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Ship domain applied to determining distances for collision avoidance manoeuvres in give-way situations

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ABSTRACT

Ship domain is often used in marine navigation and marine traffic engineering as a safety condition. The basic idea behind those applications is that an encounter of two or more ships can be considered safe if neither of ship domains is intruded by other ships. Research utilising this approach has been documented in numerous works, including publications on optimising collision avoidance manoeuvres performed to fulfil domain-based safety conditions. However, up to this point there has been no method, which would apply ship's domain to determine the last moment when a particular collision avoidance manoeuvre can still be successfully performed. This issue is addressed here. The proposed method uses a model of ship's dynamics to assess the time and distance necessary for a manoeuvre resulting in avoiding domain violations in give-way situations. The model and the method are described in detail and illustrated in a series of simulation results. The simulations cover full spectrum of typical give-way encounters in various circumstances: head-on, crossing and overtaking situations; manoeuvres limited to course alteration and those combining turns with speed reduction; open or confined waters and finally – in good and restricted visibility.

1. Introduction

A ship domain has been first introduced in (Fujii and Tanaka, 1971), where it has been defined as "*a two-dimensional area surrounding a ship which other ships must avoid*". Ever since then, ship domain concept has been used in maritime research, including recent applications to various traffic engineering-related problems: waterway capacity analysis (Liu et al., 2015), waterway collision risk analyses (Goerlandt and Kujala, 2014; Goerlandt and Montewka, 2015; Qu et al., 2011; Weng et al., 2012) and AIS-based near-miss detection (van Iperen, 2015; Wu et al., 2016; Zhang et al., 2016; Van Westrenen and Ellerbroek, 2017). However, it is collision avoidance that is arguably main purpose for ship domain's development (Pietrzykowski, 2008; Pietrzykowski and Uriasz, 2009; Hansen et al., 2013; Wang and Chin, 2015; Szlapczynski and Szlapczynska, 2017) and, as evidenced by some works, it still remains its important field of application (Szlapczynski, 2008; Lazarowska, 2016). Those applications of ship domain are based on the assumption that an encounter of two or more ships can be considered safe if neither of ship domains is intruded by other ships. However, up to this point there has been no method, which would combine ship's manoeuvrability and ship's domain to determine the last moment when a particular collision avoidance manoeuvre can still be successfully performed. This issue is addressed in the hereby paper. The presented method uses a model of ship's dynamics to assess the time and distance necessary for a manoeuvre successful in terms of avoiding domain violation. The method is inspired by action area presented in (Dinh and Im, 2016), critical range and time researched in (Hilgert and Baldauf, 1997) and critical distance introduced in (Krata and Montewka, 2015) and later extended in (Krata et al., 2016).

The rest of the paper is organized as follows. Related works and method's genesis are discussed in Section 2. The method is outlined in Section 3, which also includes description of its key algorithms. The applied ship dynamics' model is given in Section 4. Section 5 provides results obtained for an example ship. These results cover typical ship encounters in various circumstances: head-on, crossing and overtaking situations; manoeuvres limited to course alteration and those combining turns with speed reduction; open or confined waters and finally – good and restricted visibility. Results are discussed in Section 6, followed by the summary and conclusions given in Section 7.

2. Related works and the current method's genesis

Most of collision avoidance research is focused on manoeuvres done in advance, with enough time for optimisation (Kao et al., 2007; Tam

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et al., 2009; Tsou et al., 2010; Praczyk, 2015; Zhang et al., 2015; Tsou, 2016; Pietrzykowski et al., 2017). In comparison, there are relatively few works on when exactly a manoeuvre should be performed to achieve safe separation. The concept of an arena – an evasion area around a ship was first outlined in (Davis et al., 1980) and later developed in (Colley et al., 1983). Close quarters term was defined in (Hilgert, 1983), where the author observed that COLREGS (Cockcroft et al., 2012) do not give specific distances, where an evasive action is necessary. Such limit values, at which the navigator has to order the evasive actions were determined in (Hilgert and Baldauf, 1997) and the approach presented there was later applied in an on-board Manoeuvring Support System (Baldauf et al., 2014). Similarly, in (Zhang et al., 2012) a study on minimum distance for escape action was presented, based on an analysis of an encounter scenario. Following this, in (Dinh and Im, 2016) a combination of analytical approach with utilising expert navigators' knowledge was applied to determine a ship's action zone. However, the limitation of the above research was either the limited number of encounter scenarios taken into account or simplified modelling of ship's manoeuvres. Those limitations were overcome in (Krata and Montewka, 2015). Those authors were interested in determining the last moment, when collision could still be avoided by manoeuvres of the own ship alone. Their research involved a detailed analysis of the own ship's evasive action, which included precise prediction of the own trajectory based on the manoeuvrability parameters. The method was further extended in (Krata et al., 2016), where, among others, stability issues were taken into account (avoidance of excessive heel) (Matusiak and Stigler, 2012). The final result of both versions of this method was a critical distance between the own ship and a target ship determined for a given encounter situation. This critical distance represented the last moment when a manoeuvre had to be performed to avoid collision. The method was dedicated to situations, when the own ship was a stand-on one, which generated some additional assumptions. Among others, a resulting, near-zero separation between ships was assumed there for simulations. In practice, a manoeuvre would have to be initiated earlier (sometimes much earlier) if a larger ship separation is supposed to be kept.

