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A novel Real-Time Continuous Fuzzy Fault Tree Analysis (RC-FFTA) model for dynamic environment

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ABSTRACT

The purpose of this study is to provide a real-time continuous fuzzy fault tree analysis model for dynamic environment to prevent undesired events in the complex, vague, complicated, and uncertain systems. In fault tree analysis methods, occurrence probability of an undesired event (i.e. marine accidents) is computed by using statistical, extrapolation, and expert judgement methods . In the proposed method, instant data is received by sensors, run through the algorithms, and the probabilities of risk occurrence are computed continuously. Real-time sensor systems (Automatic radar plotting aid radar, bridge navigational watch alarm system, etc.) of a ship are used to validate this model by analysing the fault trees of collision and grounding. The tests prove that this model is successful for handling the trade-offs and providing continuous improvement.

1. Introduction

Fault tree analysis (FTA) is a risk assessment tool for the fields of risk, safety, and reliability (Vesely et al., 1981). A fault tree (FT) is constructed in the FTA method, which includes several parallel and sequential combinations. Gates take a significant role for connecting the events with each other. Failure rates or failure probability can be assigned as crisp or fuzzy values to the predefined basic events (BEs), and then, occurrence probability of an undesired top event (TE) is found by conducting both qualitative and quantitative evaluations (Stamatelatos and Caraballo, 2002). In the conventional fuzzy extended FTA (FFTA) approach, the input data in the FFTA studies are assigned by considering the experiences on past failures (Mahmood et al., 2013; Ding et al., 2014; Mhalla et al., 2014). For example, Mentes and Helvacioglu (2011) declare that human judgment is a requirement in offshore operation processes, if there exists no observed data of system 10 behaviour, especially in many cases where it is difficult to determine the occurrence probability in an objective manner. Then, they conduct surveys and interviews with the experts and the personnel responsible for mooring operations. Similarly, in the study of Lavasani et al. (2015a), the occurrence possibilities for the basic events (BEs) of leakage in abandoned oil, as natural-gas wells are assigned to three experts. Each expert has a weight factor and they assign linguistic expressions to the corresponding BEs by considering previous failures. Same approach is applied for the most of the FFTA applications such as chemical cargo contamination, Arctic marine accidents, etc. (Senol et al., 2015; Kum and Sahin, 2015; Ferdous et al., 2009).

This study proposes a RC-FFTA model which handles real-time continuous input data. Since the conventional FFTA methods deal with obtaining the failure possibilities of BEs, the proposed model suggests obtaining the failure possibilities of Bes when combined with their impacts on the TE. In other words, it computes the failure probabilities of BEs and TE.

In the literature, semi-quantitative approaches are mostly used for FFTA applications. Failure probabilities of BEs are employed quantitatively and the consequences are determined qualitatively by applying decision-making methods, such as analytic hierarchy process, etc. (Hyun et al., 2015; Abdelgawad and Fayek, 2012; Purba et al., 2010). As a novelty, this study provides a combination of occurrence probabilities of each BE and the consequence of the whole system.

RC-FFTA model is used for a dynamic environment, in which parameters such as speed, distance, meteorological conditions, etc. communicate directly through the algorithm. RC-FFTA provides a visual logic for using the sensors in an FT and contributors, leading to the time when TE are prioritized. Thus, RC-FFTA is used as a proactive tool to prevent TE. Performance of the system can be monitored as well. For instance, deviations from the intended route for a vessel moving ahead can be observed instantaneously. Besides, costs and resources can be optimized by controlling the impacts of contributors to the TE. It can also be used as a diagnostic tool through contingency analysis and repair times in order to control the risks. Moreover, the RC-FFTA model can be re-designed in case of a need to fulfil

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performance requirements. This work seems to be the only study in the literature that considers the RC-FFTA model where instant data are transferred from the sensors through some particular BEs.

Since this model is applicable for all vehicles, machines or systems in a dynamic environment, the subject of our study is to calculate the probabilities of grounding and collision for a ship that differs considerably from that of the conventional FTA applications, as our work explicitly incorporates sensor systems and algorithms. Therefore, input data flow is directly and continuously realized. According to the statistics of UNCTAD Secreteriat, the total fleet in the world has reached to 1749222 dead-weight tonnage, with total of 89564 ships (United Nations Conference on Trade and Development, 15.11.2015). 90% of the world transportation is conducted through ocean going vessels, which are the most significant actors in the world economy (Yan et al., 2014). Prevention systems for the ships are of significance because marine casualties are highly expensive (Sahin and Kum, 2015). The authors also point out the different variants for the connection of BEs by considering collision and grounding. The algorithm and methodology presented in this work can be utilized for all other safety, risk, and reliability issues.

2. Methodology

International Organization for Standardization (ISO 31000 - Risk management) describes risk as "Risk has consequences in terms of economic performance and professional reputation, but there are also environmental, safety and social considerations" (ISO, 2009). FTA is a risk assessment tool that identifies the root causes of unwanted incidents (Goodman, 1988). Marine accidents involve lots of possible qualitative or/and quantitative combinations of factors such as human errors, normal events and component events. The risks of an undesired event are determined by its frequency combined with impact of an event in a given period of time.

