Collision Avoidance Road Test for COLREGS-Constrained Autonomous Vehicles*

Kyle L. Woerner, Michael R. Benjamin, Michael Novitzky, and John J. Leonard

***Abstract*— Recently developed algorithms quantify and subsequently evaluate COLREGS performance in collision avoidance scenarios based on vessel track data. Combining these evaluation algorithms with proposed categories of COLREGS rules allows for testing of collision avoidance performance in accordance with protocol requirements. This paper proposes a “road test” framework for autonomous marine vehicles prior to operating outside of a testing environment. Testing and certifying agencies may adopt the proposed categories of scope and testing attributes while determining the appropriate parameters for evaluation. Adapting the evaluation criteria to several thresholds would allow for various levels of certification and locally-tailored customs. Generalization to human operators and other domains such as Rules of the Air is proposed.**

I. INTRODUCTION

Collision avoidance protocols such as the Collision Regulations (also referred to as COLREGS or Rules [2]) are written primarily for human operators resulting in a rule set that is open to some interpretation, difficult to quantify, and challenging to evaluate. The continuing migration toward autonomous collision avoidance has resulted in numerous implementations of the Rules with varying degrees of fidelity as well as large variations in authors’ real-world experience using the Rules. Prior to operations outside of a testing environment, algorithms and vessels should be evaluated for both compliance with the Rules and safety.

Recently developed COLREGS evaluation algorithms allow quantifiable and objective assessment of autonomous and human-operated vessels maneuvers for the Rules of the Road [1]. A ship’s COLREGS compliance may now be tested, evaluated, and validated using only the vehicle track data of each encounter. To allow autonomy designers to more objectively claim compliance with the written Rules and maritime customs, this paper establishes and preliminarily develops a COLREGS-based collision avoidance “road test” for autonomous marine vehicles. Figure 1 demonstrates example protocol compliance evaluation during on-water experimentation with both autonomous and human-operated vessels.

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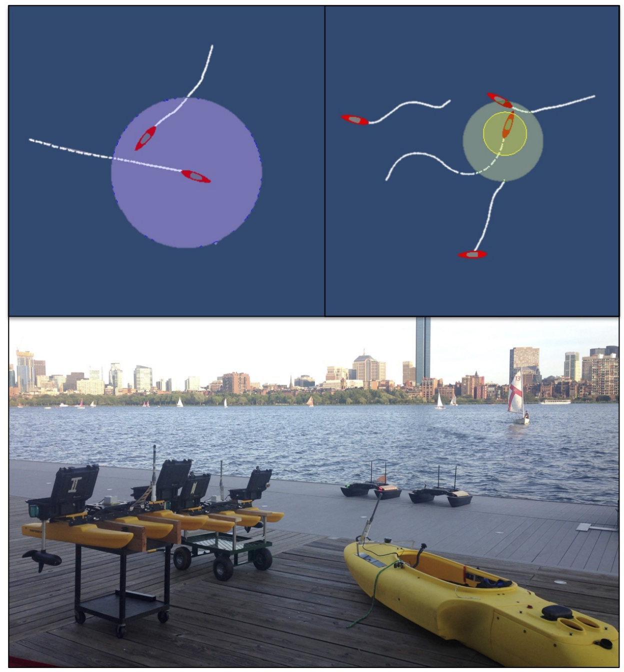

Fig. 1. Autonomous surface vessels were evaluated using the COLREGS collision avoidance protocol rules with both real-time and post-mission analysis tools using a common library of configurable metrics. Using significant at-sea experience, US and international case law, and case studies of past collisions, an evaluation library was created to quantify claims of COLREGS “compliance” within appropriate categories of scope. Both rule violations (top left) and safety violations (top right) were reported as part of the evaluation. On-water testing of M100 and M200 Clearpath® autonomous marine vehicles with a human-operated MOKAI® motorized kayak (bottom) allowed for human-robot interactions and multi-vehicle, multi-rule simultaneous encounters for testing the evaluation programs. Using quantifiable metrics for evaluating these categories of COLREGS compliance, a first-iteration “road test” for protocol-constrained collision avoidance is proposed for certifying autonomous marine vehicles to operate at sea in the vicinity of human-present vessels.

