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A risk-informed ship collision alert system: Framework and application

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ABSTRACT

Ship collisions are rare occurrences with a potential to cause significant human, monetary and/or environmental loss. One element in preventing collision accidents is the presence of a collision alert system (CAS), providing warnings to ship crews and/or personnel in Vessel Traffic Services of the collision risk in a real-time operational environment. In risk research, there is a recent focus on foundational issues related to risk concepts, perspectives and methods for describing risk, with calls for work addressing these risk-theoretical issues in application areas. Despite several proposed applications for CAS, no frameworks covering these risk-theoretic issues have been presented. Hence, the purpose of this paper is twofold. First, a framework for maritime risk-informed CAS (RICAS) is presented, including a risk-conceptual basis, a systematic description of the risk perspective and a discussion on the intended use of the risk model. A theoretical framework for the operationalization of the construct "ship collision risk" is presented, and a method for measuring this construct is introduced. Second, the framework is applied to a case-study concerning open sea navigation. An evaluation of the proposed RICAS in comparison with earlier proposed CAS methods indicates an improved performance over these.

1. Introduction

Ship collisions remain a concern for safe navigation and marine environmental protection, especially in busy waterways and sensitive sea areas (Lehikoinen et al., 2013; Qu et al., 2011; Wang et al., 2014). Various countermeasures exist to support collision prevention, including training tools (Chauvin et al., 2009), technology for maritime surveillance (Bukhari et al., 2013) and for integrated navigation support services (Hänninen et al., 2014).

Several studies have shown that human error, and lack of situational awareness in particular, are important factors contributing to collisions (Chauvin et al., 2013; Gale and Patraiko, 2007; Grech et al., 2002). A collision alert system (CAS) enhances situational awareness of ship officers or Vessel Traffic Service (VTS) personnel, aiding operational decision making. A recent analysis has shown that implementing an enhanced CAS in a VTS center may be a cost-efficient risk-reducing measure (Lehikoinen et al., 2015).

The most widely used CAS is the Automatic Radar Plotting Aid (ARPA). This technology tracks several targets and displays proximity indicators used for operational risk assessment. ARPA also includes a CAS, requiring two input values: limits for the Distance at Closest Point of Approach ($DCPA_{lim}$) and the Time to Closest Point of Approach ($TCPA_{lim}$) (Chin and Debnath, 2009).

The ARPA CAS has several drawbacks. First, there are no commonly agreed settings for the limiting values. Second, ARPA alarms sound frequently during normal navigation, causing nuisances as these are often perceived as unnecessary. This relates to the fact that ARPA only relies on DCPA and TCPA, while the same values for these indicators can, depending on e.g. relative bearing and heading, lead to a different risk interpretation and need for action. Consequently, some officers set $DCPA_{lim}$ and $TCPA_{lim}$ at zero,

Abbreviations: AHP, analytic hierarchy process; AM, ambiguous encounter; ARPA, automatic radar plotting aid; BCR, bow cross range; BCT, bow cross time; BK, background knowledge; BSQ, background situational quality; CAS, collision alert system; CI, consistency index; COLREG, International Regulations for Preventing Collisions at Sea; CR, crossing encounter; DCPA, distance at closest point of approach; *R*, risk; *E*, event; ECDIS, electronic chart display and information system; ECM-I, encounter classification model I; ECM-II, encounter classification model II; FES, fuzzy expert system; FSQ, foreground situational quality; HO, head-on encounter; INS, integrated navigation systems; MF, membership function; OS, own ship; OT, overtaking encounter; QRA, quantitative risk assessment; RICAS, risk-informed collision alert system; RNG, range; SF, safe situation; SQ, situational quality; SS, system state; TCPA, time to closest point of approach; TS, target ship; TSS, traffic separation scheme; VTS, vessel traffic service.

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effectively switching off the CAS (Baldauf et al., 2011). Third, ARPA alarms are not informative in special operations such as convoys through ice fields. Finally, in special situations, ARPA can raise an alarm only when collision is unavoidable. This is illustrated in Video 1, which shows a radar sequence of a vessel transiting the Singapore Straits (Pahdi, 2011), with settings $TCPA_{lim}$ = 2 min and $DCPA_{lim}$ = 0.3 nm. Following events are of interest. 13:09: one target in close range to starboard is tracked. 13:13: alarm sounds. 13:35: target vessel overtaking on starboard side of own vessel makes a sharp turn to port. 13:38: own vessel initiates a turn. 13:40: own ship starts turning and alarm sounds. 13:42: a collision occurs.

A number of CAS methods have been proposed, in line with developments in e-Navigation (Patraiko et al., 2010). Hilgert and Baldauf (1997) propose heuristic criteria to categorize collision risk, refined by Baldauf et al. (2011) with fast time simulation techniques. Kao et al. (2007) and Wang (2010) propose fuzzy ship domains. Lee and Rhee (2001), Ren et al. (2011) and Bukhari et al. (2013) propose fuzzy systems. Mou et al. (2010) apply dynamic adjustment factors to a baseline quantitative risk assessment. Chin and Debnath (2009) propose a CAS based on ordered probit regression modeling.