A FT is usually initiated with a TE which is followed by a number of gates and BE (Iverson et al., 2001). Mostly, critical events such are chosen as a TE. The causes for each occurrence of events are divided into the branches in a stepwise approach. The assessment maintains at each level, until the root causes or assessment boundary conditions are reached. The basic root causes are not required a further development. Root causes are shown with symbol of a circle (Stapelberg, 2008).

Principally, "OR" and "AND" gates are used as logical operators in the FT schematics. The output of the AND gate depends on any of the input events occur. This means AND gate is an intersection of sets containing all input events. One of the input event directly influence the output of the OR gate. This means OR gate is an union of the sets containing all input events (Stapelberg, 2008). Fig. 1 shows the logic symbols of the FT analysis below.

Fault Tree Analysis is developed into six steps (Dhillon, 2008):

Step 1 Defining the problem and boundary conditions. Explaining the criticality of the TE with the physical borders, beginning conditions and limitation of external loads.
Step 2 Constructing the Fault Tree Analysis model. Description and assessment of the failure events.
Step 3 Establishment of the minimal cut sets (MCSs) and path sets.
Step 4 Qualitative analysis of the FT.
Step 5 Quantitative evaluation of the logic model. Probability of the TE and reliability of the BEs.
Step 6 Reporting the results.

2.1. Notation and quantification of the probability of the logic gates

Let $Q_0(t)$ is the probability of the TE occurs at time t, $q_i(t)$ probability of the BE i occurs at time t. $Q_0(t)$ is the probability of the minimal cut set j fails at time t. Let stands for the BE i occurs at time t.

2.1.1. AND gate

Let $q_1(t) = P(E_i(t))$ for i=1,2. TE probability $Q_0(t)$ is

$$Q_0(t) = P(E_1(t) \cap E_2(t)) = P(E_1(t) \cdot E_2(t)) = q_1(t) \cdot q_2(t) \tag{1}$$

If there is a single AND gate with n events;

$$Q_0(t) = \prod_{j=1}^{n} q_j(t) \tag{2}$$

2.1.2. OR gate

Let $q_1(t) = P(E_i(t))$ for i=1,2. TE probability $Q_0(t)$ is

$$Q_0(t) = P(E_1(t) \cup E_2(t)) = P(E_1(t) + E_2(t) - E_1(t) \cap E_2(t))$$
$$= q_1(t) - q_2(t) - q_1(t) \cdot q_2(t) = 1 - (1 - q_1(t)) \cdot (1 - q_2(t))$$

If there is a single OR gate with n events;

$$Q_0(t) = 1 - \prod_{j=1}^{n} (1 - q_j(t)) \tag{3}$$

2.1.3. Cut set assessment

A minimal cut set fails if all r BEs fails simultaneously. The probability of the cut set j fails at time t is

$$\phi_j(t) = \prod_{i=1}^{n} q_{j,i}(t) \tag{4}$$

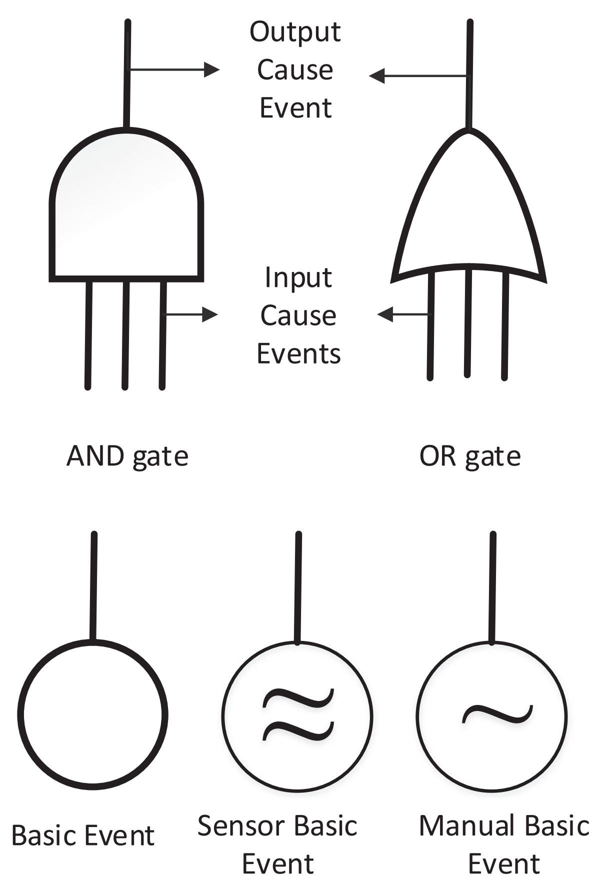

Fig. 1. The symbols of a FT.