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Collision Avoidance Maneuvers for Ships

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Abstract

THE STATE-OF-THE-ART in collision avoidance technology for ships consists of systems employing digital signal processors to compute ship tracks, target closest point of approach (CPA), and time-to-CPA. This information is presented to the ship's officers through CRT displays. Some systems provide a means for selecting and displaying trial-and-error maneuvers. Like the available shipboard radar systems, existing collision avoidance equipment relies heavily upon the ability of the ship's officer to process information and make decisions under conditions of severe stress.

This paper will discuss the potential use of a shipboard digital computer to compute additional information from the radar video data and generate maneuver cues as an aid in collision avoidance. Techniques for generating collision avoidance maneuvers will be related to ship maneuvering capability, as determined by its speed and turning characteristics. One example will be given to illustrate the relationship between CPA and miss distance for cooperative and uncooperative maneuvers, and another will show how dynamic maneuver charts can be used by a privileged vessel to decide when to take action to avoid a burdened vessel.

Introduction

The overall economic and environmental impact of maritime collisions is a subject of international concern. Each year, a significant number of ships are involved in accidents ranging from collisions with other ships and fixed objects, to strandings. Consequently, shipping fleets accrue enormous costs from direct damages, repairs, insurance fees, litigation, pollution, replacement, and out-of-service costs. Sophisticated collision avoidance systems for ships partially meet the needs of the maritime community in their attempts to deal with the problem of collisions. Yet the available systems have a number of limitations which restrict their utility. This paper will cite some of the major limitations of existing systems and indicate how a maneuver analysis technique may be used to address the problem.

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Maritime Collisions

A quantitative assessment of the primary causes of maritime collisions [1] indicates that about 85% of all collisions are due to faulty human judgment associated with navigational and steering errors. These statistics underscore the need for providing assistance to the ship's officer in determining the proper course for evasive action when confronted with the possibility of collision.

The International Rules of the Road [2], together with improved communication and navigation aids, are intended to prevent collisions between ships and reduce the loss of life and cargo. These rules have evolved over centuries of seamanship but have been the subject of much criticism [3–5]. Being based on a combination of traditional and technical factors, the rules of the road provide a means for judging maritime incidents in view of observed consequences, as opposed to specific, concrete recommendations for controlling ships.

In addition to the Rules of the Road, shipboard radar has also served as a valuable aid for mariners in avoiding collisions. However, the shipboard radar often requires time-consuming and confusing plotting efforts. More importantly, use of shipboard radar as a collision avoidance system relies upon the ability of the ship's officer to process raw information and make decisions under conditions of severe stress. The confusion generated by the relative motion problem, particularly when ships are maneuvering, can lead to selection of disastrous maneuvers. It is also noteworthy that use of radar as a collision avoidance system in no way exploits the known maneuvering capability of an observed target.

Collision Avoidance Systems

Maritime electronics firms have recently begun to market a variety of maritime collision avoidance systems. The more advanced systems employ sophisticated digital signal processing techniques for automatically acquiring and tracking targets. Target data is taken directly from the shipboard PPI radar for processing by the collision avoidance system. Part of the processing includes automatic generation of future tracks and computation of closest point of approach (CPA) and time to closest point of approach between own ship and all targets. This requires algorithms for estimating target speed and heading from the radar range and bearing data.

All of the available collision avoidance systems provide visual and aural alarms for alerting the ship's officer to the situation when a target CPA and time to CPA violate a preset threshold. Some systems include the capability for simulating and displaying trial maneuvers to aid the ship's officer in selecting course and speed changes to avoid collision. Visual information consisting of true or relative motion plots of ship tracks, closest point of approach and time to closest point of approach all serve as aids in this decision-making process.

The currently marketed collision avoidance systems have a number of limitations which prevent them from eliminating the problem of collisions between ships. A major disadvantage is the requirement that the ship's officer perform a trial-and-error search for an avoidance maneuver. This search may be extremely tedious when the ships are "in extremis" and the need for an avoidance maneuver is the greatest. In these situations, repreated attempts to find adequate maneuvers may be too time consuming. Like shipboard radars, the available collision avoidance systems rely upon the ability of the ship's officer to process raw information and make decisions under conditions of stress.

Another limitation of these systems is that the utility of the information presented to the ship's officer is strongly dependent on a "static" environment. CPA computations used in threat assessment are valid only under the assumption that the ship and target are on fixed courses. When either vessel is undergoing course changes, the CPA is continuously varying.

Conceptually, the existing collision avoidance equipment provides useful information when ships are on fixed courses with ample time for trial maneuver selection. Reliance is made solely upon own ship's behavior to avoid collision. A more complete approach to the problem of maritime collisions would address the possibility of both ships maneuvering, and would identify the limitations of cooperative and non-cooperative maneuvers. However, since these systems only display information and have no means for analytically identifying good maneuvers, it would likely be an additional burden for two ship officers to observe separate displays, select a trial-and-error maneuver, and execute them safely, even if direct voice communication were available.

In the absence of direct methods for computing collision avoidance maneuvers, equipment manufacturers have used the shipboard digital computer primarily to process radar data, drive the visual displays and compute straight-line trial-and-error maneuvers. The digital computer's capability for computing avoidance maneuvers, displaying avoidance maneuver cues, and/or acting as an on-line control system for the ship has not been exploited.

Collision Avoidance Maneuver Analysis

The basis for any new applications of digital computer technology to maritime collision avoidance systems will be an improved understanding of the fundamental dynamical properties of maneuvering ships. These insights would lead to distinct avoidance maneuvers depending on whether the vessel was a high speed and highly maneuverable surface effect ship or a relatively slow and less maneuverable super tanker.

Historically, the collision avoidance problem has been treated with an emphasis on using the current relative positions of ships, i.e., range and/or bearing, to determine avoidance maneuvers. As has been shown recently [6], a more complete description of an encounter between two ships must include relative speed and heading, in addition to relative position information. The relative heading, of course, is an indication of the other ship's *future* relative position. When the time-to-minimum range is appreciable, this variable has a very significant effect on the proper evasive maneuvers of the ships. Some currently recommended avoidance maneuvers are apparently based on the erroneous premise that a collision can occur *only* if the relative bearing is constant. While it is true that this condition will cause a collision, it is easy to find initial conditions for which a collision occurs despite large rates of change in bearing.

The technical and theoretical results given in [6] serve as a basis for a new approach to the collision avoidance problem. These results will be reviewed in the remainder of this section. The remainder of the paper is primarily concerned with demonstrating applications of those results to practical problems in collision avoidance.

The application of modern analytic techniques to the determination of collision avoidance maneuvers is best demonstrated by means of a simple example. Let the motion of the two ships be modeled by the assumption that the ships travel at constant speed and maneuver subject to a maximum turn rate constraint. Motion of the ships is controlled by the turn rate, which is assumed to be symmetrically bounded in magnitude. It is further assumed that all other factors limiting and influencing the motion of the ships are negligible (e.g., currents and navigation hazards).

For the purpose of analysis, it is convenient to attach a coordinate system to one of the ships and to describe the relative motion of the other. Fig. 1 illustrates the system variables when a coordinate frame is attached to ship A with the y-axis aligned with the ship's velocity vector. In this system, the relevant variables are the range (r) and the bearing (φ) from ship A to ship B, and the relative heading (θ) of ship B's velocity vector.

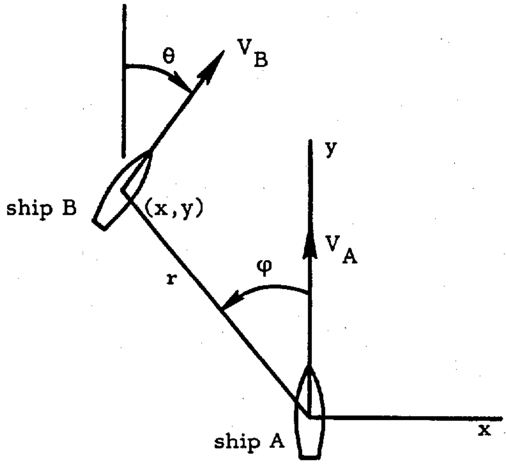

Fig. 1—Ship Encounter Geometry.

The *miss distance* between the ships is defined to be the separation between the ships when the range rate becomes zero. In this setting, an optimization problem may be formulated in which the objective is to select controls (turn rates) for each ship in such a manner that the miss distance is maximized. For ships on a fixed course, the miss distance coincides with the usual point of closest approach (CPA). For ships capable of maneuvering, the miss distance may differ greatly from the CPA, depending on the geometry.

The problem of determining turn rates which maximize the miss distance can be solved by a combination of analytic and computation methods. It is characteristic of these dynamic optimization problems that the solution produces a description of the maneuver strategies in terms of the variables in the system dynamic model. It is, therefore, convenient to work with a low order model of ship dynamics and subsequently determine the utility of the results using higher order representations of the dynamics [6].