II. COLREGS COMPLIANCE IN THE LITERATURE

Collision avoidance protocols are prevalent in many physical domains where explicit negotiation or communication is either impractical or infeasible. In common practice, these protocols are often communicated simply as having “right of way.” In ground transit, drivers are taught to yield to the driver on the right when arriving simultaneously at an intersection with stop signs [3]. Airplanes use the Rules of the Air to determine right of way and appropriate maneuvers when not under active control of an air traffic controller [4]. Surface vessels similarly abide by the COLREGS to determine right of way and appropriate maneuvers without ex-

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plicit communication [2]. Special rules within each protocol have evolved from real-world feedback; one such example is the traffic separation schemes of COLREGS when entering or exiting a harbor [5], [6]. While the Rules of the Air and COLREGS are largely similar, differences in the physical domains manifest as differences between the collision avoidance protocol requirements such as maintaining altitude separation.

Collision avoidance using COLREGS has been incorporated on autonomous vessels using various approaches since first introduced in [7]. Throughout maritime literature discussing COLREGS, the term "compliance" arises in varying context and meaning. Compliance, however, lacks objectivity partly due to the inherent vagueness of the COLREGS and partly due to the varying scope of many solutions. This intentional vagueness allows the human operator liberty to interpret the vast array of complex collision avoidance scenarios without being overly restricted from a common sense yet safe approach.

Power-driven collision avoidance implementations of COLREGS (Rules 13-18) dominate the COLREGS-related literature. Other non-collision avoidance rules of COLREGS arise as claiming compliance within the literature when discussing light configurations [8]. The varying scope of what authors claim as compliant largely depends on the scope of interest of a particular researcher. The notion of compliance, however, should be amplified with the applicable scope of the COLREGS.

Testing to date in the literature fails to demonstrate what the term compliance means in any quantifiable fashion for the collision avoidance section of the rules. Several authors claim compliance with these protocols without specifying the degree or scope of compliance [9], [10], [11]. In [9], the head-on rule was shown to appropriately eliminate all turns to port. It did not, however, appear to prefer courses that were "readily apparent" (COLREGS Rule 8) when finding a turn to starboard. Case law defines apparent course maneuvers to consist of a minimum of 35° turn while common practice often requires no less than 30° of heading change [5], [12], [13], [14]. Courts have found that head-on maneuvers with insufficient turns (i.e., not readily apparent) are in fact non-compliant and, when a collision occurs, partly to blame. With velocity vector cost functions that favor maintaining course and speed [9], improper selection of costing weights may result in less than apparent course changes. Other authors consider breaches of COLREGS that "may be in the USV's best interest" such as turning to port to avoid a collision when explicitly prohibited by the COLREGS [10]. Many authors such as [11] simply claim COLREGS compliance without any quantification or definition of scope.

The inconsistency of authors' claims of COLREGS compliance likely results from a combination of three factors including:

- the vagueness of the rules,
- the unspecified scope of each author's work, and
- the tacit assumption that the COLREGS rules as written fully encompass all collision avoidance requirements.

Case law and common practice greatly influence the requirements of COLREGS despite not being found anywhere within the written rules. Examples of on-water collisions and case law provide relevant insight into nuances of the COLREGS and their evolution over the years. Areas for increased scrutiny in autonomous collision avoidance solutions can be derived from problematic past encounters of human ship drivers. The intentional vagueness of the COLREGS including their underlying meaning as derived from the evolution of protocol-constrained collision avoidance in maritime environments, analysis of real-world examples, critiques of experienced mariners, and relevant rulings from Courts of Admiralty are presented in detail in [5], [6], [12], [15], [16].

A further complicating factor results from the disconnect between experienced mariners and autonomous designers. Few designers of marine autonomous collision avoidance algorithms have demonstrated significant experience using COLREGS in open ocean navigation for non-academic purposes or incorporated an experienced operator into the algorithm design and testing process.

III. Approach

In order to certify autonomous vessels and their collision avoidance algorithms for use outside of a dedicated testing environment, this paper proposes an examination framework comprised of a comprehensive scope of quantifiable metrics of performance. Evaluators may therefore assess the baseline level of knowledge, skills, and practical demonstrations necessary to certify an autonomously operated vessel to safely operate in the vicinity of other vessels. This is similar to a human obtaining their drivers license for operating a car.

Proposed evaluation categories include general rules, conduct of vessels, responsibilities in sight, restricted visibility, lights and shapes, sound and light signals, inter-vehicle communications, and cumulative performance [1]. To be compliant with COLREGS, a satisfactory level of performance must be met across each category of evaluation. Local customs may be achieved by using a collision avoidance protocol evaluation library consisting of tunable penalty and reward functions for each rule. A tunable collision avoidance protocol evaluation library was first presented in [1].

This paper proposes several categories of scope as a first pass means of grouping similar research and subsequent evaluation. With the development of metrics and evaluation techniques within each category of scope, performance can be reliably demonstrated to a certifying body to a required degree of satisfaction within each given category. A means would then exist to properly combine work of differing categories to produce more fully compliant solutions.

With the methods of this paper, conversations in future literature can be more exact in their meaning of compliance in protocol-constrained collision avoidance research. The scope of this road test framework includes:

- the identification of various categories for collision avoidance evaluation,

- assignment of appropriate COLREGS rules into their respective categories, and
- introduction of evaluation techniques for both human operators and autonomous collision avoidance algorithms based on admiralty case law and on-water experience.

IV. Discussion

A. Lexicon

Discussion of vehicles not completely controlled by a human present onboard in real-time often take various names with ambiguous, inconsistent titles such as “unmanned” or “drone”. Vehicles generally have three major parameters that may define their state for the purposes of discussion: human presence, element of control, and physical domain.

Human presence defines whether humans are onboard regardless of their contribution, if any, to the vehicle’s control. Human presence represents a binary state that may change over time – even during a single underway in the case of boarding a pilot for a return to port. The element of control is defined on a spectrum of human controlled to fully autonomous where it is understood that this is often neither a discrete nor permanent state.

Finally, the physical domain specifies the type of environment in which the vehicles operate (e.g., sea surface, submarine, aerial, ground, etc.). For the purposes of COLREGS road tests, this paper assumes vessels operating on the sea surface with or without human presence. While developed for the purpose of evaluating autonomous vessels of varying degrees of the element of control, the road test concept may be applied to human operators as well – whether present on the vessel or operating remotely.

B. Categories for COLREGS Scope

Collision avoidance compliance in the most general sense involves maneuvering one’s vessel to properly interact with a contact for a given initial geometry. In domains that require a protocol-based solution, specific vehicles assume the roles of stand-on or give-way depending on their geometric, propulsion, and operating conditions relative to the other. A stand-on vessel is generally required to maintain her course and speed consistent with reasonable navigational requirements as though the contact were not present (e.g., slowing to board a pilot) [5], [12], [16]. The give-way vessel similarly yields right of way to the stand-on vessel. The geometric, propulsion, and operating conditions used to determine stand-on and give-way assignments include relative geometry (e.g., being overtaken, holding a vessel off her starboard side, etc.), propulsion state (e.g., under sail, power-driven, etc.), and operating state (e.g., engaged in fishing, restricted in ability to maneuver, etc.).

To counter the disparity between compliance claims and actual performance, scope may be compartmentalized to allow quantification and certification within similar areas of requirements. COLREGS rules may therefore be separated into categories to allow a vehicle to demonstrate compliance of appropriate COLREGS subsets. International Maritime Organization guidance, US Coast Guard’s local issuance of inland-specific requirements, and other local guidelines can be adopted as appropriate to supplement or alter these testing areas.

The categories proposed to define scope of work within the international COLREGS and compliance thereof are listed in Table I and include:

- general requirements of vessels including Rules 1-3
- conduct of vessels in any condition of visibility including Rules 4-8
- special cases for channels and separation schemes including Rules 9-10
- conduct of two sailing vessels in sight of one another and operating under Rule 12
- general vessel encounters including conduct of vessels in sight of one another and operating under Rules 13-17
- responsibilities of vessels in sight of one another as exhibited in Rules 11 and 18
- conduct of vessels in restricted visibility under Rule 19
- lights and shapes required of vessels under Rules 20-31
- sound and light signals required of vessels under Rules 32-37
- inter-vehicle communications to include sending, receiving, interpreting, and appropriately acting on messages to/from other vessels or third parties (e.g., USCG district)
- cumulative performance of the above categories to ensure a satisfactory holistic approach to safe navigation and collision avoidance

TABLE I. **Categories of Scope for COLREGS Compliance Evaluation**

I	**General Rules (Rules 1-3)**
II	**General Conduct of Vessels (Rules 4-8)**
III	**Special Traffic Schemes (Rules 9-10)**
IV	**Sailing in Sight of Another Sailing Vessel (Rule 12)**
V	**Vessel Encounters in Sight of One Another (Rules 13-17)**
VI	**Responsibilities in Sight of One Another (Rules 11, 18)**
VII	**Restricted Visibility (Rule 19)**
VIII	**Lights and Shapes (Rules 20-31)**
IX	**Sound and Light Signals (Rules 32-37)**
X	**Inter-vehicle Communications**
XI	**Cumulative Performance Including Local Customs**

Rule categorization allows one designer to claim compliance within one or more categories (for example, maneuvering requirements of power driven vessels) while deferring evaluation of rules related to other areas (for example, sound identification and response) to other authors. By defining the scope of applicable rules and demonstrating quantifiable levels of compliance within each category of rules, autonomous collision avoidance algorithm designers can more exactly articulate their contributions to the literature. It should be noted that evaluation within the scope of one category may rely on compliance of another category to some degree. For example, because Category II includes maintaining a lookout, determining safe speed, determining risk of collision, and taking action to avoid a collision, it heavily influences evaluation of Categories III-VII.

