New idea about realizing automatic collision avoidance on the sea

Yao Jie　　Wu Zhaolin

(Dalian Fisheries College, Dalian Maritime University)

Summary: The rapid development of computer technology and widely application of artificial intelligent provide technology support for realizing navigation automation on the sea, which has achieved great success in shipping advanced countries like Japan, England, America, Germany and also in the developing country, China. However, it still remains in the studying period up to now in aspects of collision avoidance decision-making mathematical model and reasoning mechanism. In this paper, approaches are proposed to establish the collision avoidance automation system. One of them is based on the former studies to realize automation system by make use of finite state machine theory and following the International regulations for Preventing Collision at Sea, 1972. The others are to establish the new idea about automatic collision avoidance system by taking advantage of the free flight idea, hybrid system, game theory used in air traffic management studies in recent years and the common characteristics in both air and sea traffic management.

1. Introduction

Together with the rapid development of technology in field of navigation, GPS, GMDSS and ECIS are popularized in the bridge of ships. It enhances the safety of navigation at sea greatly and promotes the automation of shipping management and navigation. However, it still remains a long way to go for realizing automatic navigation completely. The key problem is to realize automatic collision avoidance. Since 80's of 20 century, with the development in computer technology, the studies in the field of automatic collision avoidance at sea ran into rather new stage, and great successes have been achieved in the shipping developed countries, such as Japan, Great England, US and Germany [1][2][3]. In China, studies of automatic collision avoidance system (ACAS) began in 70's of 20 century. Some achievements have been got in about thirty years in mathematical model of collision avoidance decision making, ship's domain and ACAS [4][5][6][7].

Though a lot of studies have been done by specialists and experts in domestic and abroad in the aspects of mathematical model of collision and ACAS, it does still not reach agreement in models and reasoning mechanism. Especially there are few studies in multi-ship collision avoidance comparing with the studies in the land traffic and air traffic control. William A. O'Neil[9], Secretary-General of International Maritime Organization once said in a IPS-IMO International Conference on the Malacca and Singapore Straits: 'the comparison between air traffic control and that of ship has often been made and it is accepted that there is no doubt that positive traffic control is essential in civil aviation. The principles of control exists in all other modes of transport and there is no reason for extending it to shipping, when safety would be enhanced'. In view of this, this paper tries to make use of some thinking, such as concepts of free flight, hybrid system and differential game in air traffic control in the study of ship collision avoidance automation, proposes new idea about automatic collision avoidance realization.

2. Future Sea Traffic Control System

C. Tomlin and others in the UCB [10][11] proposed a new architecture for Air Traffic Management through studying the present ATM and its facing challenge. Within the proposed ATM, the concept of free flight allows each aircraft to plan its trajectories in real time, and in the new decentralized architecture some of the current air traffic control functionality is moved on board aircraft. The hybrid control and theory of games are applied in the new ATM to make conflict prediction and generate resolutions.

J. Godhavn[12] and others proposed future Sea Traffic Management Systems (STMS) motivated by the ATMS. A hierarchical structure has to be utilized due to the high complexity with both a great number of control decisions (Discrete events) and a multiple set of low-level control laws (Continuous systems). A hierarchical control architecture for an STMS is shown in Fig.1.

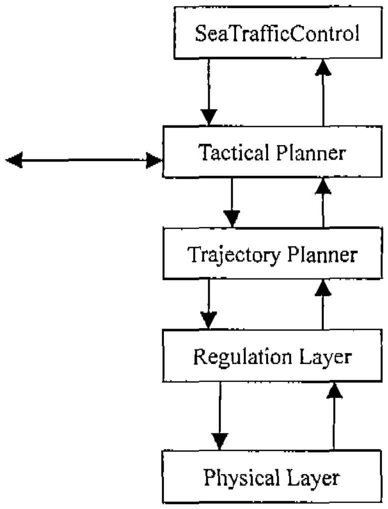

Fig.1. Architecture of STMS control

Sea Traffic Controller, on the top of the structure, is a discrete event control unit responsible for monitoring, coordination, and scheduling. Overall safety and performance is taken care of on this level. The STC monitors the motion of the ships with its own position sensors, which typically is a set of radars. The actual commands from the STC are packages with a sequence of via-points to each ship. A via-point is a set of coordinates (x_i, y_i) and a time interval $[t_{i,\min}, t_{i,\max}]$.

The second level of the STMS is a Tactical Planner. A detail tactical plan is generated from the information given by the STC. A tactical plan takes the via-points and partitions the route into segments with different control modes. Typical control modes are:

—Conventional mode: constant speed along strait lines or parts of circles .

—Speed mode: Change speed, most often during strait line motion.

—Stop-on-track mode: Stop ship and hold position.

—Come alongside quay (CAQ) mode: Special trajectories for approaching the dock.

The via-points generated by the STC have to be very dense to guarantee safety. To reduce the workload and to increase the flexibility of the system, it is desired that only a limited number of via-points be considered for regular traffic. Some rules for collision avoidance are hence necessary for the Tactical Planner. The autopilots on board should be able to detect and solve possible conflicts without involving the STC.

The third level is a Trajectory Planner. A smooth reference trajectory is generated, where performance limitations of the ship and detailed dynamical model of the ship with disturbances and input saturation limits are considered.