In this example, the solution produces a description of maneuvers for ship A and ship B in terms of the range, bearing and relative heading. This solution is depicted in Fig. 2 for a particular initial relative heading of $\theta = 60°$ for two identical ships, and all distances have been normalized by the minimum turn radius of the ships.

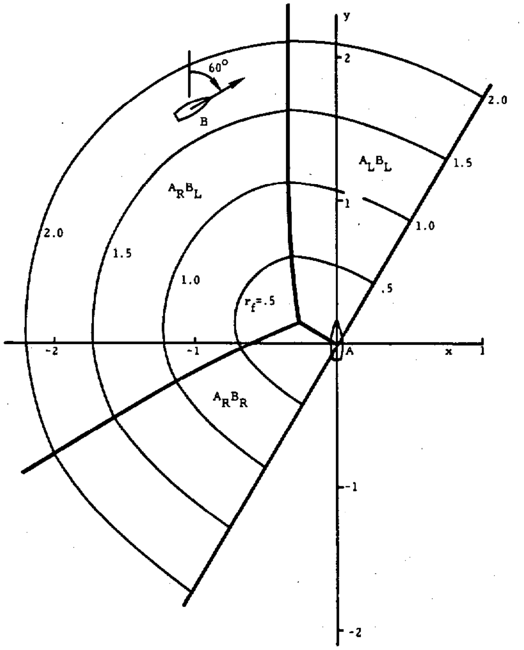

Fig. 2—Maneuver Regions for θ = 60°.

The results of Fig. 2 show for every range (r) and bearing (φ) exactly what pair of maneuvers should be executed when the relative heading is $\theta = 60°$. If maneuvers are required, either ship turns right or left with maximum turn rate, depending on their relative geometry. The heavy boundary lines define "maneuver regions" for the two ships, and it may be seen that the position plane is divided into four distinct regions. The notation A_RB_L indicates that ship A should turn right and ship B should turn left in order to maximize the miss distance. In the unlabeled region to the right of the slanted line passing through the origin, the range rate is positive, indicating that collision avoidance maneuvers are unnecessary.

The family of miss distance contours in the range-bearing plane about ship A indicate the locus of all initial conditions having a specified miss distance, denoted by r_f. For an initial relative heading of 60°, these contours indicate the maximum possible separation when the range rate vanishes, provided that both ships cooperate to maneuver. For example, any encounter initiating on the contour with $r_f = 1.0$ and $\theta = 60°$, will be such that optimal cooperative maneuvering by both ships leads to a miss distance equal to one turn radius of the ships.

Complete solution of this example problem requires identification of the optimal avoidance maneuvers for every combination of range, bearing and relative heading. The technical solution of this problem was presented by one of the authors in [6], and the results are shown in Fig. 3 for θ = 30°, 60°, 90°, 120°, 150°, and 180°. The maneuver diagrams developed in [6] are reproduced here to assist the reader who is unfamiliar with that work, and, more importantly, to support the purpose of this paper's attempt to describe practical applications for maneuver diagrams.

It can be seen in Fig. 3 that the optimal maneuvers are functions of all three system variables. That is, for a given relative range and bearing, the maneuvers are functions of the relative heading; for a fixed bearing and relative heading, the maneuvers are functions of the relative range; and for a fixed relative heading and range, the maneuvers are functions of bearing. Consequently, maneuver rules which fail to include all three pieces of information have limited utility.

Comparison of CPA and Miss Distance

Contours of CPA can be combined with miss distance contours for a given initial relative heading to obtain a more complete assessment of collision danger than can be made on the basis of CPA or time-to-CPA alone. An encounter between two ships becomes critical when the miss distance contours indicate unsatisfactory values for the final separation. In Fig. 4, with ship B navigating on the contour of CPA = 1, relative motion is on a straight line. The intersection of this straight line with the miss distance contours shows when maneuvers should be executed to achieve a pre-specified miss distance. The important distinction to be made here is that CPA is based on the assumption that the ships won't maneuver while the miss distance directly incorporates ship maneuvering capability.