V. ROAD TEST FRAMEWORK

In order to certify autonomous collision avoidance algorithms for on-water use outside of a testing environment, vehicles should complete a road test comprised of a comprehensive scope of examination using quantifiable metrics of performance. To be compliant with the appropriate protocol rule set, a satisfactory level of performance must be met across each category of evaluation as defined in Table I. Differing degrees of road tests may be possible for various operational levels of certification. A nominal road test consists of satisfactorily obtaining passing scores for all applicable categories of scope identified in Table I as set by the appropriate certification authority.

A. *Collision Avoidance Algorithm Examination*

Sections of the road test that require involvement of the collision avoidance algorithms should include detailed examination of the following:

- determination of obligations and governing rule(s) for both ownship and the contact for various geometric configurations at time of visual or radar detection
- determination of appropriate precedence (e.g., sailing vessels, etc.)
- determination of role hierarchy when nested rules apply (e.g., ownship overtaking a vessel that is already overtaking a third (slower) vessel)
- identification of redundant contacts and performing contact fusion
- releasing priority for contacts past CPA and opening or otherwise no longer posing a risk of collision (e.g., agreement or signalling of right-of-way passage)
- verification of unsaturated CPU loading for up to N-simultaneous contacts, where N is set by the certification authority

B. *Attributes of the Road Test*

To ensure a sufficiently robust algorithm for on-water interactions with other vessels, the road test should incorporate the following attributes:

- non-canonical and reasonably exhaustive geometries (thorough geometric testing approaches such as the iterative geometric testing of [17] are encouraged)
- multi-vehicle, multi-rule scenarios
- conflicting simultaneous collision avoidance rules
- conflicting mission, rule, and navigational priorities
- various initial ownship and contact speeds
- non-compliant contacts (delayed / insufficient action or entirely disregarding Rules)
- over-constrained encounters
- robot-robot and robot-human interactions
- exercise of a default safe mode[1]
- statistical significance of testing encounters
- broadcasting appropriate signals (including distress) to other vessels or shoreside entities as necessary

[1]A default safe mode might represent a turn to starboard or taking all way off the vessel and sounding an appropriate signal.

C. *Multi-Vehicle, Multi-Rule Test Scenarios*

Multi-vehicle, multi-rule scenarios create situations where precedence must be determined by the collision avoidance algorithms. In some situations, an action for one vehicle of higher precedence may be an appropriate maneuver for the other vehicle as well. In other situations, action for one vehicle may directly conflict with the preferred behavior for the second if it were encountered alone. An appropriate decision, however, is required to appropriately determine which vehicle, if any, has the higher precedence or greater risk of collision. Maneuvering for a head-on vehicle while ownship is simultaneously crossing stand-on for the second contact is an example of precedence, as shown in Figure 2.

Other scenarios require cautious action such as when overtaking an already-overtaking vessel. Care must be taken to ensure no hindrance of either of the other two vessels, especially in the choice of overtaking side. Figure 3 demonstrates an example nested overtaking situation.

In situations where ownship may be overtaking another vessel and find itself simultaneously in a crossing situation, a decision must be made as to whether to safely continue the overtaking maneuver or to break off and maneuver for the crossing contact. This largely depends on collision risk, initial geometry, and subsequent assignment of stand-on or give-way responsibilities. Examples for these scenarios include Figures 4 and 5.

Crossing while simultaneously head-on presents a significant challenge to elementary collision avoidance algorithms. This geometry checks the collision avoidance algorithm to ensure that a stand-on vessel will indeed relax itself of maintaining course and speed when prudent navigation concerns warrant deviation. Example canonical situations of crossing while simultaneously head-on are shown in Figure 6 (give-way) and Figure 7 (stand-on).