The fourth level is Regulation Layer. The trajectory generated on the previous level is fed to the Regulation Layer. Individual robust linear or nonlinear controllers are then applied for the fifferent control modes. Each of these controllers has its own set of active and inactive actuators and measurements.

The Lowest layer is Physical Layer. The commands are realized in this layer and the actual states of the ship feedback to the Regulation Layer through sensors and actuators.

3. Future Automatic Navigation System at Sea

In fact we can get the future Automatic Navigation System at Sea (ANSS) if we change our view of the STMS. The functions of the STC actually are the functions of the future VTS. The tasks and functions of the second layer to the lowest layer are totally the tasks and functions of the ship itself.

The major objectives of the first layer of the ANSS are to design trajectory and to resolve conflicts between ships. The objectives of the other layers are to control the ship on its designed trajectory to the destination under the condition of itself and the prevailing circumstances. Therefore, to realize the future STMS or ANSS completely, the key is to realize the automatic collision avoidance at sea.

4. Assessment of the risk of collision at sea

The challenge confronted to realize automatic collision avoidance at sea is to predict if there exists any risk of collision between ships. Specialists and expert in domestic and abroad have done a lot researches on this problem and achieved success [13]. The main assessment method used at present are numeric method, probability of collision calculation, plotting, PAD, collision course and speed method, ship domain. There are different assessment method in numeric evaluation the risk of collision, such as Fuzzy comprehensive assessment, Fuzzy reasoning and artificial network assessment method.

5. Automatic Decision-making System for Collision Avoidance at Sea

There are two ways to make automatic decision-making system for collision avoidance at sea (ADSCAS) at present. One of them [2][3][5][8] is to make use of the artificial intelligent, and the system consists of databank, database of knowledge and inference unit. The kernel of the system is its database of knowledge, in which are the rules of the road. The advantages of the system are: the decisions made are in compliance with the rules of the road, the practice of the sea, and satisfied with the requirements of seamanship. On the other hand, it is very difficult for the system to make good decision when one of the two ships in situation does not comply with the rules of the road, especially when more than two ships encounter. The another way is to take the advantages of the differential games to establish ADSCAS. Its advantage is in certain condition, no matter what action the other ship took it is impossible for the other ship to enter the domain of owhship. However, the computation is complicated, and for more than two ships encounter situation it is very difficult to generate resolution. It is still under study, and remains long way to go.

6. New idea about realizing automatic decision-making for collision

avoidance between ships

6.1 Realize automatic decision make by making use of Finite State Machine

A finite state machine (FSM) is a representation of an event-driven system. In an event-driven system, the system transitions from one state to another prescribed state provided the condition defining the change true.

For example, use a state machine to represent a car's automatic transition. The transmission has a number of operating states: park, neutral, drive , reverse, and so on. The system transitions from one state to another when a driver shifts the stick from one position to another, for example, from park to neutral.

We consider applying the FSM to the first way to establish automatic decision-making system in the inference unit. Literature [14] has details about event-driven hybrid system and its verification.

6.2 Making use of Differential Games in Automatic Decision-making System

Non-cooperative decision-making for collision avoidance means that one of the encountered ships takes action to avoid collision without coordination with the others. The ships are treated as players in a n players, zero-sum noncooperative dynamic game. Each player is aware only of the possible actions of the other ships. These actions are assumed to lie within a known set but with their particular values unknown and uncontrolled. Each ship solves the game considering the worst possible case. The performance index over which the ships are competing is the relative distance between the ships, required to be above a certain threshold which is determined by the size of its domain.

A two-ship scenario is considered. Let

$$\dot{x} = f(x,u,d,t) \qquad x(t_0) = x_0 \tag{1}$$

model the dynamics of the relative motion, where $u \in U$ is the control input of one ship, called it the evader, and $d \in D$ is the control of the other, called the purser. The actions of the evader are controlled whereas the actions of the purser are unknown and uncontrolled, but are known to lie within the disturbance set D. Thus, the actions of the evader are modeled as control inputs whereas the actions of the purser as disturbances.

The requirement for collision avoidance is encoded in a cost function $J_s(x_0,u,d)$ and is simply the distance between the two ships. A trajectory of system (1) is called safe if

$$J_s(x_0,u,d) \geq C \tag{2}$$

for some constant C determined by the size of ship domains. I a zero-sun, noncooperative game, the purser tries to minimize the distance between the ships whereas the evader tries to maximize it.

A saddle solution to the game exists when there exists input u^* and disturbance d^* such that

$$J_s(x_0,u^*,d^*) = \max_{d\in D}\min_{u\in U} J_s(x_0,u,d) = \min_{u\in U}\max_{d\in D} J_s(x_0,u,d) \tag{3}$$

If a saddle solution exists, the optimal policy for the evader is u^* whereas the worst possible distance by the purser is d^*. If the trajectory of (1) corresponding to the saddle solution (u^*,d^*) is safe, then collision is avoided by the evader for the worst possible purser disturbance. In this case, collision is avoided regardless of what the purser will do as long as the evader chooses its optimal policy. This allowed the evader to choose a control policy which guarantees safety without having to communicate or cooperate with the purser. This is the fundamental idea in noncooperative conflict resolution.

