AUTOMATIC COLLISION AVOIDANCE SYSTEM FOR SHIPS USING FUZZY CONTROL

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1. ABSTRACT

The author proposes an automatic collision avoidance system controlled by an on-board computer. The system consists of the following four parts; the detection of target ship(s) from radar signal, decision of the collision risk, course and speed change commands and course control autopilot. All parts except the detection are treated and done by fuzzy reasoning or fuzzy control. Fuzzy control is quite similar to the human control and so flexible even to unexpected environmental changes.

Computer simulation is done for the various encounter conditions of a target ship and the results are found to be reasonable and reliable as compared with human behaviours. The system is also applied to the collision avoidance very close to the course changing point or with conflicting behaviours of a target ship. For both cases, the system is found to work properly.

2. INTRODUCTION

Collision avoidance manoeuvre is one of the most difficult problems in automation of ship operation. We should consider various situations surrounding the own ship such as own and target ships' manoeuvring characteristics, restrictions of the navigation lines and legalistic limitations etc. In the actual navigation, highly experienced experts such as captains only can make a suitable decision according to their knowledges with some navigational aids. Therefore, we should link some decision making software such as an expert system to the automatic collision avoidance system for the purpose of the practical applications.

In the present study, however, as a first stage of the future integration, the author deals with automatic collision avoidance manoeuvres against one threatening ship, while the own ship is sailing along the scheduled path. The system decides the timing and the mannner of avoidance manoeuvres, if necessary, and sends proper commands to the steering and engine control subsystem. The system also includes an autopilot itself and all parts are realized by fuzzy reasoning or fuzzy control, which is quite similar to human behaviours and may be easily linkable to an expert system.

3. SYSTEM CONFIGURATION

The proposed system consists of the following subsystems:

(A) Avoidance manoeuvres subsystem
(B) Track keeping subsystem
(C) Steering and engine control subsystem

Besides, two other subsystems are provided, which are useful or necessary for computer simulation.

(D) System monitoring subsystem
(E) Ship dynamics subsystem

In the following sections, each subsystem will be explained in detail. For all subsystems (A), (B) and (C), fuzzy reasoning or fuzzy control is used. So, first of all, a brief description about fuzzy theory will be made. For more detail information, please refer to the related publications.

4. FUZZY CONTROL

4.1 Fuzzy theory

Fuzzy theory was first introduced by Zadeh[1] to treat fuzzy concepts restrictly in mathematical way. He used fuzzy subset for this purpose. Let $\underline{A}$ be a subset and $\underline{a}$ be an element of an unknown set. In the usual set, $\underline{a}$ should be an element of $\underline{A}$ or not an element of $\underline{A}$ (see Fig. 1). On the contrary, in the fuzzy subset, the degree of membership of a concept is represented by a membership function $\mu_A(\underline{a})$ $(0 \leqq \mu_A(\underline{a}) \leqq 1)$. In other words, the boundary of the set is "fuzzy" (see Fig. 2). If the value of $\mu_A(\underline{a})$ is nearly zero, $\underline{a}$ is almost unlikely an element of $\underline{A}$ but cannot be denied. If the value of $\mu_A(\underline{a})$ is nearly one, $\underline{a}$ is undoubtfully an element of $\underline{A}$ but cannot be declared.

For more concrete example, Fig. 3 illustrates an example of membership functions of the concepts "young" and "old". We can easily understand the "fuzzy" situation of 30's or 40's from the fugure.