A situation that accounts for both contact lumping and

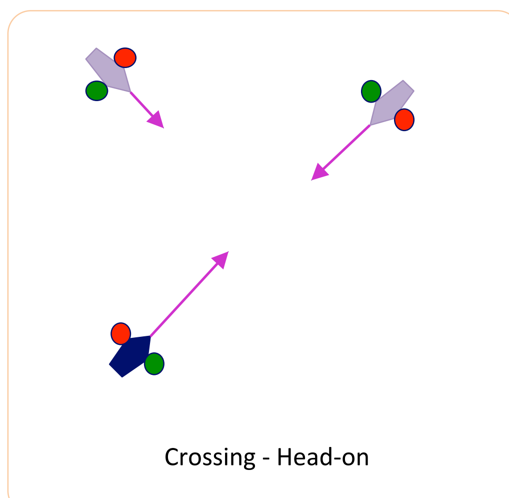

Fig. 2. When a vehicle finds itself crossing as the stand-on vessel while also head-on with a second contact, it must maneuver for the head-on vessel in a safe and prudent fashion. Ownship is the dark blue vessel.

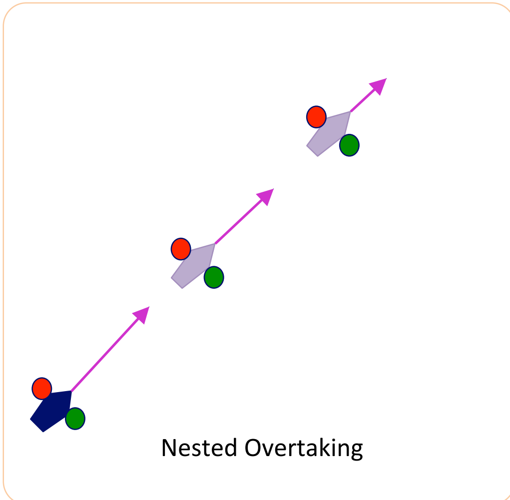

Fig. 3. Nested overtaking vessels must decide how best to safely pass without interfering with the already-maneuvering vehicles. Ownship is the dark blue vessel.

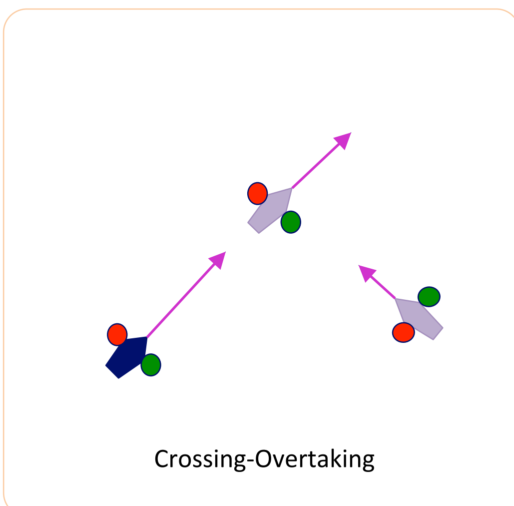

Fig. 4. Nested crossing-overtaking vessels must account for an approaching stand-on vessel while aborting or safely continuing the overtaking of the slower vessel ahead. Ownship is the dark blue vessel.

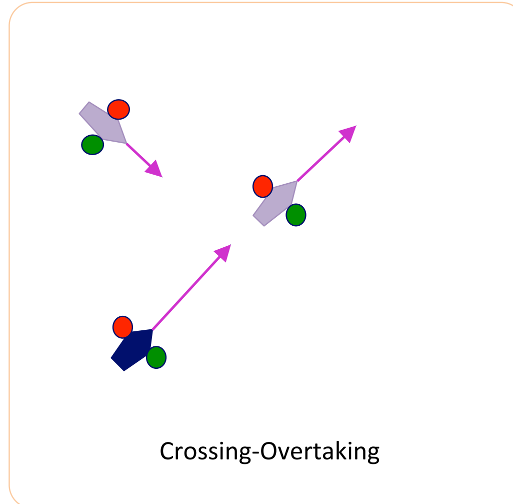

Fig. 5. Nested crossing-overtaking vessels must account for an approaching give-way vessel while likely continuing the overtaking of the slower vessel ahead. Ownship is the dark blue vessel.

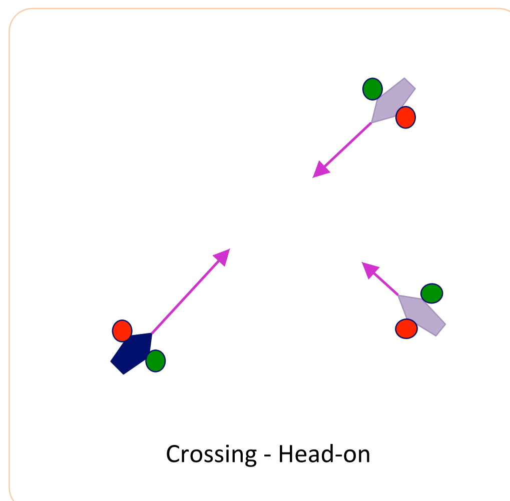

Fig. 6. When a vehicle finds itself crossing as the give-way vessel while also head-on with a second contact, it must maneuver such as to take appropriate head-on action and properly give-way in a safe and prudent fashion. Ownship is the dark blue vessel.

ensuring a robust response to Rule 14 is the multi-contact head-on scenario such as the one of Figure 8. An example of a robust response to Rule 14 includes a vessel taking head-on action even if the contact is initially slightly starboard of track [5].

VI. Conclusion

The International Maritime Organization and other governing bodies may choose to include these metrics as a means to inform both regulation and policy in maritime collision avoidance protocols.

Further discussion and research is needed to fully incorporate local customs and laws within COLREGS (including U.S. Inland Rules), alternative protocols, and special arrangements such as those made by bridge-to-bridge radio.

This constitutes the first known road test framework for autonomous collision avoidance and would allow consistent testing and certification of algorithms with configurable metrics prior to fielding. Differing degrees of road tests may be possible for various levels of certification for operation including initial testing, initial fielding, supervised operations, and unrestricted operations. Performance areas, attributes, and a general framework important for a collision avoidance road test are presented. Evaluation of humans to the same standards as robots naturally extends from this paper including standardization of practical examinations throughout the maritime community.

While the motivation of these techniques applies to improvement of autonomous marine collision avoidance under

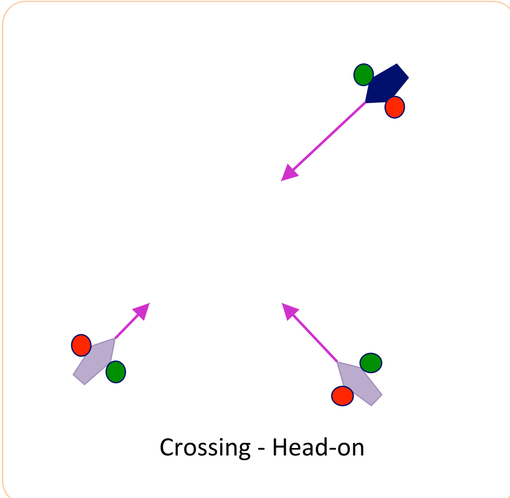

Fig. 7. When a vehicle finds itself crossing as the stand-on vessel while also head-on with a second contact, it must maneuver such as to take appropriate action for the head-on vessel. Ownship is the dark blue vessel.

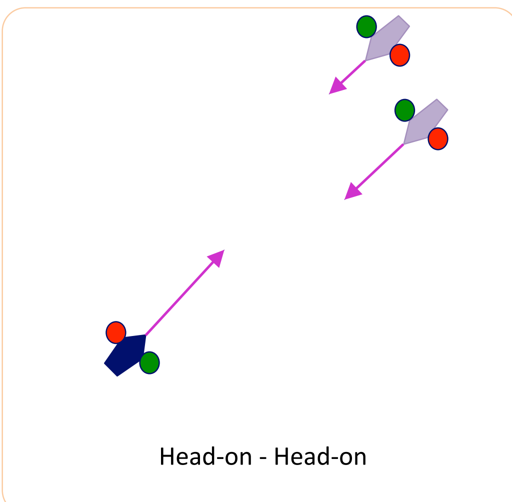

Fig. 8. Head-on encounters with a risk of collision must maneuver such as to pass port-to-port even when a contact may initially be starboard of track at time of detection. Ownship is the dark blue vessel.

the protocol constraints of COLREGS, the concepts for protocol evaluation extend naturally to alternative protocols and other physical domains with protocol constraints such as the Rules of the Air.

A. Abbreviations and Acronyms

COLREGS - international rules as formalized at the Convention on the International Rules for Preventing Collisions at Sea, developed by the International Maritime Organization, and ratified as an international treaty by Congress. These rules were further formalized by the U.S. International Navigational Rules Act of 1977 [2], and are sometimes referred to as the Collision Regulations outside the United States.

CPA - closest point of approach; point of global min. range
USV - uninhabited/unmanned surface vessel

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