The safety of a particular control policy also depends on the initial relative configuration x_0. The set of safe initial relative configurations is defined as

$$V_s = \{x_0 \in R^n \mid J_s(x_0,u^*,d^*) > C\} \qquad (4)$$

If the initial relative configuration does not belong in V_s then collision avoidance is not guaranteed. In that case, noncooperative methods alone will not suffice. If, however, $x_0 \in V_s$, then safety guaranteed by choosing the control policy u^*. In general, given an initial relative configuration $x_0 \in V_s$, the following set

$$U_s(x_0) = \{u \in U \mid J_s(x_0,u,d^*) \geq C\} \qquad (5)$$

is defined as the set of control policies which guarantee safety from relative configuration x_0. Since all $u \in U_s(x_0)$ guarantee safety from x_0, it is advantageous to find control policy $u \in U_s(x_0)$, which minimizes deviation from the nominal trajectory. Deviation from the nominal trajectory is encoded in a cost function J_ε, which is usually a quadratic function of the tracking error. Therefore minimization of the tracking error, which guarantees safety from relative configuration x_0, is performed by solving the following optimal control problem

$$\min_{u \in U_s(x_0)} J_\varepsilon \qquad (6)$$

6.3 Using Potential and Vortex field to realize automatic decision-making

Potential and vortex field approach was adopted to solve the conflicts among aircraft in literature [16]. We consider applying it in the automatic decision-making for collision avoidance at sea. Ship's domain and arena are applied here. When the domains of the ships encountered crossing the collision is assumed to exist. A ship can take any effective avoidance action when the other ship is outside its arena and prevent the other ship coming into its domain.

Consider a scenario of m ships encountered. There are n ships around ith ship, its current position is denoted by $\vec{x}_i = (x_i, y_i)$ and desired destination (next via-point for example) $\vec{x}_{d,i} = (x_{d,i}, y_{d,i})$. Then an attractive potential function is defined as

$$\Phi_a = \frac{1}{2}(\vec{x}_i - \vec{x}_{d,i})^2 \qquad (7)$$

In order to achieve the desired destination, a force proportion to the negative gradient of the Φ_a is required.

To prevent collisions between neighbors i and j, the following symmetric repulsive field is defined associate with each ship

$$\Phi_r = \begin{cases} -\frac{1}{2\delta_r}(r_{ij} - (r+\delta_r))^2 & r \le r_{ij} \le r+\delta_r \\ 0 \end{cases} \qquad (8)$$

where $r_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$ is the distance between ship i and ship j, (x_i, y_i) and (x_j, y_j) is the function of time, r_i is the i th ship's domain, δ_r is the radius of arena。The repulsive force is generated by the gradient of Φ_r。

A vortex field, tangential to the repulsive field, is also associated to each ship's arena to ensure that all ships turn in the same direction:

$$\Phi_v = \begin{bmatrix} \frac{\partial \Phi_r}{\partial y} \\ -\frac{\partial \Phi_r}{\partial x} \end{bmatrix} \qquad (9)$$

The trajectory is given by the superposition of the forces generated form the potential and vortex fields. The attractive force gives the heading to the destination and is independent of the distance from the destination. The x position full planner governing differential equations for ship i in $r \le r_{ij} \le r+\delta_r$, are given as:

$$\dot{x}_i = -\frac{x_i - x_{d,i}}{\sqrt{(x_i - x_{d,i})^2 + (y_i - y_{d,i})^2}} + k_r \sum_{j=1, j\ne i}^{n} \frac{1}{\delta_r}\left\{\frac{r+\delta_r}{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}} - 1\right\}(x_i - x_j)$$
$$+ k_v \sum_{j=1, j\ne i}^{n} \frac{1}{\delta_r}\left\{\frac{r+\delta_r}{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}} - 1\right\}(y_i - y_j) \qquad (10)$$

$$\dot{y}_i = -\frac{y_i - y_{d,j}}{\sqrt{(x_i - x_{d,i})^2 + (y_i - y_{d,i})^2}} + k_r \sum_{j=1, j\ne i}^{n} \frac{1}{\delta_r}\left\{\frac{r+\delta_r}{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}} - 1\right\}(y_i - y_j)$$
$$+ k_v \sum_{j=1, j\ne i}^{n} \frac{1}{\delta_r}\left\{\frac{r+\delta_r}{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}} - 1\right\}(x_i - x_j) \qquad (11)$$

where k_r and k_v are the strengths of the repulsive and vortex field respectively. It is assumed that all the ship have the same field strength. For $r_{i,j} > r + \delta_r, \forall j$, the differential equations for ship i are simplified because only the attractive potential contributes to its velocity potential field.

Using the differential equations above, several different conflict resolution scenarios can be generated for two or more ships.

6.4 Using Brownian Motion for realizing automatic decision-making for collision avoidance at sea

Hu Jianghai [18][19][20][21] worked out a Brownian-motion method for computing the probability, which was used to analyze the highway safety and predict the conflicts among aircraft and generate resolution. He used braid group to classify maneuvers for multiple aircraft, and computed demonstrations with eight and sixteen aircraft.

We consider using the Brownian-motion method to calculate the probability of conflicts between ships and collision resolution generation. It may be a better way to solve multi-ship collision avoidance problem.