In risk and safety research, there is a recent focus on foundational issues (Aven and Zio, 2014; Le Coze et al., 2014), with calls for devising frameworks for risk-informed applications, focusing on issues such as how to understand and describe risk, and on suitable methods for measuring risk.

For policy-oriented maritime transportation risk analysis, focusing on effects of countermeasures on risk and/or its geographical distribution, some theoretical frameworks exist, based on system simulation (Harrald et al., 1998), traffic conflict technique (Debnath and Chin, 2010) or Bayesian Networks (Montewka et al., 2014; Goerlandt and Montewka, 2015a). However, no theoretical frameworks for CAS applications have been proposed, explicitly focusing on the risk-theoretical issues intended by Aven and Zio (2014). Goerlandt and Kujala (2014) furthermore identified a need for conceptual frameworks for understanding the ship–ship encounter processes and its relation to collision risk. Despite the various developed CAS applications, no such frameworks have been proposed.

In light of the above, the aims of this paper are twofold. First, a framework for risk-informed maritime CAS (RICAS) is proposed, useful for developing CAS applications for different navigational environments and in specific operations such as convoy navigation in ice. The framework includes a risk-theoretical basis (Section 2), an analysis of the construct "ship collision risk", relating the encounter process with the risk perspective (Section 3), and a method for measuring this construct (Section 4). Second, the framework is applied and a RICAS is proposed for open sea navigation (Section 5). A discussion is made in Section 6. Section 7 concludes.

2. Risk-theoretical basis

In devising a risk framework, a distinction needs to be made between risk as a concept and the measurement of risk, which requires the formulation of a suitable risk perspective. Additionally, the intended use of risk assessment in decision making needs consideration (Aven and Zio, 2014). The first two issues are considered in this section, the use of the risk model is elaborated upon in the discussion (Section 6.3).

2.1. Risk concept: how risk is understood

There are various definitions of and philosophical positions related to the risk concept. Definitions typically involve constituents as probability, uncertainty, possibility, scenarios, events, consequences and/or expected values (Aven, 2012). Diverse philosophical positions relate to one's position on the realist–constructivist continuum, i.e. whether risks are considered realities, existing in a world independent of an assessor, or whether risks are thought constructs, inherently tied to an assessor (Goerlandt and Montewka, 2015b; Klinke and Renn, 2002; Shrader-Frechette, 1991).

The following conceptual definition is adopted: risk is a concept used to refer to the possible but uncertain occurrence of a situation where something of human value is at stake. For further clarifying our understanding of risk and for providing a background for the applied risk perspective and intended risk model use, some characteristics are briefly considered.

First, conceptualizing risk as above results in the understanding that risk has no ontology but rather is of a cognitive nature (Solberg and Njå, 2012; Thompson, 1986).

Second, taking possibility as a fundamental component of risk implies that statements about risk are tied to an assessor and thus subjective (Solberg and Njå, 2012). Hence, a constructivist understanding of risk is adopted, further implying that the risk analysis does not describe a "true", mind-independent risk, but a reflection of somebody's mental construct (Shrader-Frechette, 1991; Goerlandt and Montewka, 2015b).

Third, the risk concept involves the concept of a situation, which can be understood as a contextual whole, consisting of a set of circumstances. Situations have a complex structure, including a focus, foreground, background and horizon (Brown, 2012). Situations include objects, events, agents, their relations, the background on which all these appear, and a qualitative experienceable unity. The risk concept can be seen as a tool for focusing on specific events in relation to their environing situation.

Fourth, risk is action-oriented and often related to a decision (Aven, 2009; Thompson, 1986). Depending on the decision context, the risk concept is used to either focus on the occurrence of the event, on the consequences if this event occurs, or on both. In maritime CAS, focus is on accident prevention and thus avoidance of the event occurrence. Consequently, risk assessment focuses on the possibility of occurrence rather than on the possible consequences.

2.2. Risk perspective: how risk is described

Understanding risk as above, the adopted risk perspective is addressed, i.e. the systematic approach to describe risk. This can be summarized as (where "$\sim$" signifies "is described by"):

$$R \sim I(SQ(SS)) \rightarrow E \mid BK \quad (1)$$

Risk R is described by indicator I, reflecting an interpretation of the possible occurrence of an event (E), based on a mental projection (denoted "$\rightarrow$") in light of a number of situational qualities (SQs). These qualities are in themselves interpretations based on observable system states (SSs). Both the interpretation of SSs as SQs and the interpretation I based on SQs are based on a background knowledge (BK). This perspective is well suited for operational settings, where risk is continuously assessed in changing conditions. Some characteristics of the indicator as a measurement tool are considered, focusing on the intended application for CAS.

First, the constructivist basis of the risk indicator is elaborated on. Fundamental in interpretation risk is a mental projection of a possible future system state, based on an evaluation of the current situation, assuming that the future will evolve from the present with some continuity. This interpretation (i) relates the SQs to the imminence of the event occurrence, (ii) follows from an appreciation of a deviation from what is considered a reference