Applications of Maneuver Analysis

Collision avoidance maneuver analysis provides the framework for answering the funda-

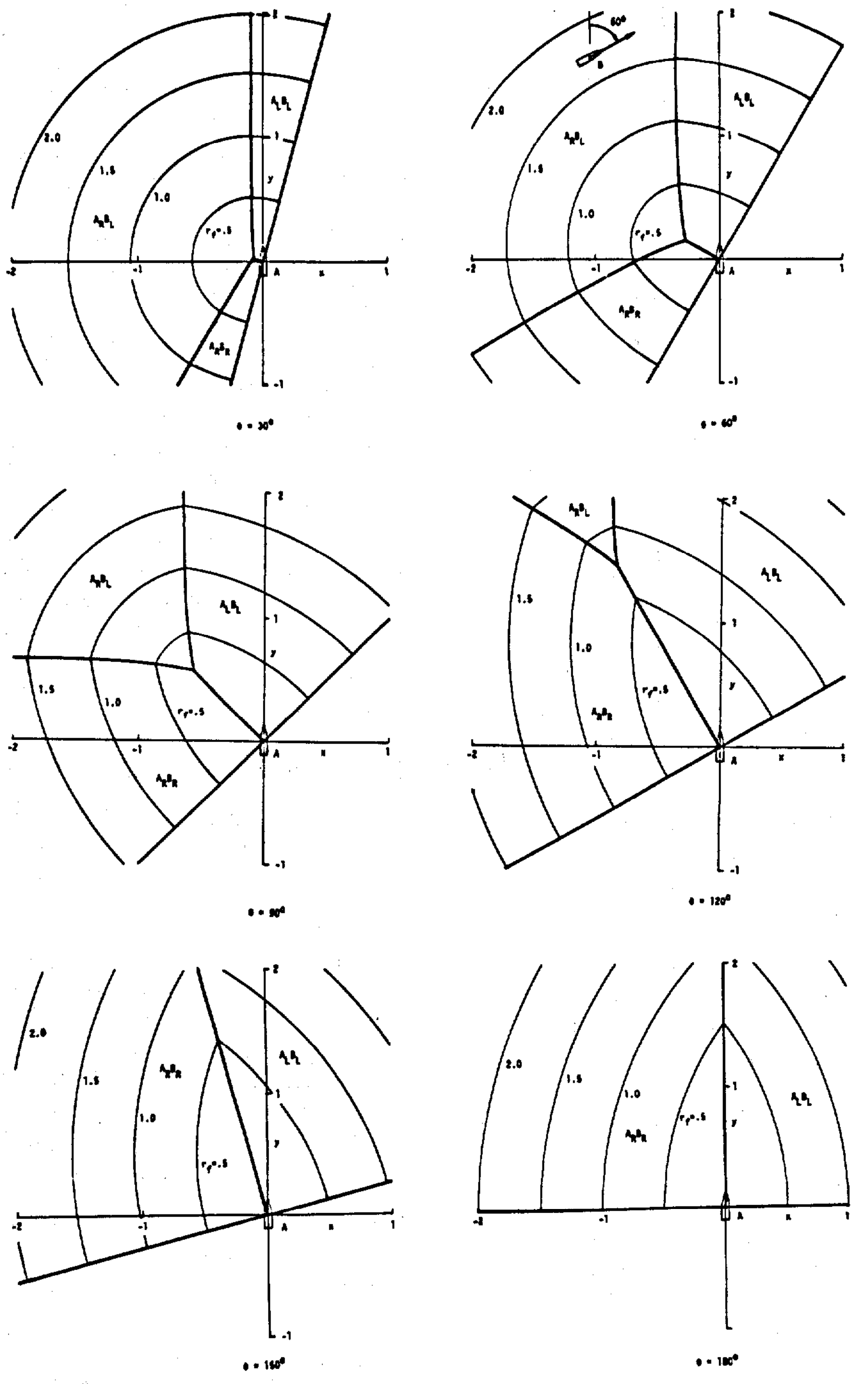

Fig. 3—Maneuver Regions for Various Relative Headings.

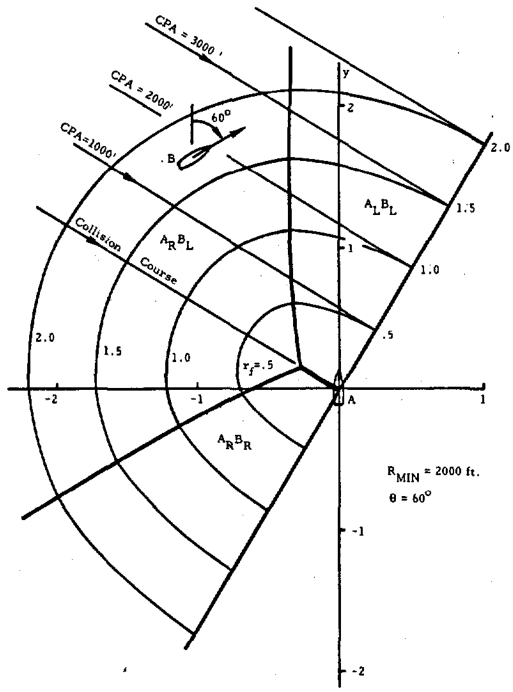

Fig. 4—Comparison of CPA and Miss Distance Contours.