The major contributors to the uncertainty in the ship motion are wind, sea and current. Which can be defined as perturbation and modeled as a Brownian motion (BM). Intuitively, the probability of conflicts is the proportion of sample paths leading to a collision among all possible paths. BM gives us a measure of the probability of each path. This approach enables us to easily derive a resolution algorithm for collision avoidance.

1. Model and Probability of Conflicts (PC) Approximation

Consider two ships, labeled 1 and 2, moving on the sea. Assume without loss of generality that at time $t = 0$, ship 1 is at the origin of a coordinate frame, sailing from left to right with a velocity $\vec{u}_1 = (u,0)^T \in R^2$, while ship 2 is at position $\vec{z}_0 \in R^2$, sailing with a velocity $\vec{u}_2 \in R^2$ which makes an angle θ wit ship 1。 If ship 2 enters the domain of ship 1 a conflict occurs, or vice versa.

For the positions $\vec{z}_1(t)$ and $\vec{z}_2(t)$ of the two ships, we propose a kinematic model of the following form:

$$\vec{z}_1(t) = \vec{u}_1 t + \sum \vec{B}_1(t) \qquad (12)$$

$$\vec{z}_2(t) = \vec{z}_0 + \vec{u}_2 t + T(\theta)\sum \vec{B}_2(t) \qquad (13)$$

where $\sum = diag(\sigma_a, \sigma_c)$, σ_a, σ_c model the variance growth rate in the along track and cross track component respectively $(\sigma_a > \sigma_c)$. $T(\theta)$ is the matrix corresponding to a counterclockwise rotation by θ. $\vec{B}_1(t)$ and $\vec{B}_2(t)$ are independent standard 2-D BM's. Subtracting (12) from 13 leads to

$$\Delta\vec{z}(t) = \vec{z}_0 + \Delta\vec{u} \cdot t - \vec{W}(t) \qquad (14)$$

By transformation, we can assume that the motion of ship 1 is a standard 2-D BM starting from the origin, while the motion of ship 2is of constant velocity $\vec{v} = (v_1, v_2)^T$ starting from

$\vec{s} = (s_1, s_2)^T$

$$\vec{s} = P^{-1}\vec{z}_0, \qquad \vec{v} = P^{-1}\Delta\vec{u} \qquad (15)$$

Define x_d as the distance from the origin to the trajectory of ship 2, and a as the distance from ship 2 at $t = 0$ to the projection of the origin on the direction line of $\vec{v} = (v_1, v_2)^T$.

$$x_d = \frac{|s_1 v_2 - s_2 v_1|}{\sqrt{v_1^2 + v_2^2}}, \qquad a = -\frac{s_1 v_2 + s_2 v_1}{\sqrt{v_1^2 + v_2^2}}$$

In the new coordinate system, a positive indicates that the two ships are approaching each other and the minimal separation during the encounter is x_d. On the other hand, a negative a indicates that they are sailing away from each other and the minimal separation occurs at $t = 0$. Moreover, the circular domain of sip 2 is transformed into an ellipse centered initially at $\vec{s}$ and with the boundary described by:

$$\lambda_1^2(x - s_1)^2 + \lambda_2^2(y - s_2)^2 = R^2/2 \qquad (16)$$

moving along with ship 2. A conflict occurs if and only if the 2-D BM ever wanders into this moving ellipse.

PC for collision can be approximated by [19]:

$$P_{nm} \approx Q(\frac{x_d - L}{\sqrt{t_0}}) - Q(\frac{x_d + L}{\sqrt{t_0}}) \qquad (17)$$

2. Algorithm for Collision Avoidance

In the section of 7.3, an algorithm for collision avoidance is proposed based on the potential and vortex field method. However, since the potential and vortex field defined depends only on the distance, the generated maneuvers sometimes contain abrupt turn. Since PC derived in (17) contains information about both distance and relative velocity, it is expected to be a better candidate for forming a conflict resolution algorithm.

Consider the case when two ships start from position $\vec{z}_1(0), \vec{z}_2(0)$ sailing at a constant speed u_1, u_2 and have destinations $\vec{d}_1, \vec{d}_2$ respectively. At each time t, P_{nm} can be calculated based on their position and velocity. We define three headings of interest:

Current heading C_c: Course along which the ship is sailing.

Destination heading C_d: Course defined by the current position and its destination.

Gradient heading C_g: Course corresponding to the highest decrease of PC, i.e., the course determined by the negative gradient of P_{nm} as a function of the current position.

The proposed resolution scheme is quite simple: at each time step. each ship updates its course as

$$C_{next} = \begin{cases} \overline{C} & \text{if} \left|\overline{C} - C_c\right| < \beta \\ C_c + \beta \operatorname{sgn}(\overline{C} - C_c) \end{cases}$$

where β is the maximum allowed turn angle per time step, and $\overline{C} = P_{nm}C_g + (1 - P_{nm})C_d$. Intuitively, if P_{nm} is high, then decreasing P_{nm} becomes a priority, hence C_g should be pursued more. If instead, P_{nm} is negligible, then C_c should be kept. In any case, the deviation of the new course from the current one should not exceed β。

7. Conclusion

The key problem of automatic collision avoidance study is the automatic decision-making for collision avoidance. Whereas the foundation for realizing automatic decision-making for collision avoidance is that once the risk of collision is deemed exist, what algorithm should be taken to find a safe and effective resolution. One way is to follow the rules of the road taking inference method, which is used in the present available automatic collision avoidance system. The shortage of this way is that because there are a lot of uncertainties in the rules of the road and some situation is not defined in the rules, such as multiple ship encounter situation, it is difficult to realize automation in those special cases. Another way is adopting Differential Games theory, Hybrid System to design the algorithm without thinking of the rules of road. The shortage is that the generated resolution may not compliance with the rules of the road. Together with the rapid development of science and technology, and the advanced computer technology, the revolution will surely happen in the filed of navigation technology at sea. To realize automatic collision avoidance at sea is not a far away to go. In fact this paper only proposes some new idea about realizing automatic collision avoidance, it still need further study to verify.

Rreference

1.Saburo TSURUTA, Hisashi MATSUMURA. Basic research on an expert system for navigation at sea. The Journal of Institute of Navigation, No.77, 1987

2.F. P. Coenen, G. P. Smeaton and A.G.Bole. A Knowledge-based collision avoidance. The Journal of Navigation. Vol.42, 1989

3.M. Grabowski and W. A. Wallace. An Expert System for Maritime Pilots: Its Design and Assessment Using Gaming. Management Science. Vol. 39, No. 12, 1993

4.Yang Baozhang, Shi Aiguo, Kang Qiang and Yue Feng, The Ship collision avoidance automation system in the future, Compilation of Papers of IAIN'94.

5.Wang Jingquan, Collision Avoidance Expert System in Open Sea, Collections of Academic Exchange Papers of Japan-SINO Institute of Navigation, 1995

6.Qi Zhixong, Lan Peizhen, Comprehensive Decision-making System, The Journal Of Dalian Maritime College, Vol.18, No.3, 1992.

7.Weng Yuezong, Knowledge and Expert System in Field of Collision Avoidance, The Navigation of China, 1994

8.Zheng Zhongyi, Research on Automatic Decision-making System of Vessel Collision Avoidance, Ph. D Thesis, Dalian Maritime University, 2000.

9.William A. O'Neil, IPS-IMO International Conference on the Malacca and Singapore Straits, Singapore, 1999

10. Claire Tomalin, George J. Pappas, Jana Kosecka, John Lygeros and Shankar Sastry, A Next Generation Architecture for Air Traffic Management. In International Conference on Intelligent Robots and Systems(IROS), Grenoble, 1997.

11. Shankar Sastry, G. Meyer, Claire Tomalin, John Lygeros, D. Godbole and G. Pappas, Hybrid Control inAir Traffic Management Systems. UC Berkeley Memo UCB/ERL M95/82 October 1995.

12. John-Morten Godhavn, Trygve Lauvdal and Olav Egeland, Hybrid Control in Sea Traffic Management Systems.

13. Zhao Jinsong, The Principles of Collision Prevention at Sea. Press of Dalian Maritime University, 1999.

14. Alongkrit Chutinan, Hybrid System Verification Using Discrete Model Approximations. Ph. D thesis, Carnegie Mellon University, 1999

15. Claire Tomalin, George J. Pappas, and Shankar Sastry, Conflict Resolution for Air Traffic Management: A case study in multi-agent hybrid systems. Technical report, UCB/ERL M96/38, Electronics Research Laboratory, University of California, Berkeley, 1996.

16. Jana Kosecka, ClaireTomalin, George J. Pappas and Shankar Sastry, Generation of Conflict Resolution Maneuvers for Air Traffic Management. In International Conference on Intelligent Robots and Systems (IROS), Grenoble, 1997.

17. A. Masoud. Using hybrid vector-harmonic potential fields for multi-robot, multi-target navigation in stationary environment. In Proceedings of IEEE conference on Robotic and Automation, 1996.

18.Jianghai Hu, A Study of Conflict Detection and Resolution in Free Flight, M. S. thesis, University of California, Berkeley, 1999.

19. Jianghai Hu, John Lygeros, Maria Prandini, and Shankar Sastry, Aircraft Conflict Prediction and Resolution using Brownian Motion, In IEEE Conference on Decision and Control, Phonix, AZ, 1999.

20. Jianghai Hu, Maria Prandini, and Shankar Sastry, Optimal Maneuver for Multple Aircraft Conflict Resolution: A Braid Point of View, In IEEE Conference on Decision and Control, Sydney, Australia, 2000.

21. Jianghai hu, John Lygeros, Maria Pradini and Shankar Sastry, A probablistic framework for highway safety analysis. In IEEE Conference on Decision and Control, 1999

“紧迫局面”微分对策避让决策数模

蔡烽　石爱国　杨宝璋 周立鑫

（海军大连舰艇学院　　中国：大连）

摘要：本文对船舶会遇过程中“紧迫局面”和“紧迫危险”下的避让特点进行了分析，绘出了适合当时局面的微分对策避让决策模型。其基本思路是：不管来船采取什么行动，在一定条件下，我船总能采取动态的、连续的最优对策。当两船操纵性能各有优劣时，可用定性微分对策求解。

关键词：　船舶避让　微分对策　避碰自动化

船舶碰撞是最严重的海事之一。为减少船舶碰撞，以 IMO（国际海事组织）为代表的国际航海界采取了不少举措，诸如制定并实施《国际海上避碰规则》、《1978 年海员培训、发证和值班标准国际公约》等一系列法规，提出了《本组织关于人的因素的看法、原因和目标》等多项建议，取得了好的效果。但要从根本上减少船舶碰撞事故，我们认为还必须引进新的技术手段，主要是用船舶避碰自动化系统（ACAS）装备船舶。

船舶避碰决策软件是 ACAS 的核心软件，已有不少研究成果。本文是基于以运筹学为基础的避碰决策软件，其要点可概括如下：当有碰撞危险时，远距离及简单情况，可用几何避碰算法作出决策；复杂情况，可用几何矩阵决策求解；当处于紧迫局面时，则需用微分对策获得动态的、连续的优化对策。我们所研究的 ACAS，是建立在专门研制的“来船操纵性辨识子系统”和“来船动态判别子系统”的基础上的。通过这两个子系统，可以迅速获得来船 K、T 指数及转向、变速的动态信息[1][2]。本文仅介绍这种 ACAS 的紧迫局面微分对策避让决策数模。

1. 关于紧迫局面

1.1 对“紧迫局面”有多种诠释，受到我国航海界重视的观点是：

——“紧迫局面”是一个阶段或一个过程。

——“当两船接近到单凭一船的行动（包括大幅度行动）已经不能达到安全距离上驶过”，则紧迫局面已经形成。

——“紧迫局面”的下限即是“紧迫危险”，亦即“单凭一船的行动已不能避免碰撞”。

——“紧迫局面”也是一个阶段，它的下限是“碰撞已不可避免”，船舶机动的目的，是“减少碰撞可能造成的损失[3][4]”。

1.2 直航船“可独自采取行动的时机”，应在紧迫局面形成之前。从数模角度说，应在紧迫局面形成之前，结束行动。

1.3“紧迫局面”船舶避让决策，适宜采用微分对策。

1.4 船舶处于“紧迫危险”时，可以考虑采用操纵图表的方法进行避让。

2. 双船微分对策避碰数学模型

2.1 基本概念

2.1.1　微分对策可以这样定义：诸方进行对策活动时，要用微分方程组来描述对策现象或规律的一种对策，它有定性和定量之分。定量和定性微分对策的根本区别是：定量对策的各方，追求的是某一性能指标，例如最短的避让时间。定性微分对策不是研究某一性能指标的

极值，而是某种结局能否实现，例如能否在一定距离内让开米船。

我们认为，可以用定性微分对策，也可以用定量微分对策求解紧迫局面的避让决策。而用定性微分对策，所得的解更接近安全避让的目标。所以这里只叙述用定性微分对策求解避让决策。紧迫局面下的避让，航向、航速一般均要改变，因而适宜采用双作变向变速型定性微分对策。

定性微分对策的双方，其对策结局有四种可能性：

序号	我船（避）	米船（追）	结　局
1	航速高、旋回直径大	航速低、旋回直径小	如米船一开始就在界栅我方一方之内，总有碰撞可能
2	航速高、旋回直径小	航速低、旋回直径大	我船总可能避开米船
3	航速低、旋回直径大	航速高、旋回直径小	米船总可能避开我船
4	航速低、旋回直径小	航速高、旋回直径大	如我船一开始就在界栅米船一方之内，总有碰撞可能

准确地说，就是避让一方如操纵性占有绝对优势，在紧迫局面下，总存在碰撞可能性或避开的可能性。如果双方的操纵性各有优劣，关键看初始位置：如果米船在界栅上或某区域之外，只要操纵得当，总能避开米船。如果米船在界栅某区域之内，如果其机动总是与我船“不协调”，就总存在碰撞的可能性。

2.1.2 界栅

界栅把操纵性各有优劣的避让双方的对策状态空间剖分成两部分：一部分叫捕获区，只要我船进入该区，不论采取何种策略，总可能与米船发生碰撞。另一部分叫躲避区，只要我船在该区，不论米船采取何种策略，总有可能不发生碰撞。在双方各有优势、避让极不协调、类似于对抗的情况下，两船相对运动的最优轨线，就是界栅，双方沿界栅恰能互相让过。它类似几何避碰中的“危险扇面”。

在几何避碰原理中，我们知道如果我船航速低于米船，则可从我船船位辐射出一个扇面，只要米船在临界扇面之内，总存在碰撞的可能性。如机动得法，使米船保持在临界扇面之外，就不存在碰撞的可能性。

界栅的意义类似于临界扇面，但界限不是直线，而是复杂的因条件不同而不同的曲线。

2.1.3 海上实践表明，在紧迫局面或紧迫危险时，由于环境、心理因素的作用，两船的避让机动往往是“不协调”的，带有“对抗”的性质，这是此时的决策宜于采用微分对策的原因。即使船舶拥有 AIS（Automatic Identification System—船载自动识别系统），在多船会遇的情况下，两艘处于紧迫局面的船舶，仍然适宜采用本决策系统。若出现会遇双方非“对抗”的情况，藉助微分对策得出的避让决策虽然不是最优的，却也是相对优化的决策，有利于避免碰撞。

2.2 数学模型[6][7]

2.2.1 设我船 W、目标船 M 均可作变速变向运动，速度分别为 V_W，V_m，航向分别为 ϕ_W，ϕ_m，加速度分别为 a_W，a_m，转向控制分别为 K_W，K_m，加速度控制分别为 Ψ_W，Ψ_m。设 W 的目标集（即船舶领域，或据当时情况确定的围绕船体的一个安全范围）为半径为 r 的圆，即：

$$D(x,y)=x^2+y^2-r^2=0 \tag{1}$$

2.2.2 运动方程

(1) 绝对坐标系运动方程

设 (x_w,y_w)，(x_m,y_m) 为 W、M 的坐标位置，则有：

$$\begin{cases}\dot{x}_w = V_w \mathrm{Sin}\phi_w \\ \dot{y}_w = V_w \mathrm{Cos}\phi_w \\ \dot{x}_m = V_m \mathrm{Sin}\phi_m \\ \dot{y}_m = V_m \mathrm{Cos}\phi_m \\ \phi_w = \dfrac{V_w}{R_w}k_w \\ \phi_m = \dfrac{V_m}{R_m}k_m \\ \dot{V}_w = a_w \cdot \psi_w \\ V_m = a_m \cdot \psi_m \end{cases} \tag{2}$$

这里，Rw、Rm 为 W、M 的最小旋回半径。

(2) 相对坐标系运动方程

用旋转变换

$$\begin{cases}x=(x_m-x_w)\cos\phi_w-(y_m-y_w)\sin\phi_w \\ y=(x_m-x_w)\sin\phi_w+(y_m-y_w)\cos\phi_w\end{cases} \tag{3}$$

即将坐标系建立在 W 上，W 的航向即为坐标系的 y 轴。则在相对坐标系中，运动方程为：

$$\begin{cases}x(t) = V_m \mathrm{Sin}\psi - y\dfrac{V_w}{R_w}k_w \\ y(t) = V_m \mathrm{Cos}\psi + x\dfrac{V_w}{R_w}k_w - V_w \\ \dot{\psi}(t) = \dfrac{V_m}{R_m}k_m - \dfrac{V_w}{R_w}k_w \\ \dot{V}_w(t) = a_w \cdot \psi_w \\ V_m(t) = a_m \cdot \psi_m \end{cases} \tag{4}$$

这里，$\psi=\phi_m-\phi_W$。(4)即状态变量 (x,y,ψ,Vw,Vm) 的非线性微分方程。

2.2.3. 求对策问题的解

(1) 写出 Hamilton 函数

$$
\begin{aligned}
&H(x,y,\psi,Vw,Vm,t)=\lambda^{T}\cdot\left(\dot{x},\dot{y},\dot{\psi},\dot{V}w,\dot{V}m\right)\\
&=\lambda_1\left(Vm\sin\psi-y\frac{Vw}{Rw}Kw\right)+\lambda_2\left(Vm\cos\psi+x\frac{Vw}{Rw}Kw-Vw\right)\\
&+\lambda_3\left(\frac{Vm}{Rm}Km-\frac{Vw}{Rw}Kw\right)+\lambda_4 a_w\psi_w+\lambda_5 a_m\psi_m
\end{aligned}
\tag{5}
$$

(2) 根据定性双边极值原理：

$$
\max\min H\left(\overline{\lambda},\overline{x},\psi_w,Kw,Km\right)=\min\max H\left(\overline{\lambda},\overline{x},\psi_w,Kw,Km\right)
\tag{6}
$$

由(4)得：

$$
\begin{aligned}
&H=\left(-\lambda_1 y+\lambda_2 x-\lambda_3\right)\frac{Vw}{Rw}Kw+\lambda_3\frac{Vm}{Rm}Km+\lambda_4 a_u\psi_u\\
&+\lambda_5 a_m\psi_m+\left(\lambda_1 Vm\sin\psi+\lambda_2 Vm\cos\psi-\lambda_2 Vw\right)
\end{aligned}
\tag{7}
$$

则最优策略为：

$$
\begin{cases}
Kw^{*}=sign\left(-\lambda_1 y+\lambda_2 x-\lambda_3\right)\\
Km^{*}=sign\lambda_3\\
\psi_u^{*}=sign\lambda_4\\
\psi_m^{*}=-sign\lambda_5
\end{cases}
\tag{8}
$$

符号函数 signZ 定义如下：

$$
signZ=\begin{cases}
1 & Z>0\\
0 & Z=0\\
-1 & Z<0
\end{cases}
\tag{9}
$$

；

其伴随方程为：

$$
\begin{cases}
\dot{\lambda}_1=-\dfrac{\partial H}{\partial x}=-\dfrac{Vw}{Rw}Kw\\
\dot{\lambda}_2=-\dfrac{\partial H}{\partial y}=\dfrac{Vw}{Rw}Kw\lambda_1\\
\dot{\lambda}_3=-\dfrac{\partial H}{\partial \psi}=-\lambda_1 Vm\cos\psi+\lambda_2 Vm\sin\psi\\
\dot{\lambda}_4=-\dfrac{\partial H}{\partial Vw}=-\dfrac{Kw}{Rw}\left(-\lambda_1 y+\lambda_2 x-\lambda_3\right)+\lambda_2\\
\dot{\lambda}_5=-\dfrac{\partial H}{\partial Vm}=-\lambda_1\sin\psi-\lambda_2\cos\psi-\lambda_3\dfrac{Km}{Rm}
\end{cases}
\tag{10}
$$

其末值条件为：

$$\begin{cases} \lambda_1(t_1) = -\mu \dfrac{\partial D(x,y)}{\partial x} = -2\mu x(t_1) \\ \lambda_2(t_1) = -\mu \dfrac{\partial D(x,y)}{\partial y} = -2\mu y(t_1) \\ \lambda_3(t_1) = -\mu \dfrac{\partial D(x,y)}{\partial \psi} = 0 \\ \lambda_4(t_1) = -\mu \dfrac{\partial D(x,y)}{\partial Vw} = 0 \\ \lambda_5(t_1) = -\mu \dfrac{\partial D(x,y)}{\partial Vm} = 0 \end{cases} \tag{11}$$

2.2.4. 写出倒向方程

实际求解，必须已知初始条件，此时只有界栅和目标集的切点才可能是确知的，所以必须倒着进行求解。为确定目标集的可用部分边界，也必须根据倒向原理将上述方程写成倒向方程。

倒向轨线方程为：

$$\begin{cases} \bar{x}(\tau) = -V_m \sin\psi + y\dfrac{V_W}{R_W}K_W & x(0) = x_0 \\ \bar{y}(\tau) = -V_m \cos\psi - x\dfrac{V_W}{R_W}K_W + V_W & y(0) = y_0 \\ \hat{\psi}(\tau) = \dfrac{V_W}{R_W}K_W - \dfrac{V_m}{R_m}K_m & \psi(0) = \psi_0 \\ \hat{V}_W(\tau) = -a_W\psi_W & V_W(0) = V_W^0 \\ \hat{V}_m(\tau) = -a_m\psi_m & V_m(0) = V_m^0 \end{cases} \tag{12}$$

倒向伴随方程为：

$$\begin{cases} \bar{\lambda}_1(\tau) = \dfrac{V_W}{R_W}K_W\lambda_2 \\ \bar{\lambda}_2(\tau) = -\dfrac{V_W}{R_W}K_W\lambda_1 \\ \bar{\lambda}_3(\tau) = \lambda_1 V_m \cos\psi - \lambda_2 V_m \sin\psi \\ \bar{\lambda}_4(\tau) = \dfrac{K_W}{R_W}(-\lambda_1 y + \lambda_2 x - \lambda_3) - \lambda_2 \\ \bar{\lambda}_5(\tau) = \lambda_3\dfrac{K_m}{R_m} + \lambda_1 \sin\psi + \lambda_2 \cos\psi \end{cases} \tag{13}$$

初值条件为：

$$\begin{cases} \lambda_1(0) = -2\mu x(0) = \lambda_1^0 \\ \lambda_2(0) = -2\mu y(0) = \lambda_2^0 \\ \lambda_3(0) = \lambda_3^0 \\ \lambda_4(0) = \lambda_4^0 \\ \lambda_5(0) = \lambda_5^0 \end{cases} \tag{14}$$

2.2.5 求解最优轨线和最优控制的公式相当繁复，具体可参考文献[7]。

2.3 求解步骤

（1） 首先确定可用部分边界 BUP。

（2） 由此计算初始最优控制变量 $K_W^*(0)$、$K_m^*(0)$、$\psi_W^*(0)$、$\psi_m^*(0)$。

（3） 由轨线公式计算下一时刻 $x(\Delta)$，$y(\Delta)$，$\psi(\Delta)$，$V_W(\Delta)$，$V_m(\Delta)$。

（4）适当选定正乘子 μ 后，能计算乘子 $\lambda_1(\Delta)$、$\lambda_2(\Delta)$、$\lambda_3(\Delta)$、$\lambda_4(\Delta)$、$\lambda_5(\Delta)$。

（5）由求最优控制变量公式解得下一时刻 $K_W(\Delta)$、$K_m(\Delta)$、$\psi_W(\Delta)$、$\psi_m(\Delta)$。

（6）循环计算，直至界栅或超过对策空间为止。

3 操纵图表法

紧迫危险时，船舶由于惯性很大，决策通常是一次性的而非连续性的，可以考虑采用操纵图表法决策。

实施时，可以选用由英国航海学会提出的避碰机动图表[5]，或文献[8]提出的方案。

文献[8]依据某公司和某部近几年来来处理的国内外重大海上船舶间碰撞案例，和对航海院校毕业生、教师、现职远洋船长、驾驶员的调查和测试，得出以下和 1970 英国航海学会操纵图表相似的紧迫危险上限避让决策的结论。

参考文献

[1]杨宝璋,石爱国．舰船避碰自动化系统．大连:海军大连舰艇学院,1996.

[2]蔡烽．确定性 ACAS 总体设计及双船避碰决策数模[硕士论文]．大连:海军大连舰艇学院,1997.

[3]蔡存强．海上避碰规则导论．北京:人民交通出版社,1992.

[4]司玉琢,吴兆麟．船舶碰撞法．大连:大连海运学院出版社,1992.

[5]A．N．Cockcrcft 海上避碰规则指南(第四版)．大连:大连海运学院出版社,1992.

[6]张嗣瀛．微分对策．北京:科学出版社,1983.

[7]董志荣．微分对策的基本原理及其在军事对抗中的应用．北京:国外船舶技术,1983.

[8]廖建洲．紧迫局面时的应急避碰操纵．'91 中国航海学会驾驶专业委员会学术讨论会，1991.