ARTICLE IN PRESS

Mechanical Systems and Signal Processing xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Enhance GO methodology for reliability analysis of the closed-loop system using Cyclic Bayesian Networks

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ARTICLE INFO

Article history:
Received 29 June 2016
Received in revised form 19 August 2017
Accepted 4 October 2017
Available online xxxx

Keywords:
Closed-loop system
GO methodology
Reliability analysis
Cyclic Bayesian Networks

ABSTRACT

GO methodology is a success-oriented method for reliability analysis of complex safety critical system, which existing in various fields, such as aircraft carrier, nuclear plant, petrochemical plant, etc. However, the traditional GO methodology is insufficient in modeling the system with feedback signals, which are common in those systems. The challenge lies in modeling the closed-loop feedback process and its algorithms. To address this issue, an approach based on Cyclic Bayesian Networks (CBNs) is presented in this paper to enhance its capability of feedback modeling. In the approach, Type 9 operator is the key element to be introduced to simulate a component with feedback signal, and then the GO model can be cyclic to represent a system with feedback loops; furthermore, we compare the decision capability of the GO and BN methodologies in dynamic structure and uncertainty handling. Considering the complexity of the analysis of the GO method, the cyclic GO model is mapped to its corresponding CBNs according to some mapping rules. And leveraging matured algorithms and toolkit of BNs, we can not only obtain the probability of each node in each state via failure propagation, but also identify critical events given the event occurrence via backward reasoning. Eventually, a case of chemical treatment tank liquid level controlling minus-feedback system is analyzed to demonstrate the approach's feasibility, and by enhancing the capability with loop structured system modeling, the approach makes GO methodology more practical in more modern complex engineering systems with feedback loops.

1. Introduction

In recent years, the importance of reliability analysis in the industrial field has significantly increased and several reliability analysis techniques [1–4] have various systems. Among these, GO method [5], with its characteristics of the intuitiveness and visibility, has been extensively employed in industrial fields, such as aircraft carrier, nuclear energy plant, petrochemical plant, etc. In GO method [6,7], the operators represent components or logical relationship in a system, which can be connected by the signal- flows. In this regard, GO model could be established by the system schematic diagram smoothly; in addition, GO model can also provide rich reliability information through the modeling process, i.e. all signal flow probabilities in each state, system success or failure probabilities.

In practical engineering, feedback control is very common. A typical example exists in nuclear power plants, in which the electricity of sub-systems is fed by mainline system [8,9]. Generally, the closed-loop or feedback system is defined as one

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https://doi.org/10.1016/j.ymssp.2017.10.006
0888-3270/© 2017 Published by Elsevier Ltd.

system where the controlled output signal is measured and fed back by the control computation. Moreover, a control system is required to respond to the given inputs and initial conditions by a controlled manner. Meanwhile, the design of the reliability and stability can obviously have a great impact on the control efficiency.

Unfortunately, analyzing the reliability of these feedback control systems are not supported by the well accepted classical reliability analyzing methods, such as RBD, FTA and traditional GO [6], which can only model the static dependency of a system rather than dynamic relations between components, for instance the specific closed-loop feedback dependency. Thus, previous literature has attempted to develop efficient ways for analyzing of reliability for the closed-loop system. Many researchers have tried to break the logical loops and develop new logic without loops in the condition of the relatively weak dependencies among the support system [10,11]. The authors have also proposed using the GO-FLOW method for breaking the logical loop [12,13]. Another method was to a designing method for patterns of-recursive program transformation [14]. Recently, an exact method for solving logical loops by using Boolean algebra [8,15] has been pointed out in reliability analysis. However, among these researches there is a lack of research on reliability directly according to the established model of the closed loop. To our best knowledge, Yi, Xiaojian created a new operator to describe the closed-loop feedback link [16]. Nevertheless, introducing external operators usually increases the complexity of programming and configuration. Hence, the primary goal of this paper is to enhance the GO model to support the closed-loop systems by introducing the inherent Type 9 operator. This method can solve the reliability analysis on the system with feedback signals, and ulteriorly consummate the GO theory and arithmetic.

However, the application of the enhanced GO model introducing the Type 9 operator is still constrained in the analysis process. In GO method, the original quantification algorithm combines all signal states by calculating joint probabilities, making the process of calculation very tedious and time-consuming. Furthermore, the state-space explosion may occur especially for the time-sequential problem and the multiple state problem. On the other hand, Bayesian Networks (BNs) [17–20] increasingly used in reliability analysis, especially for updating the prior probability of known variables given new evidences. As the well-studied statistical tool in probabilistic systems, BNs (Pearl, 1988) [21] is originated in the field of artificial intelligence and used as a robust and efficient framework for reasoning with uncertain knowledge. BNs is a directed acyclic graph in which discrete random variables are assigned to each node, as well as the arcs which signify direct dependencies between the linked nodes and the conditional dependence on the parent nodes. The inclusion of the local dependencies in a BN can avoid a complete state-space description for a large scale system, which makes it an appealing method for reliability analysis. So far, the combination of BNs and other approaches have attracted widespread attention. Bobbio [22], Boudali and Dugan [23], Montani [24], and Khakzad et al. [25] showed how to convert fault trees (FTs) into BNs. Other relevant works have been done by mapping event trees into the BNs [26]. Sklet [27], Nivolianitou [28], and Weber [29] qualitatively compared the BNs with other methods such as FTs, event tree, and Petri nets for accident analysis in different areas. Most recently, Liu, Y. X [30] proposed that any T-S fault tree can be directly mapped into a BN by the fuzzy possibilities. Therefore, the two approaches of GO and BNs should be combined to improve the efficiency of the reliability analysis for a complicated system. On the other hand, BNs is initially used in the open-loop systems, however, some specific areas including closed-loop systems have not been thoroughly investigated. For this reason, an approach based on Cyclic Bayesian Networks (CBNs) [31] is presented to enhance GO method's capability of modeling and analyzing of complex closed-loop systems.

The main contributions of this paper are summarized as follows: (1) At modeling level, by improving the type 9 operator, we increase the ability to describe the feedback and make no effect to the former structure, which make it convenient for analyst to comprehend and model a system with feedback loops; (2) At the algorithmic level, the Cyclic Bayesian Networks (CBNs) aren't merely the previous hierarchical modeling, but creatively proposed the new Cyclic Bayesian Networks (CBNs) based on the Dynamic Bayesian Networks (DBN), and we introduce the mapping rules of convert cyclic GO model to its corresponding Cyclic Bayesian Networks (CBNs). Concerning the matured algorithms and analysis software of BNs, we can easily obtain the system failure information and the posterior marginal probability distribution. Moreover, BNs are becoming widely used for dependability and uncertainty analysis, which ensures the CBNs with good adaptation for complex closed-loop system.

This paper is organized as follows. A brief introduction of the GO methodology and the cyclic GO model with closed-loops is presented in Section 2. Section 3 briefly explains the characteristics of BNs, the mapping relations with GO methodology, and research of CBNs. Subsequently, Section 4 described in detail the mapping procedure from enhanced GO model to Cyclic Bayesian Networks (CBNs). Section 5 validates the effectiveness of the proposed method with the example of chemical treatment tank liquid level controlling minus-feedback system. Finally, Section 6 full text summary of research work, proposes the recommendations for the future work.

2. Reliability analysis based on GO methodology

2.1. GO methodology

GO methodology [32] is a method of system reliability with success-oriented. The GO model is composed of operators and signal-flows, and the operators represent components or logical relationships in the system and the signals represent connections between the components. In GO model, there are 17 kinds of operators [5,33] shown in Fig. 1. All operators, which