The current paper is inspired by (Krata and Montewka, 2015) and the works of their predecessors, but the central idea of that paper is here combined with a ship domain model: we are interested in a distance and time to potential collision, which still make it possible to avoid violation of a specified ship domain. Additionally, the collision avoidance action is supposed to fulfil a number of configurable conditions dictated either by COLREGS or by a navigator. For a given encounter situation a considered turn should:

- be made to starboard or port only, depending on the particular encounter and visibility conditions,
- not exceed a given angle of rudder.

3. The method's overview

Contrary to (Krata and Montewka, 2015; Krata et al., 2016) the current method is mostly dedicated for situations when own ship is the give-way ship. While COLREGS specify what action should be taken depending on the encounter type, it is up to the navigator of the own ship to decide when exactly to perform a manoeuvre. This decision may depend on the intended separation, which is represented here by a ship's domain.

A scheme of the method's main algorithm, is given in Fig. 1. The method applies a degree of domain violation (DDV) – a parameter indicating to what extent a ship's domain will be intruded during a close quarters situation (Szlapczynski and Szlapczynska, 2016).

In brief, the method works as follows. It reads the necessary input parameters and detects potential domain violations. If a domain violation is predicted based on the current data, the encounter situation is classified and the action type is chosen. For a chosen action type and

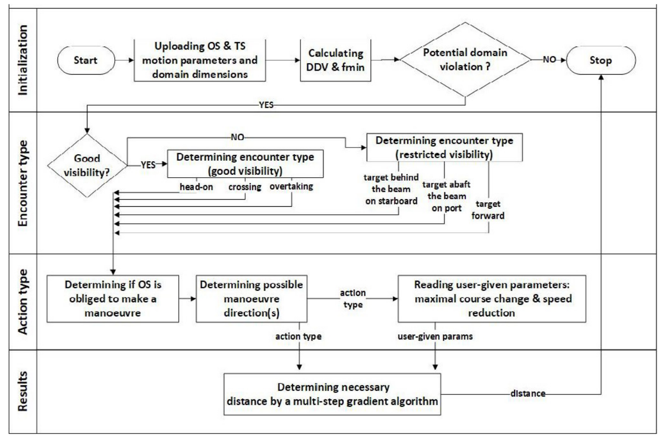

Fig. 1. A method determining time and distance necessary for avoiding domain violations.

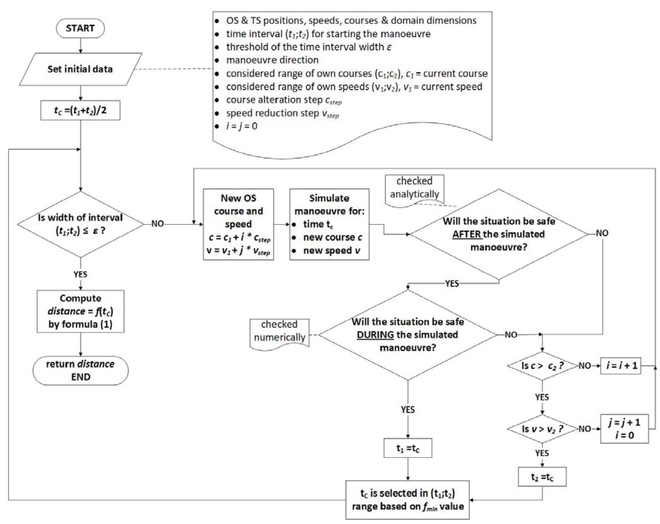

Fig. 2. A multi-step gradient algorithm determining safe time, at which a manoeuvre should be initiated.

auxiliary user-specified parameters, the method determines the time for initiating the manoeuvre by means of a gradient algorithm, which is shown in Fig. 2.

The gradient algorithm (Fig. 2) works as follows. At first a set of initial parameters is read, comprising of both ship parameters (including positions, speeds and courses and threshold for the time range ε) and action type parameters (including manoeuvre direction and ranges of considered course and speed alterations). Then a candidate time t_c is introduced and initialized. The algorithm detects potential domain violations of a manoeuvre initiated at time t_c. Domain violations are checked during and after performing the manoeuvre. Because the latter might be done analytically (meaning faster computations), “after manoeuvre” check is performed before “during manoeuvre” check. Depending on whether the manoeuvre done at t_c is safe or not, the considered time range is narrowed up to or down to t_c. A new t_c value is then selected from the updated (t_1,t_2) range based on the results of domain violation check and the simulation is repeated. The algorithm ends, when the range $(t_1;t_2)$ gets smaller than the threshold value ε. Once the action time t_c is determined (Fig. 2), the action distance is computed according to formula (1) and returned by the algorithm:

$$d(t_c) = \sqrt[2]{V_r t_c + 2\left(V_{r_x} X_r + V_{r_y} Y_r\right) t_c + X_r + Y_r} \tag{1}$$

where: