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THE DESIGN OF FUZZY COLLISION-AVOIDANCE EXPERT SYSTEM IMPLEMENTED BY H_∞- AUTOPILOT

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Keywords: Fuzzy Collision-Avoidance Expert System, H_∞- Autopilot.

ABSTRACT

Collision avoidance is one of the urgent topics on ship voyage at sea. Experts' experience is still essential when a ship is in the danger of colliding with the others nowadays although a lot of electronic voyage supported apparatuses have been equipped on ships. To include these experts' experiences to resolve the problems of collision, we design a fuzzy collision-avoidance expert system that includes a knowledge base to store facts and rules, an inference engine to simulate experts' decision and a fuzzy interface device. Either a quartermaster or an autopilot system can then implement the avoidance action proposed in the research. To perform the ship task of collision-avoidance effectively, a robust autopilot system that is based on the state space H_∞ control methodology is designed to steer a ship safely for various outer surroundings at sea in performing course keeping, course-changing and route-tracking more robustly. The integration of fuzzy collision-avoidance and H_∞ autopilot systems is then proposed in this paper.

INTRODUCTION

In recent years, shipping is rapidly developed in marine nations to meet the growing economic demands. In order to remedy the shortage of personnel and to improve the safety of navigation, vessels tend to be getting more and more automatic and intelligent. In this paper, we use the concepts of the fuzzy set theory and fuzzy inference method to design a fuzzy collision-avoidance system. To fit time-varying environments, static obstacles with no prior position information and moving ships with unknown trajectories are considered in this study for ship navigation. Fuzzy logic is applied to guide a ship from a starting point toward the target trajectory without colliding with any obstacle or other ships. Intuitive motions of human beings are modeled into fuzzy rules such that the ship has the capability, like human beings, of avoiding obstacles or other moving ships. These fuzzy rules can be dynamically weighted according to the nearness state of the found obstacles or target ships. Furthermore, the proposed approach can also be used for the navigation of multiple ships, with few modifications to the original algorithm.

When a ship navigates at the sea, the influence of the ship speed, the depth of water and the draft of ship will cause a change on the system dynamic property. Besides, the influence of the currents, winds and waves will cause extra inputs to the system. These uncertain factors may also make the closed-loop system unstable. To eliminate the ill effects of these uncertain factors, we apply H_∞ theory to design an auto-pilot in this paper to find an optimal control law such that the system still has certain robustness under the worst exogenous input while it keeps the closed loop system stable and ensuring certain degree of accuracy in tracking target trajectories. This paper is organized as follows : Section 2 illustrates the development of ship collision-avoidance, ship and obstacle safety domains, traffic separation schemes and avoid actions. Section 3 describes the applications of fuzzy theory and basic configuration of fuzzy logic. Section 4 proposes the design process of H_∞ autopilot, including the theorem for obtaining the state space solution of H_∞ optimal control. Section 5 presents the computer simulation results for the proposed integrated system, which is a combination of fuzzy collision-avoidance system and the H_∞ autopilot system, to demonstrate the feasibility of the proposed integrated system. Finally, a summary of this paper and main conclusion of this study are described in section 6.

COLLISION-AVOIDANCE OF SHIPS

Benefited from the development of modern science, high technology is now widely used in the field of navigation. Satellite navigation and communication systems have been successfully applied to minimize the problems faced by the sailor and, as a result, the prob-

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lem of collision-avoidance becomes relatively more important. Besides, collision accidents are increasing as ships increase in size, in speed and in number. The problem of collision-avoidance has thus become an urgent issue.

For the above reasons, the major maritime countries of the world have given a great deal of attention to this problem. A solution to the above problem is to establish navigation regulations, to strengthen traffic control, and to improve the technical level of seafarer training, as well as to study collision-avoidance system.

In order to get the maximum favorable effect of economics, the new-built ships tend to be getting bigger and to be operated more automatically. The COLREGS (The International Regulations for Preventing Collisions at Sea) are the legal provisions to coordinate the behavior of ships when there is a risk of collision at sea. However, many of these rules are qualitative and can only be used after quantifying these rules. Therefore it causes difficulties in the implementation of the COLREGS by sailors in practical situations. For this reason, many researchers in western maritime countries began to study the quantitative methods in the early fifties and sixties. Their results established some terms about ship collision such as the distance at the closest point of approach (DCPA) and the time needed to reach the closest point of approach (TCPA).

Fig. 1 describes the concepts of the DCPA and TCPA. It can be used to determine the possibility of collision between two ships and the remaining time for taking collision-avoidance action to avoid the risk. Note that to avoid a possible collision, the DCPA and TCPA must be considered simultaneously. The appraisal index proposed by Kearon [3] is the weighted sum of the squares of DCPA and TCPA:

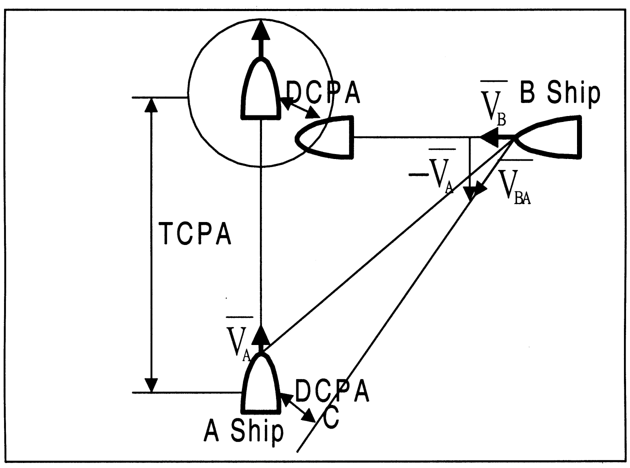

Fig. 1. Graphical interpretation of the DCPA and TCPA.

$$\lambda_i = (\boldsymbol{a}\ DCPA_i)^2 + (\boldsymbol{b}\ TCPA_i)^2$$

$$\boldsymbol{i} = 1, 2, 3, \ldots \boldsymbol{n} \tag{1}$$

where

λ_i: appraisal index
$\boldsymbol{a}$, $\boldsymbol{b}$: weightings
$\boldsymbol{i}$: number of target ships

When λ_i reaches a preset threshold value, the collision-avoidance action must be taken. Statistic analysis of experimental data is explored by Holmes as an alternative method to appraise the danger of ship collision. Shimizu uses the method of fuzzy reasoning and fuzzy control to establish a model for determining the time needed for taking-collision avoidance action. This research uses basic fuzzy theory to design a fuzzy collision-avoidance system, which is an effective one. In recent years, because of the increase of international trade, the current commodities and the flattop building for exploring oil have made the traffic more complex at the sea. In order to resolve the increased danger of collision, we begin to use the concepts of "Ship and Obstacle Safety Domain Theory." The definition of a ship domain proposed by Goodwin [20] is : "The surrounding affective waters that the navigator of a ship wants to keep clear of other ships or fixed objects." Basically the shape or the size of a ship safety domain is affected by the following factors:

1. Physical factors: the size of ships, traffic density and relative speed, etc.,
2. Environment factors: weather, visibility, etc., And
3. Psychology factors: navigator's work record, etc.

As to the size of a ship safety domain, researchers in many countries have different research results, but they have a same viewpoint, that is : "the meetings caused by different direction ships have different safety domains because of the difference of ships' sizes, speeds, relative positions and directions." The safety domain defined by Goodwin [20] can be divided into three sectors:

Sector 1 (starboard sector) : $0 \le \theta \le 112.5$
Sector 2 (port sector) : $247.5 < \theta < 360.0$
Sector 3 (astern sector) : $112.5 < \theta < 247.5$

The radius of each sector in Dover Strait and North Sea is listed in Table 1.

Because this ship safety domain is not continuous, it will increase the complexity in computer simulation. Thus, Davis *et al* [21] improves upon Goodwin's safety domain to make its domain boundary continuous. Then, Japanese scholar Toyoda and Fuji [22] did an experi-

Table 1. the value of each sector's radius in different waters unit : (n.m.)

	Sector 1	Sector 2	Sector 3
Dover Strait	0.82	0.75	0.10
North Sea	0.85	0.70	0.45

Table 2. the adopt strategy of the privilege ship and the burden ship

	Heading- on encounter	Crossing encounter	Overtaking encounter	By- overtaking encounter
Privilege ship		✔		✔
Burden ship	✔	✔	✔	

ment on ship domain for large, middle and small ships and he realizes that a ship's safety domain has connection with its length and that the domain is not symmetric. The starboard sector is the largest one, the port sector is the next and the astern sector is the smallest one. However, the size of the astern sector increases as a ship increases in its length. Thus, considering a conservative ship safety domain, a circle with 8 times ship-length radius is used to describe a ship's safety domain in this research. If other ships enter the ship's safety domain, the proposed fuzzy collision-avoidance system will provide an advice to avoid possible collision.

In recent years, there has been a considerable increase in the number of structures used for offshore oil exploitation. Thus, an obstacle safety domain should also be built to avoid collision. The obstacle's size and shape, the depth of surrounding water and the draft of the ship determine the safety domain size of an obstacle. For simulation convenience, we select a circle with 1.2 times obstacle-length radius as our obstacle's safety domain.

The first traffic separation schemes in the world are practiced in Dover Strait in 1967. Traffic separation scheme is mainly composed of the separation line, the separation zone and the course borderline. For various types of terrain, the separation lines and separation zones can be described as follows:

1. Apply nature obstacles, striking targets in geography to separate the coming and the adverse ships.
2. Utilize the inshore traffic zone to separate the coming and going ships.
3. Construct a fan-shaped zone for a port to separate the course alley.
4. Construct a ring-shaped separation zone close to ships' gathering point.

The width of a course alley in open waters is set to be about 5-3-5, i.e., both sides of a course alley have a width of 5 miles respectively and a width of 3 miles is used as the center separation zone, to 20-10-20 [18].

According to the COLREGS, when a ship encounters the others at sea, the burden or the privilege ship can be identified by the strategy listed in Table 2 [19].

In any potential collision situation, the navigator faces two questions : Do I risk a collision? If so, should I take avoiding actions and what actions should be taken while considering all vessels in the vicinity? When an encounter involves risk of collision, i.e., the DCPA is less than the radius of the ship's safety domain, the system should take actions to avoid the collision. In Fig. 1, the ship A is the burden ship and the ship B is the privileged one. If both ships keep their current course and speed, the ship B will pass through the closest point of approach (CPA) with a relative speed V. Since the DCPA in this case is less than the distance needed for safety, the ship A has to turn right to obtain a sufficient DCPA before passing CPA. However, if the ship A changes it's navigation speed to V, the encountering situation as shown in Fig. 2 will be safe in the sense that the DCPA is greater than or equal to the safety distance. For the cases of crossing alleys, some regulations should be followed, which is explained in references [18] and [19]. To offer proper advice to avoid collision between ships, the collision-avoidance system is designed based on Fuzzy set theory and is described in the next section.

FUZZY COLLISION-AVOIDANCE SYSTEM

During the past decade, fuzzy logic control has emerged as one of the most active and fruitful areas for research in the application of fuzzy set theory, fuzzy logic and fuzzy reasoning [4]. Since fuzzy reasoning can be done in linguistic ways, which can effectively simply the complexity in modeling system dynamics, especially for nonlinear and ill-defined systems like ships, we use the fuzzy logic to design ship collision-avoidance system in the paper. The basic operation of a fuzzy set can be illustrated as follows:

(A) fuzzy set A can be expressed as [6, 8]

when U (the universe of discourse) is discrete, a fuzzy set A can be represented as

$$A = \frac{\mu_A(\chi_1)}{\chi_1} + \frac{\mu_A(\chi_2)}{\chi_2} + \cdots + \frac{\mu_A(\chi_n)}{\chi_n} \tag{2}$$

where $\frac{\mu_A(\chi_i)}{\chi_i}$ represents the relationship of the generic element χ_i of U and its grade of membership $\mu_A(\chi_i)$.

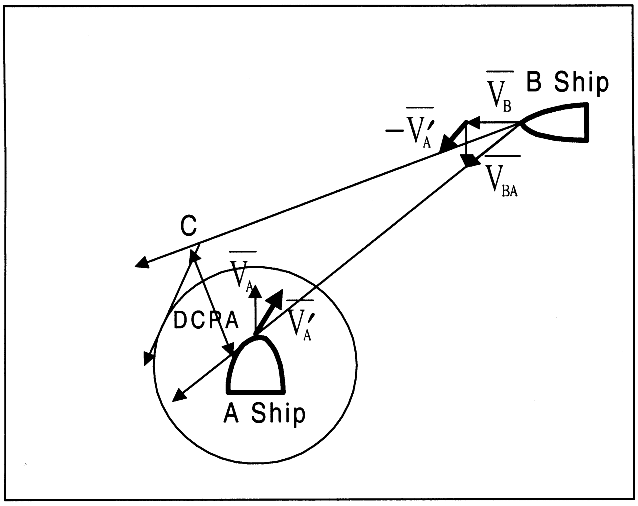

Fig. 2. Graphical interpretation of avoiding action.

(b) Fuzzy Intersection

The membership function $\mu_c(x)$ of the intersection $A \cap B$ is defined for all $\mu \in U$ by

$$\mu_C(\chi) = \min\{\mu_A(\chi), \mu_B(\chi)\} = \mu_A(\chi) \wedge \mu_B(\chi) \quad (3)$$

(c) Fuzzy Union

The membership function $\mu_c(x)$ of the union $A \cup B$ is defined for all $\mu \in U$ by

$$\mu_C(\chi) = \max\{\mu_A(\chi), \mu_B(\chi)\} = \mu_A(\chi) \vee \mu_B(\chi) \quad (4)$$

(d) Fuzzy Complement

The membership function $\mu_{\bar{A}}(x)$ of the complement of a fuzzy set A is defined for all $\mu \in U$ by

$$\mu_{\bar{A}}(\chi) = 1 - \mu_A(\chi) \quad (5)$$

(e) Fuzzy Relation

If A and B are fuzzy relation in $X \times Y$ and $Y \times Z$, respectively, the composition of A and B is a fuzzy relation denoted by and the membership function $\mu_c(x, z)$ of the composition A and B is defined by

$$\mu_C(x, z) = \mu_{A \bullet B}(x, z) = \sup\{\min[\mu_A(x, y), \mu_B(y, z)]\} \quad (6)$$

or

$$c_{ij} = \bigvee_k \{a_{ik} \wedge b_{kj}\}$$

Based on the above fuzzy operation concepts, the basic configuration of a fuzzy logic controller (FLC) is proposed and shown in Fig. 3, which comprises four principal components: a fuzzification interface, a knowledge base, an inference engine and a defuzzification interface. The main functions of these four components can be described as follows:

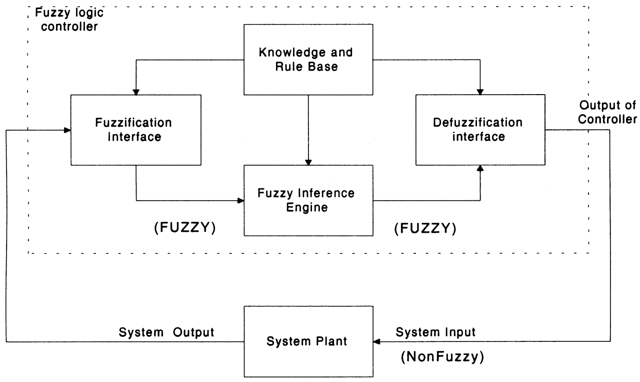

Fig. 3. Basic configuration of fuzzy logic controller.

(1) The fuzzification interface involves the following functions:

(a) It receives the state variables from the plant.

(b) It transfers the range of values of input variables into corresponding universes of discourse.

(c) It performs the function of fuzzification that converts input data into suitable linguistic values.

(2) The knowledge base consists of a “data base” and a “linguistic control rule base”:

(a) The database provides necessary definitions, which are used to define linguistic control rules and fuzzy data manipulation in an FLC.

(b) The rule base characterizes the control policy and control goals of the domain experts by means of a set of linguistic control rules.

(3) The inference engine is the most important kernel and it is the decision-making center of a FLC, which is designed by simulating human thinking model.

(4) The defuzzification interface performs the following functions:

(a) It yields a non-fuzzy control action from an inferred fuzzy control action.

(b)It converts the range of values of output variables into corresponding universes of discourse.

Fuzzification is related to the vagueness and imprecision in a natural language. It is a subjective valuation to transform measurement data into valuation of a subjective value. Hence it can be defined as a mapping from an observed input apace to labels of fuzzy sets in a specified input universe of discourse. Since the data manipulation in a FLC is based on fuzzy set theory, fuzzification is necessary and desirable at an early stage. In fuzzy control applications, the observed data are usually crisp. A natural and simple fuzzification approach is to convert a crisp value into a fuzzy singleton A within the specified universe of discourse. That is, the membership function of A is equal to 1 at the point as zero at other places.

A fuzzy system is characterized by a set of linguistic statements based on expert knowledge. The expert knowledge is usually as "if-then" rules, which are easily implemented by fuzzy conditional statements in fuzzy logic. Fuzzy control rules have the form of fuzzy conditional statements that relate the state variables in the antecedent and process control variables in the consequence. Many experts have found that fuzzy control rules provide a convenient way to express their domain knowledge. This explains why most FLC are based on the knowledge and experience that are expressed in the language of fuzzy "if- then" rules. The general form of the fuzzy control rules in the case of two-input single-output systems is:

IF x is A_1 and y is B_1 THEN z is C_1
IF x is A_2 and y is B_2 THEN z is C_2
...
IF x is A_n and y is B_n THEN z is C_n

where x, y, and z are linguistic variables representing the process state variable and control variable, respectively. A_n, B_n and C_n are the linguistic values of the linguistic variables x, y and z in the universe of discourse U, V, and W, respectively. In what follows, we consider some useful properties of the FLC inference engine [6, 9, 14].

[Theorem1]

$$(A', B') \cdot \bigcup_{i=1}^{n} R_i \Rightarrow \mu_{C'}(z) = (\mu_{A'}(x), \mu_{B'}(x))$$

$$\cdot \max_{x,y,z} (\mu_{R_1}(x, y, z), \cdots, \mu_{R_n}(x, y, z))$$

$$= \sup_{x,y,z} \max_{x,y,z}\{\min [(\mu_{A'}(x), \mu_{B'}(y)), \mu_{R_1}(x, y, z)],$$

$$\cdots, \min [(\mu_{A'}(x), \mu_{B'}(y), \mu_{R_n}(x, y, z)]\}$$

$$= \max_{x,y,z} \{[(\mu_{A'}(x), \mu_{B'}(y)) \cdot \mu_{R_1}(x, y, z)],$$

$$\cdots, [(\mu_{A'}(x), \mu_{B'}(x)) \cdot \mu_{R_n}(x, y, z)]\}$$

As new inputs, x and y, respectively belong to new fuzzy sets A' and B', which have no direct relationship to the existing fuzzy relation formulas R_1, R_2, ... R_n, we need extra operation on these fuzzy sets in this case.

[Theorem2]

For the intersection operation of fuzzy sets, the minimum and the product methods are formulated as follows:

If $\mu A_i \times B_i = \mu A_i \wedge \mu B_i$ then
$(A', B') \bullet (A_i \text{ and } B_i \Rightarrow C_i) = [A' \bullet (A_i) \Rightarrow C_i]$
$\cap [B' \bullet (B_i \Rightarrow C_i)]$

If $\mu A_i \times B_i = \mu A_i \times \mu B_i$ then
$(A', B') \bullet (A_i \text{ and } B_i \Rightarrow C_i) = [A' \bullet (A_i \Rightarrow C_i)]$
$\times [B' \bullet (B_i \Rightarrow C_i)]$

The above two formulas imply that we need to make a combination of the membership function operation and the logic operation. Because A_i and $B_i \Rightarrow C_i$ is not easy to be operated, we partition it into two parts and evaluate them separately.

[Theorem3]

If the inputs are fuzzy singletons, namely, $A' = x_0$, $B' = y_0$, based on the minimum operation and the product operation rules, we have the following four different operations:

$$\alpha_i^{\wedge} \wedge \mu_{C_i}(z)$$

$$\alpha_i^{\wedge} \bullet \mu_{C_i}(z) \qquad \alpha_i^{\wedge} = \mu_{A_i}(x_0) \wedge \mu_{B_i}(y_0)$$

where

$$\alpha_i^{\bullet} \wedge \mu_{C_i}(z) \qquad \alpha_i^{\bullet} = \mu_{A_i}(x_0) \bullet \mu_{B_i}(y_0)$$

$$\alpha_i^{\bullet} \bullet \mu_{C_i}(z)$$

The above theorems explain the process of fuzzy inference. Fig. 4 gives a graphic interpretation of theorem 3 in terms of minimum operation rule, while

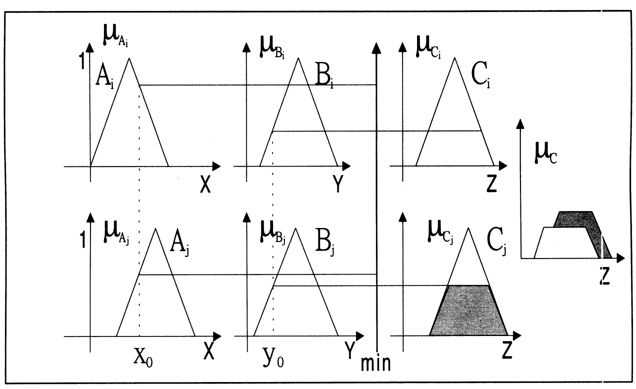

Fig. 4. Graphical interpretation of fuzzy inference under minimum rule.

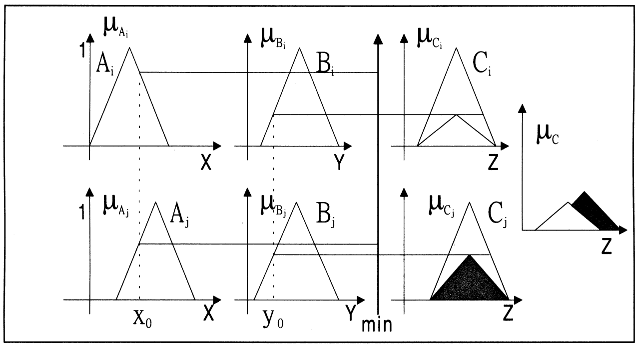

Fig. 5. Graphical interpretation of fuzzy inference under product rule.

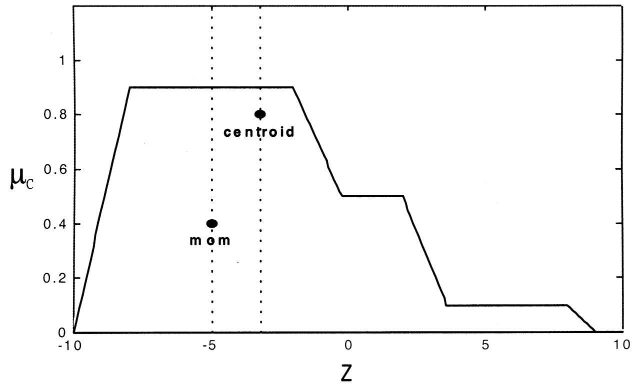

Fig. 6. The general output of fuzzy logic controller.

Fig. 5 offers a graphic interpretation of theorem 3 in terms of product operation rule.

Basically, defuzzificaton is a mapping from a space of fuzzy control actions defined over an output universe of discourse into a space of non-fuzzy control actions. It is employed because a crisp control action is required in many practical applications. At present, the commonly used defuzzification strategies may be described by the method of the center of area or the mean of maximum [6]:

(a) The Center of Area Method (COA)

The widely used COA strategy generates the center of gravity of the possibility distribution of a control action. In the case of a discrete universe, this method yields

$$z_{COA} = \frac{\sum_{i=1}^{n} \mu_C(z_i)\, z_i}{\sum_{i=1}^{n} \mu_C(z_i)} \tag{7}$$

The notation n in the above equation is the number of quantitative levels of the output.

(b) The Mean of Maximum Method (MOM)

The MOM strategy generates a control action that represents the mean value of all local control actions whose membership functions reach the maximum. In the case of a discrete universe, the control action may be expressed as :

$$z_{MOM} = \sum_{i=1}^{m} \frac{z_i}{m} \tag{8}$$

In the above equation, z_i is the support value. At this value, the membership function reaches the maximum value $\mu_C(z_i)$, and m is the number of the support values. Fig. 6 shows a graphic interpretation of the various defuzzification strategies mentioned above.

These fuzzy approach skills are now applied to design a ship collision-avoidance system, which is composed of five fuzzy-controlled modules: the detecting obstacle or ship near-far module, the keeping away from the static obstacle module, the avoiding encountering ship module, the tracking target-course module and the ship speed-control module. The fuzzy rules of each of control modules are derived from human being's intuitive motions of adopting collision-avoidance actions and they apply the above fuzzy theorems and operation processes.

When one ship encounters obstacles or other ships, its radar will detect whether they are in left front, right front or direct front of the ship. The data obtained from radar are then the inputs of the detecting obstacle or ship near-far module. The output of this module is the nearness degree of the found objects, which is used to determine each of the weights of the keeping away from static obstacle module, the avoiding encountering ship module, the tracking target-course module and the speed-control module. If one of the obstacles or target ships detected by radar is closer to the ship, it will have a larger weight value. When the value is greater than a preset threshold value, which is decided by the ship safety domain and the fuzzy rules mentioned before, for any of these modules, the module would then be started up to take actions to avoid a possible collision. The design process of fuzzy collision-avoidance is illustrated in Fig. 7.

When own ship is in the danger of colliding with obstacles or encountering ships, the fuzzy collision-avoidance system proposed above will advise a proper avoidance action to resolve the risk. The avoidance action can then be implemented by either a quartermaster or an autopilot system. The objective of H_∞ control problem is to obtain an H_∞ optimal control law such that the transfer function between the exogenous input and the controlled output is minimum while keeping the closed-loop system stable. In the next section, we will design an autopilot with H_∞ theory to ensure that the

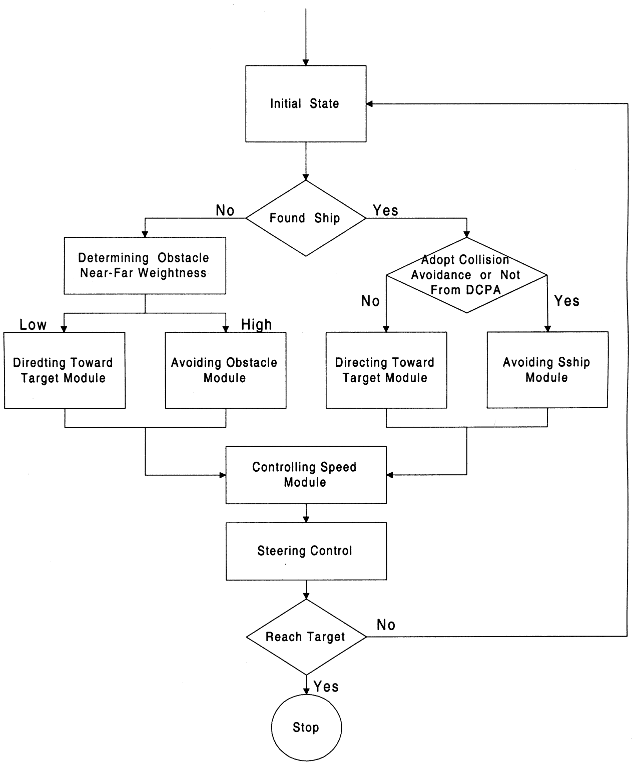

Fig. 7. The flow chart of fuzzy collision avoidance.

ship can avoid collision while keeping a good performance even under the worst exogenous input. The avoidance action advised by the fuzzy collision-avoidance system can be implemented by H_∞ autopilot system. In other words, the integration of fuzzy collision-avoidance and H_∞ autopilot systems will be proposed below.

DESIGN OF AUTOPILOT

The earlier autopilots are sorts of mechanical construction and are only able to provide simple control actions. Then, the proportional-plus-integral-plus-derivative type (PID-type) controllers are introduced and electrical and electronic equipment, which make the autopilots more flexible but have to be adjusted manually when the ship's dynamics or disturbances change, replace the mechanical devices. Katebi and Byrne (1988) [16] use the adaptive control theory to develop the adaptive auto-pilot system whose parameters can be adjusted automatically when the ship's situation or disturbances change. Besides, a lot of researches are made in the field of artificial intelligence (AI) and its application to control problems, such as the development of the AI knowledge-based and expert systems, the neural-networked and self-organizing fuzzy controllers

However, when a ship navigates at sea, its performance may be influenced by its own speed, its draft, the depth of water, the encountering situations and the surrounding currents, winds and waves, etc., which cause extra inputs to the system dynamics. These uncertain factors may also cause the system unstable. For this reason, the H_∞ autopilot system is a feasible alternative because of it excellent disturbance rejection capability.

H_∞- control theory considers the worst-case of the inputs. In other words, it ensures a good performance of the closed-loop system even to the worst situation. H_∞ norm in the frequency domain is defined as:

$$\| G_1 \|_{H_\infty} = \sup_{\omega} \sigma_{\max} \left| G_1(j\omega) \right| \tag{9}$$

$G_1(s)$: Transfer Function, $s = j\omega$, $j = \sqrt{-1}$

The objective of the H_∞ control problem is to obtain an optimal H_∞ control law such that the transfer function between exogenous input and controlled output is minimum while keeping the whole closed loop system stable. The "Standard Problem" is considered in the state space form as follows:

$$\dot{X}(t) = AX(t) + B_2 u(t) + B_1 w(t)$$

$$Y(t) = C_2 X(\mathrm{t}) + D_{21} w(t)$$

$$Z(t) = C_1 X(t) + D_{12} u(t) \tag{10}$$

where A, B_1, B_2, C_1, C_2, D_{12}, D_{21} are constant matrices of appropriate dimensions.

In Eqn (2), $X(t) \in R^n$, $Y(t) \in R^p$, $\mathrm{u}(t) \in R^m$, $w(t) \in R^r$ and $\mathrm{Z}(t) \in R^l$ denote the state, the measurement output, the control law, the exogenous input and the control output, respectively. We suppose that = °Awhere is the controller constant gain matrix. The exogenous input typically consists of reference inputs, disturbance, and sensor noises. The components of the controlled output are tracking errors, control efforts, etc. The objective of the control problem is to obtain an optimal control law such that for any exogenous input $w(t)$ in a pre-specified ball Ω of $L_2[0, \infty)$, the controlled output $\|z(t)\|_2$ is minimum, i.e., the transfer function between exogenous input and controlled output is minimum in $L_2[0, \infty)$. By defining Ω in the normalized form

$$\Omega = \{w(t) | w(t) \in L_2[0, \infty), \|W(t)\|_2 \le 1\} \tag{11}$$

the theorem proposed by Hwang in 1993 [1] can now be applied.

Theorem 1.

For a plant in the standard form of Eqn. (10), suppose (A, B_2) is controllable, (C_2, A) is observable, $D_{12}^T D_{12} = I$, $D_{12}^T C_1 = 0$ (the orthogonal assumption). Then, the H_∞-optimal control law $u(t)$ minimizing $||Z||_2$ under the worst exogenous input in a pre-specified ball in $L_2[0, \infty)$ is given by:

$$u(t) = -B_2^T K_1 X(t) \tag{12}$$

where K_1 is the positive definite solution of the Algebraic Riccatic Equation (ARE):

$$A^T K_1 + K_1 A + K_1(B_1 B_1^T - B_2 B_2^T)K_1 + C_1^T C_1 = 0 \tag{13}$$

If Eqns. (12) and (13) is under the assumption of a white Gaussian input, the $u(t)$ is given by

$$u(t) = -B_2^T K X(t) \tag{14}$$

where K is the positive definite solution of the ARE:

$$A^T K + KA - KB_2 B_B^T K + C_1^T C_1 = 0 \tag{15}$$

However, in many cases it is difficult to form the standard problem satisfying the orthogonal condition, $D_{12}^T C_1 = 0$. Therefore, to facilitate use of the H_∞ approach, the orthogonal assumption must be removed. For this reason, the following theorem leading to a more general solution of the time-varying H_∞-optimal control problem is developed.

Theorem 2.

For a plant in the standard form of Eqn. (10), suppose (A, B_2) is controllable, (C_2, A) is observable, $D_{12}^T D_{12} = I$, then, the H_∞-optimal state feedback control law $u(t)$ minimizing $||Z||_2$ under the worst exogenous input in a pre-specified ball in $L_2[0, \infty]$ is given by:

$$u(t) = -(B_2^T K_1 + D_{12}^T C_1)X(t) \tag{16}$$

where K_1 is the positive definite solution of the ARE:

$$0 = (A - B_2 D_{12}^T C_1)^T K_1 + K_1(A - B_2 D_{12}^T C_1) + K_1(B_1 B_1^T$$
$$- B_2 B_2^T) K_1 + C_1^T (I - D_{12} D_{12}^T)(I - D_{12} D_{12}^T) C_1 \tag{17}$$

For a linear time-invariable systemexpressed in the following form:

$$\dot{x}_s(t) = A_s x_s(t) + B_s u(t) + G_s D_s(t)$$

$$\dot{x}_S(t) = A_S x_S(t) + B_S u(t) + G_S(t) D_S(t) \tag{18}$$

where A_s, B_s, C_s and G_s are Augmented matrices described in [1].

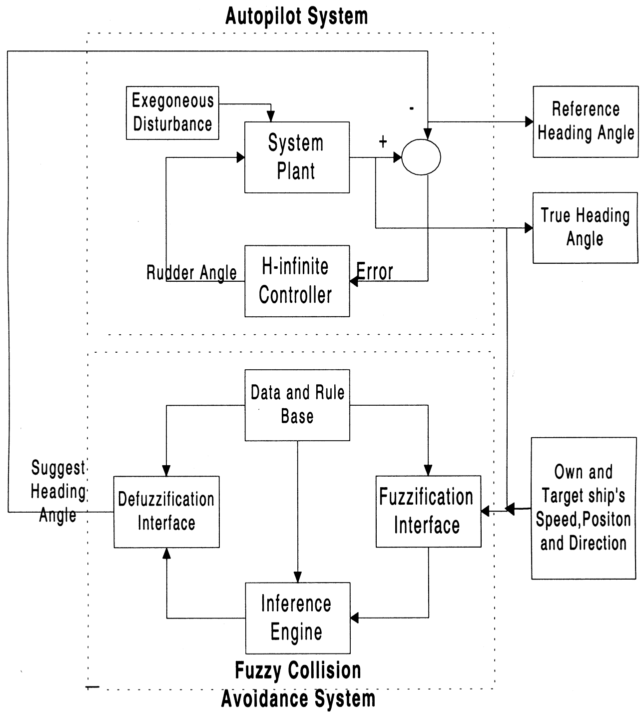

Fig. 8. Diagram of the integration of fuzzy collision-avoidance and H_∞ autopilot system.

It can easily be transformed into a standard form as shown in Eqn. (10) by the formulation methods mentioned in [1]. The above theorems can then be applied to obtain an optimal controller for the proposed autopilot. Based on the above strategy, the system block diagram of the proposedautopilot system is designed and shown in Fig. 8. By integrating the proposed fuzzy collision-avoidance and autopilot systems, the avoidance action advised by fuzzy collision-avoidance system can then be implemented by H_∞ autopilot system.

COMPUTER SIMULATION RESULTS

In this section, the methodology developed in the previous sections is applied to an oil tank [17], whose system parameters are known, so as to prove the feasibility of the proposed integrated system. The ship is of length 331 m, width 52 m, mould depth 26 m, mould draft 20 m and weight 285944 tons.

The dynamic equation of the ship at 15 knots is:

$$\dot{x}_S(t) = A_S x_S(t) + B_S u(t) + G_S(t) D_S(t)$$

$$y_s(t) = C_s x_s(t)$$

where

$$A_s = \begin{bmatrix} -0.2019\times 10^{-1} & -0.1199\times 10^{2} & 0 \\ -0.3679\times 10^{-4} & -0.3996\times 10^{-1} & 0 \\ 0 & 1 & 0 \end{bmatrix} \quad (19)$$

$$B_s = \begin{bmatrix} 0.1415\times 10^{0} \\ -0.9786\times 10^{-3} \\ 0 \end{bmatrix} \quad (20)$$

$$C_s = [0 \quad 0 \quad 1]$$

$$G_s = \begin{bmatrix} 7.6703\times 10^{-4}\sin 4t & 0 \\ 0 & 1.1069\times 10^{-5}\sin 6t \\ 0 & 0 \end{bmatrix}$$

The state vector $x_s = [v \ \ r \ \ \varphi]^T$ represents the sway velocity, the yaw angle velocity and the yaw angle of the ship, respectively. The control input $u(t)$ denotes the rudder angle of the ship. Disturbance $D_s(t)$ contains the sidelong force and yaw moment induced by sea waves. In simulation, the disturbance is chosen as a unit step input. The dynamic equation of the rudder can be expressed as:

$$\frac{\delta}{\delta_c} = \frac{1}{1+\tau s}$$

Where δ is the output rudder angle, δ_c is the input rudder signal of the steering system, and τ is the time constant of the system. Therefore, the plant, which includes the ship's model and the steering system, can be rearranged as:

$$\begin{bmatrix} x_s(t) \\ \delta(t) \end{bmatrix} = \begin{bmatrix} A_s & B_s \\ 0 & -\frac{1}{\tau} \end{bmatrix}\begin{bmatrix} x_s(t) \\ \delta(t) \end{bmatrix} + \begin{bmatrix} G_s(t) \\ 0 \end{bmatrix} D_S(t) + \begin{bmatrix} 0 \\ \frac{1}{\tau} \end{bmatrix} \delta_c(t)$$

$$y_s(t) = [C_s \quad 0]\begin{bmatrix} x_s(t) \\ \delta(t) \end{bmatrix}$$

To study the course tracking performance of the ship, the servo compensator and the weighting function are chosen as $(A_c, B_c, C_c) = (-0.001, 850, 1)$ and $(A_1, B_2, C_3) = (-0.001, 0.22, 1)$, respectively. To ensure good disturbance-rejection capability for all kinds of exogenous inputs, other than pure white Gaussian signals, the proposedautopilot formulation is used in this example.

It is assumed that the positions, the heading angles and the speeds of own ship and the encountering ships can be obtained from the on-line outputs of a Radar, a Loran-C, a G.P.S., a Doppler Log, an electromagnetic log or an automatic radar plotting apparatus (ARPA). When a ship navigates at sea, there are numerous encountering cases, fifty of which are discussed in details by Imazu. To demonstrate the feasibility of the proposed integrated system, three typical and complex encountering cases among these fifty situations are explored. They represent the encountering cases of avoiding obstacles, crossing a single alley and crossing double allies, which are shown in Fig. 9, Fig. 11, and Fig. 13 respectively. They are denoted as the case 1, the case 2 and the case 3 in these figures.

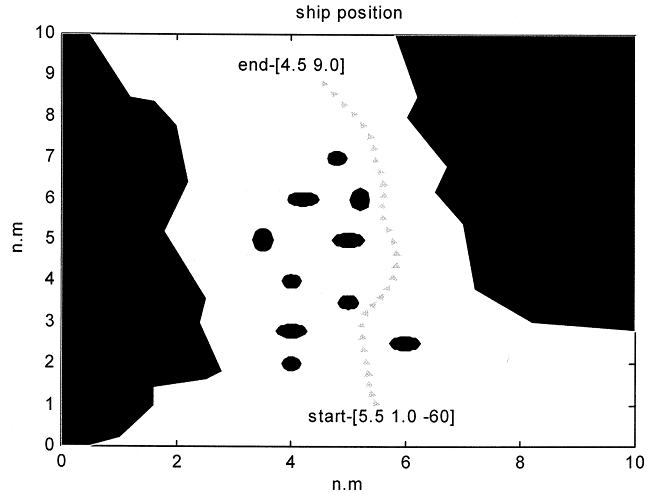

Fig. 9. Suggested path for avoiding obstacles (case1).

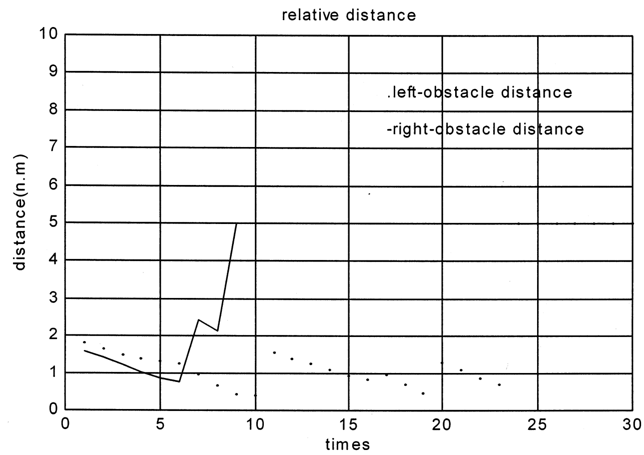

Fig. 10. Relative distance from the obstacles for case1.

For the encountering obstacles, the computer simulation results reveal that the proposed fuzzy collision-avoidance system advises a dotted-line ship path as shown in Fig. 9. Fig. 10 gives the relative distance between the ship and obstacles, which clearly indicates that the system can effectively avoid a possible collision with these obstacles. The path advised by the proposed fuzzy collision-avoidance system is then executed by the H_∞ auto-pilot, which achieves a perfect route-tracking as shown in Fig. 15 under the surrounding disturbances while the details of the path tracking

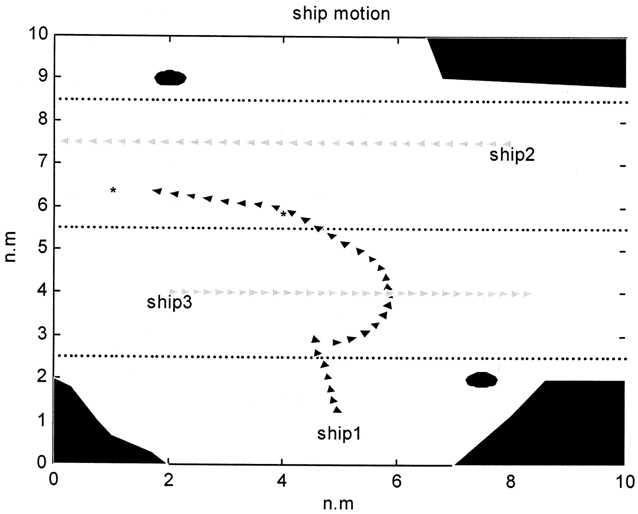

Fig. 11. Suggested path to avoid collision in the case of crossing a single alley (case2).

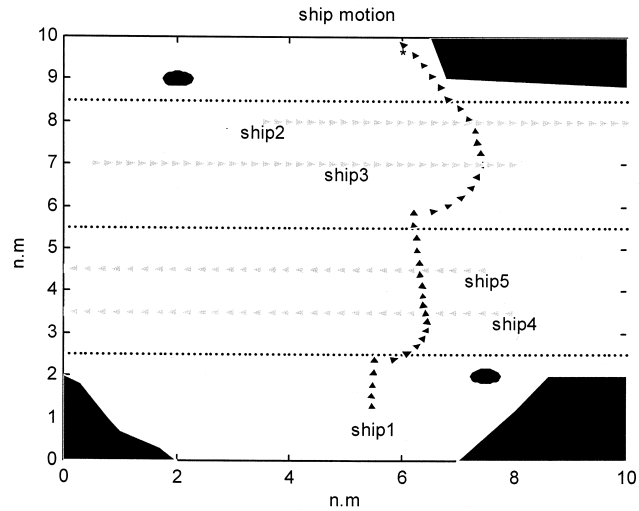

Fig. 13. Suggested path to avoid collision in the case of crossing double allies (case3).

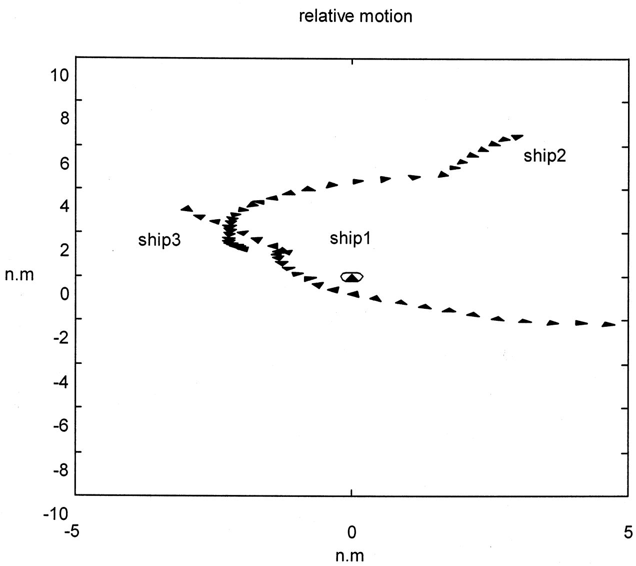

Fig. 12. simulation of crossing single alley for case2.

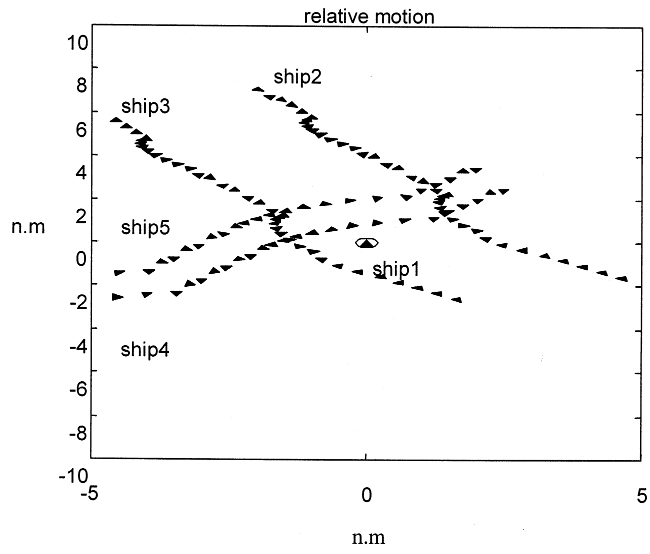

Fig. 14. Relative position between the encountering ships for case3.

errors are given in Fig. 16.

The encountering case shown in Fig. 11 shows how the fuzzy collision-avoidance system instructs the ship 1 to avoid the collision with the ships 2 and 3 in crossing a single-alley. The relative position between the encountering ships shown in Fig. 12 indicates that the avoidance action is successful. By applying the H_∞ autopilot to the system, Fig. 17 shows that an excellent tracking result can be achieved even under a persistent disturbance mentioned before. The tracking errors of the suggested path are small and are shown in Fig. 18.

In Fig. 13, the ship 1 meets four ships and two obstacles when it intends to cross the double allies. The navigating path suggested by the fuzzy collision-avoidance system is shown in Fig. 13, which demonstrates its feasibility of the fuzzy collision-avoidance system in Fig. 14. The path advised by the proposed fuzzy collision-avoidance system is then executed by the H_∞ autopilot, which can still achieve a good route-tracking precision as shown in Fig. 19 even under various surrounding disturbances. The details of the path tracking errors are given in Fig. 20.

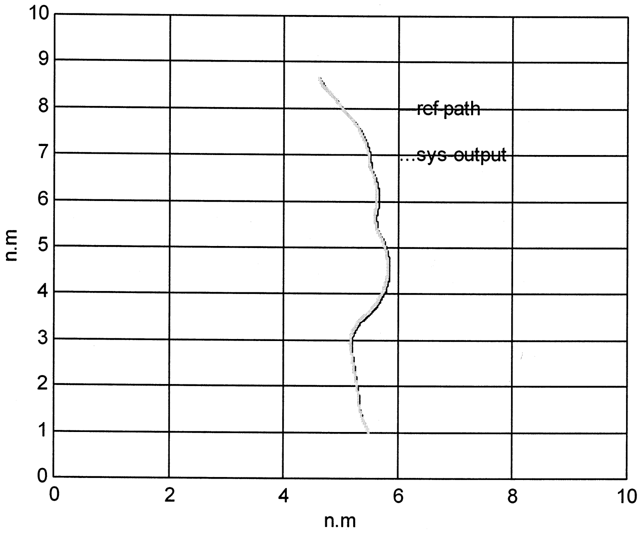

Fig. 15. Path tracking executed by the autopilot for case1.

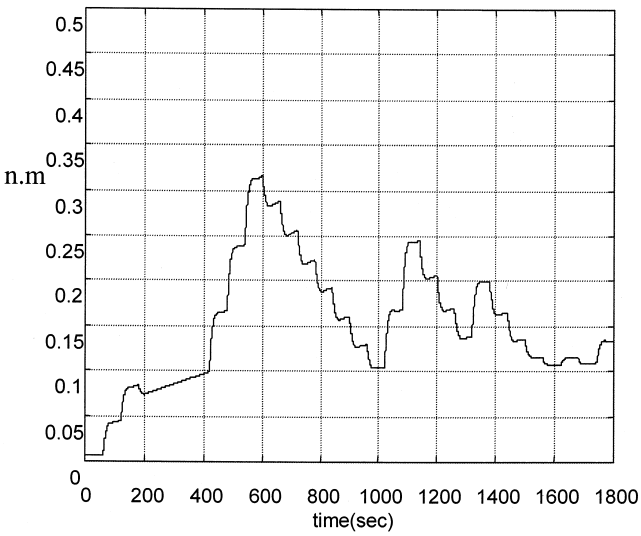

Fig. 16. The tracking errors in case1.

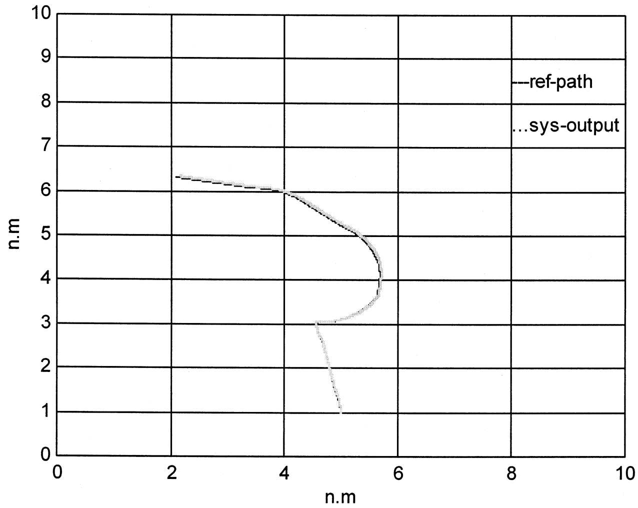

Fig. 17. Path tracking executed by H_∞-autopilot for case2.

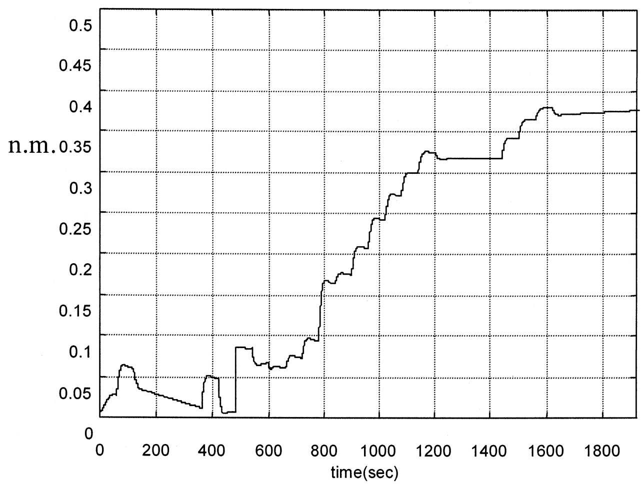

Fig. 18. Tracking errors in case2.

CONCLUSION

As international trade increases, vessels tend to be bigger and to be operated more automatically, yet collision accidents are also increasing as ships increase in size, in speed and in number. The problem of collision-avoidance, therefore, becomes an urgent issue. The fuzzy collision-avoidance system, cooperated with navigators, explored in this paper, is used to avoid collisions between ships. When own ship is in the danger of colliding with obstacles or target ships, the fuzzy collision-avoidance system will advise a proper avoidance action to resolve the risk. Either a quarter-master or an autopilot system can then implement the avoidance action.

The objective of H_∞ control problem is to obtain an H_∞ optimal control law such that the transfer function between the exogenous input and the controlled output is minimum while keeping the closed-loop system stable. In this research, we designed an autopilot with H_∞ theory to ensure that the closed-loop system still has certain robustness under the worst exogenous input. The integration of fuzzy collision-avoidance and H_∞ autopilot systems is proposed in this paper. The avoidance action advised by fuzzy collision-avoidance system can then be implemented by H_∞ autopilot system.

Computer simulation results reveal that with the aid of the integration of fuzzy collision-avoidance sys-

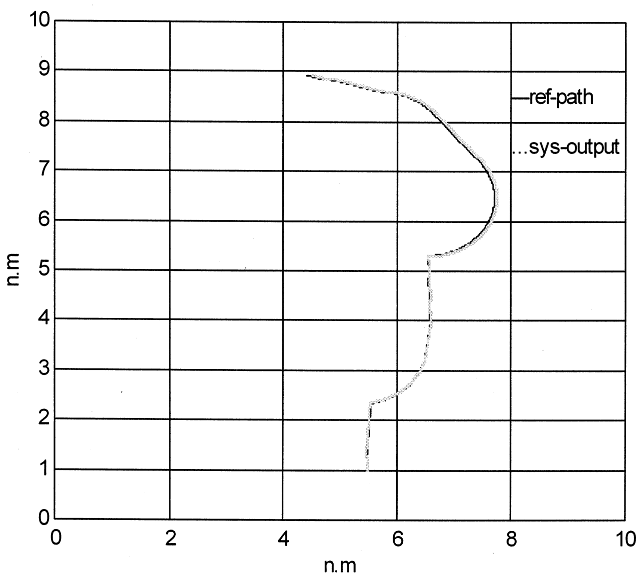

Fig. 19. Path tracking executed by H_∞- autopilot for case3.

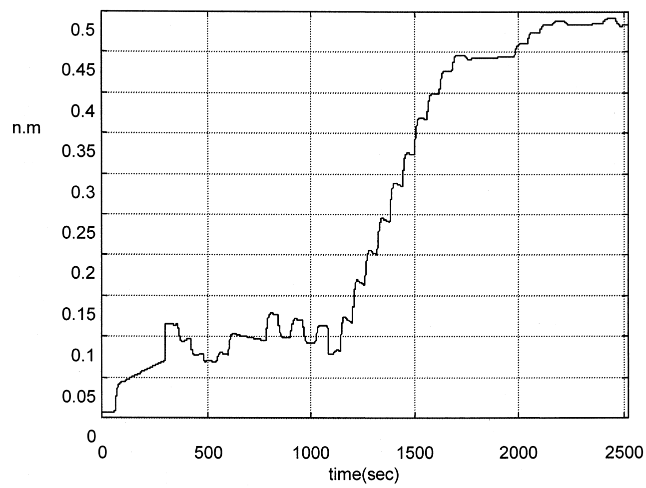

Fig. 20. Tracking errors in case3.

tem and H_∞ auto-pilot system designed in this paper, ships can advise a proper avoidance action to avoid the risk of collision at the right time and can track the desired path within allowable range to reach the target port.

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輔以H_∞–控制操舵系統之模糊避碰系統的設計

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摘 要

船舶避碰是海上運輸中相當重要課題之一。不論從以前傳統的目視航行到現在藉著電子設備來輔助航行，當船舶面臨碰撞危機時幾乎都還是依賴航行者的經驗。這種方式在以前交通不是如此擁擠時還能使用，但在現今海上貿易量大幅增加且船舶趨向大型化下，除了船舶的噸位、速度、數量都急劇增加外，再加上海上林立的鑽探設施，使得現在的海上交通日趨複雜，因此如果我們仍延用以往的方式來解決碰撞問題，則很可能會因爲人爲的疏忽而造成無法挽回的損失。這一點在開闊水域尚且如此，如果船舶在一些非開闊水域中將會更爲明顯！本文利用H_∞–控制和模糊理論來設計的H_∞–操控避碰系統，協助航行官員處理有關船舶在面對障礙物或在分道航行制中橫越巷道時之避碰的問題。當吾船與目標船或障礙物之間遭遇碰撞危機時，本研究所設計之模糊避碰系統能夠適時採取避碰措施，以化解碰撞危機。而此避碰系統所建議的避碰航向方面的操控，則是直接由本文所設計的H_∞–控制之操舵系統來執行。最後本文經由電腦模擬來驗證所設計之避碰操舵系統的可行性；模擬結果顯示：當吾船航行於非開闊水域之中，此避碰操舵系統確實能夠化解碰撞危機。