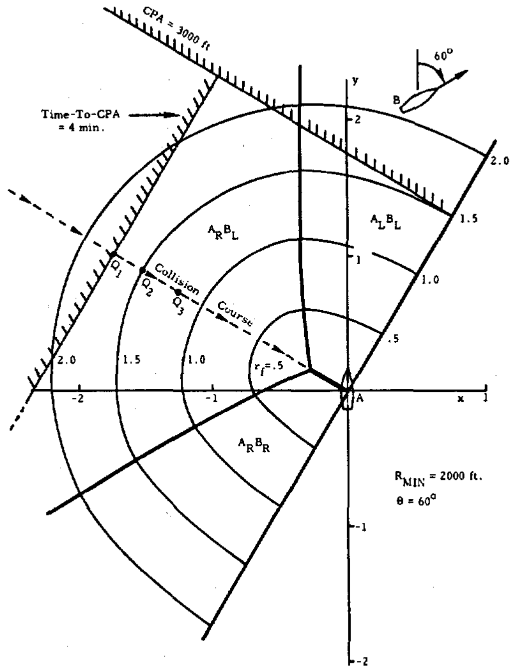

Fig. 5—Cooperative Maneuver Regions and Collision Alarm Thresholds.

mental question of determining how ships should maneuver to avoid collisions and for identifying and specifying mechanization requirements for candidate collision avoidance systems.

A shipboard collision avoidance system employing collision avoidance maneuver logic would use a digital computer to perform real time collision assessment on targets. Collision avoidance maneuver logic would process real time information on own ship's and target ship's behavior to compute collision avoidance maneuvers and generate appropriate display data. Depending on whether data exchange between ships is feasible, the maneuvers could be either cooperative or non-cooperative. The maneuvers would be displayed for use at the discretion of the ship's officer. In any event, the miss distance information would supplement the CPA information to provide more accurate threat assessment and provide guidance for setting alarm thresholds.

Combination of the shipboard computer, sensors, displays and maneuver logic would produce a system having capability to further reduce the information processing burden on the ship's officer. This would be particularly true in conditions of severe stress when human blunder is most likely. Decision aids could be provided using real time displays of miss distance and collision avoidance maneuvers.

Collision avoidance equipment usually features adjustable thresholds for CPA and time-to-CPA alarms. For the example shown in Fig. 5, alarm boundaries corresponding to a CPA of 3000 feet and a time-to-CPA of 4 minutes have been drawn for ships traveling at a speed of 10 knots and having a turn radius of 2000 feet. For a ship on a collision course (relative path passing through the origin) the miss distance that can be achieved if both ships maneuver is equal to 3500 feet (Q1). On the other hand, to achieve at least a 3000 ft. miss distance, the maneuvers must be initiated by both ships no later than 3.5 minutes before the CPA would be reached. This time is determined by the intersection of the 3000 ft. miss distance contour and the CPA contour passing through the origin (Q2). Similarly, if one minute elapses before both ships respond to the alarms and commence maneuvers, the miss distance is reduced to 2500 feet (Q3).

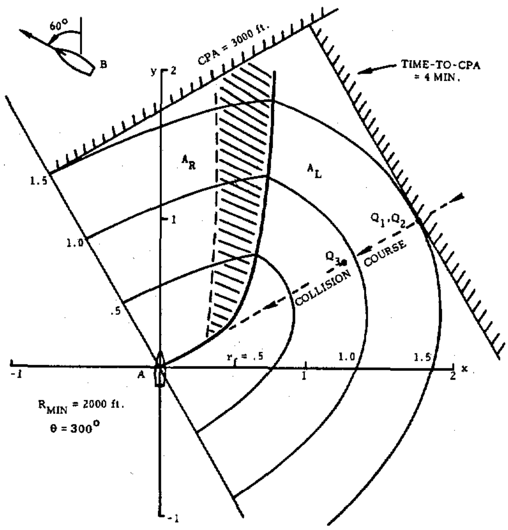

Fig. 6—Non-Cooperative Maneuver Regions and Collision Alarm Thresholds—Burdened Vessel.

