_4I_7I_9 \cdot I_3I_2I_6I_8 \cdot I_3I_2I_6I_7I_9 \cdot I_1I_2I_6I_7I_9 = \\ &= I_1I_2I_3I_4I_5I_6I_7I_8I_9 \end{aligned} \tag{6}$$

While robots are only in two states of active and fail then *I*s just take values 0 or 1. So, the reliability of the system is,

$$R_{SYS}=R_1R_2R_6R_8 \,.\, R_3R_5R_7R_9 \,.\, R_4R_7R_9 \,.\, R_3R_2R_6R_8 \,.\, R_3R_2R_6R_7R_9 \,.\, R_1R_2R_6R_7R_9 = R_1R_2R_3R_4R_5R_6R_7R_8R_9 \quad (7)$$

Since we consider homogenous robots having similar reliability, the reliability of the systems is,

$$R_{SYS}= (0.845)^9= 0.22.$$

Now, the cut paths are determined using the block diagram. Cut paths are the ones that are failed when all components on them are failed. The cut paths are listed below:

$\{L_1,L_3,L_6\}$; $\{L_1,L_3,L_7\}$; $\{L_2,L_3,L_4\}$; $\{L_2,L_3,L_7\}$; $\{L_2,L_5,L_4\}$; $\{L_2,L_5,L_7\}$; $\{L_6,L_3,L_4\}$; $\{L_6,L_3,L_7\}$; $\{L_6,L_5,L_4\}$; $\{L_6,L_5,L_7\}$; $\{L_6,L_9\}$; $\{L_8,L_9\}$; $\{L_2,L_9\}$; $\{L_7,L_8\}$.

Then, the corresponding structure function is,

$$\phi(I_1,\ldots,I_9)= \phi(I_1I_3I_6, I_1I_3I_7, I_2I_3I_4, I_2I_3I_7, I_2I_5I_4, I_2I_5I_7, I_6I_3I_4, I_6I_3I_7, I_6I_5I_4, I_6I_5I_7, I_6I_9, I_8I_9, I_2I_9, I_7I_8)= [1-(1-I_3)(1-I_1)(1-I_6)] \,.\, [1-(1-I_3)(1-I_1)(1-I_7)] \,.\, [1-(1-I_2)(1-I_3)(1-I_4)] \,.\, [1-(1-I_2)(1-I_3)(1-I_7)] \,.\, [1-(1-I_2)(1-I_5)(1-I_4)] \,.\, [1-(1-I_2)(1-I_5)(1-I_7)] \,.\, [1-(1-I_6)(1-I_3)(1-I_4)] \,.\, [1-(1-I_6)(1-I_3)(1-I_7)] \,.\, [1-(1-I_6)(1-I_5)(1-I_4)] \,.\, [1-(1-I_6)(1-I_5)(1-I_7)] \,.\, [1-(1-I_6)(1-I_9)] \,.\, [1-(1-I_8)(1-I_9)] \,.\, [1-(1-I_2)(1-I_9)] \,.\, [1-(1-I_7)(1-I_8)].$$

and the reliability of the system is,

$$R_{sys}=(R_1R_3R_6, R_1R_3R_7, R_2R_3R_4, R_2R_3R_7, R_2R_5R_4, R_2R_5R_7, R_6R_3R_4, R_6R_3R_7, R_6R_5R_4, R_6R_5R_7, R_6R_9, R_8R_9, R_2R_9, R_7R_8)= [1-(1-R_3)(1-R_1)(1-R_6)] \,.\, [1-(1-R_3)(1-R_1)(1-R_7)] \,.\, [1-(1-R_2)(1-R_3)(1-R_4)] \,.\, [1-(1-R_2)(1-R_3)(1-R_7)] \,.\, [1-(1-R_2)(1-R_5)(1-R_4)] \,.\, [1-(1-R_2)(1-R_5)(1-R_7)] \,.\, [1-(1-R_6)(1-R_3)(1-R_4)] \,.\, [1-(1-R_6)(1-R_3)(1-R_7)] \,.\, [1-(1-R_6)(1-R_5)(1-R_4)] \,.\, [1-(1-R_6)(1-R_5)(1-R_7)] \,.\, [1-(1-R_6)(1-R_9)] \,.\, [1-(1-R_8)(1-R_9)] \,.\, [1-(1-R_2)(1-R_9)] \,.\, [1-(1-R_7)(1-R_8)].$$

where the numerical value of reliability is obtained to be 0.8741.

4. Conclusions

In this paper, two methods were adapted to evaluate the reliability of a complex system includig robots in a production system. The proposed model considered binary state robots that are functioning as material handling devices in a production system. In this approach, the reliability block diagram was presented, based on which the structure of robots were determined. Then, using decomposition and minimal paths and cuts methods the reliability of a complex system was computed. As for future research directions the following can be pointed out:

- Considering multiple state system of a robot instead of using a binary state;
- State transition consideration in modelling and evaluation of reliability for the proposed robotic system;
- Developing a predicitve maintenance plan in parallel with relaibility evaluation.

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