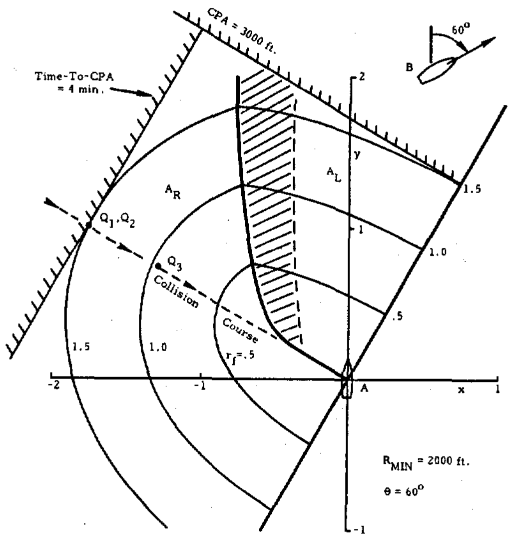

Fig. 7—Non-Cooperative Maneuver Regions and Collision Alarm Thresholds—Privileged Vessel.

Maneuver analysis techniques may be applied to the situation in which own ship is the only ship that maneuvers. Figure 6 shows the appropriate maneuver boundary and miss distance contours for all initial positions having a relative heading of 300°. The dashed line is the cooperative maneuver boundary for ship A, and the region between this line and the noncooperative maneuver boundary is where distinct maneuvers are required, depending on whether ship B is cooperating. At the alarm threshold, Q1, the miss distance is 3000 feet. To achieve a 3000 foot miss distance, the maneuver must commence immediately. If one minute elapses before the maneuver is initiated, the miss distance is reduced to less than 2000 feet. For long tankers, this margin of safety may be considered inadequate.

The maneuver region contours shown in Fig. 6 are particularly useful for assessing the threat of collision when ship A is burdened. A quick examination of B's location on the chart for a particular relative heading—be it static or dynamic—indicates whether the CPA and miss distance are satisfactory*. Given an unsatisfactory miss distance, the main contribution of the chart is that it indicates when A should maneuver and which maneuver A should make in order to maximize the miss distance. In a dynamic environment where the relative heading is not stationary, this information would be most valuable under conditions where the ship's officer must rely on radar. The maneuver chart effectively removes the confusion generated by the relative motion problem. In this case, the motion of the target would not be restricted to a set of maneuver region contours for one value of θ, but would move through the three dimensional space spanned by r, ϕ and θ. A family of charts, like those shown in Fig. 3 would be used in real time to assess the danger and determine the precise moment when the maneuver should be initiated.

A very important problem for the mariner arises in situations where own ship is privileged and it is not clear whether the burdened vessel detects the presence of the privileged vessel and intends to maneuver. Here the mirror image of Fig. 6 serves as a useful guide to help the privileged vessel decide when to maneuver. Fig. 7 shows the maneuver region, the miss distance contours, and alarm thresholds that could be used to determine when to maneuver. For example, at point Q1 the time to collision is four minutes, and the chart indicates that if the vessel

* In a dynamic situation the CPA may not be a valid measure of threat.

at Q1 fails to give way the best that ship A can achieve is a miss distance of 3000 feet, provided that the maneuver (A_R) is executed immediately. A delay of one minute results in a miss distance of under 2000 feet. By examining the burdened vessel's path across the miss distance contours (for a given CPA path) the officer of the privileged vessel has a clear and simple means for making the critical decision to maneuver out of the path of the burdened vessel.

Another noteworthy distinction between miss distance and CPA is that CPA is a measure of danger if neither ship maneuvers, while miss distance is a measure of danger that takes into account the maneuvers that could be made to avoid collision.

Comments

The example presented in this paper is simply to indicate the potential that exists in the application of maneuver analysis techniques to the problem of collision avoidance for ships. A more complete determination of the use of these techniques for nonidentical ships must be made before a full assessment of their merit can be made. Investigation of model inaccuracies and an extensive error analysis are required to substantiate the results obtained under the assumption of low order ship dynamics and perfect sensor information. Knowledge of the maneuver region behavior for various ships (cooperating or noncooperating) makes possible the examination of information requirements, sensor accuracies, and computer sizing for implementation of collision avoidance algorithms.

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