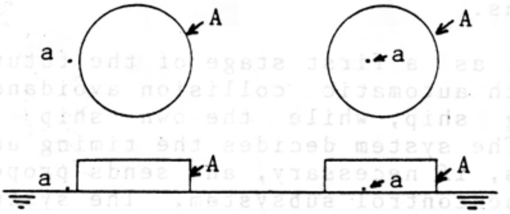


Figure 1. Two possible situations in usual set theory

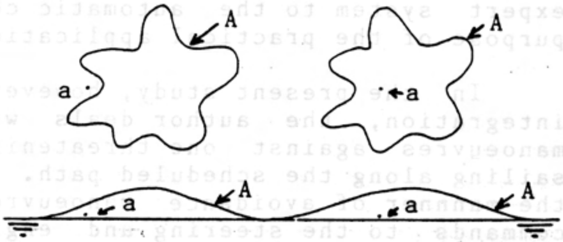


Figure 2. Concept of a fuzzy subset

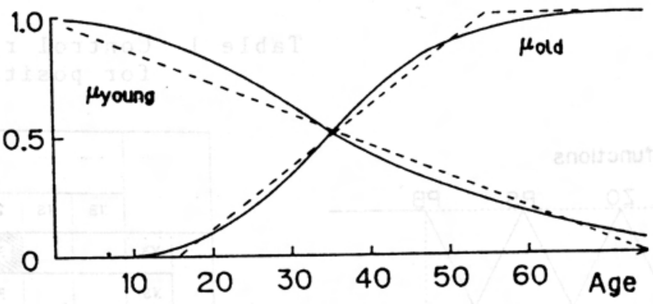


Figure 3. Membership functions of the concepts "young" and "old"

As well as the fuzzy subset theory, the fuzzy arithmetic may be defined, by which fuzzy theory becomes to be applied in various fields of engineering.

In the next section, an example of fuzzy control will be shown for explaining terminology and methodology.

4.2 Example of fuzzy control — position keeping —

(Problem) Control the speed $\underline{u}$ of a mass to keep its position $\underline{x}$ at the origin. The mass has one freedom of movement direction and there acts uniform noise between -0.2 to 0.2 per a unit time.

Let the position error be

$$e = x - 0 \tag{1}$$

and the fuzzy variables be

NB : negative big
NS : negative small
ZO : zero
PS : positive small
PB : positive big

The membership functions of these fuzzy variables are shown in Fig. 4 and the control rules are summarized in Table 1, for example. The same set of fuzzy variables and the same set of membership functions are used for $\underline{e}$, $\underline{\dot{e}}$ and $\underline{u}$, for the sake of simplicity, but they may be different in general. In Fig. 4, we can read, for example, the degree (0∿1) of the concept 'NS' is defined around -0.5 and between -1 to 0.

In Table 1, we read, for example in the hatched part that

"IF the deviation $\underline{e}$ is negative big
AND IF its derivative $\underline{\dot{e}}$ is zero,
THEN change its speed $\underline{u}$ to positive big."

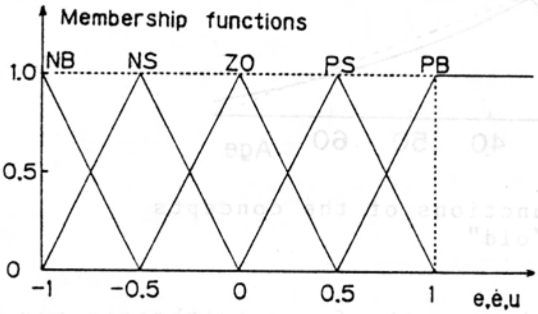


Figure 4. Membership functions for position keeping

Table 1 Control rules for position keeping

		ė				
		NB	NS	ZO	PS	PB
e	NB			PB		
	NS			PS		
	ZO	PB	PS	ZO	NS	NB
	PS			NS		
	PB			NB		

Let us assume the deviation and its derivative are $\underline{e}_0$ and $\underline{\dot{e}}_0$ respectively, the membership function of PB for speed $\mu_{PB}(\underline{u})$ will be modified by $\mu_{NB}(\underline{e}_0)$ and $\mu_{ZO}(\underline{\dot{e}}_0)$ that

$$\mu^*_{PB}(u) = \{ \mu_{NB}(e_0) \wedge \mu_{ZO}(\dot{e}_0) \} \cdot \mu_{PB}(u) \qquad (2)$$

where $\wedge$ denotes 'AND' operation or minimum selection. Applying Eq.(2) to all rules in Table 1, we can define the modified membership function of output speed that

$$\mu(u) = \mu^*_{NB}(u) \vee \mu^*_{NS}(u) \vee \mu^*_{ZO}(u) \vee \mu^*_{PS}(u) \vee \mu^*_{PB}(u) \qquad (3)$$

where V denotes 'OR' operation or maximum selection. The most possible control output may be obtained from the centre of gravity of $\mu(\underline{u})$ that

$$u_0 = \frac{\int u\mu(u)\, du}{\int \mu(u)\, du} \qquad (4)$$

Fig. 5 shows the above mentioned procedure illustratively.

Fig. 6 is the demonstrative comparison of thus obtained fuzzy controller (a) and conventional PD controller (b). In the case of PD control, fluttering according to the noise is observed, although it depends upon control parameters. In the case of fuzzy control, however, some 'filtering effect' similar to human operation may be observed.

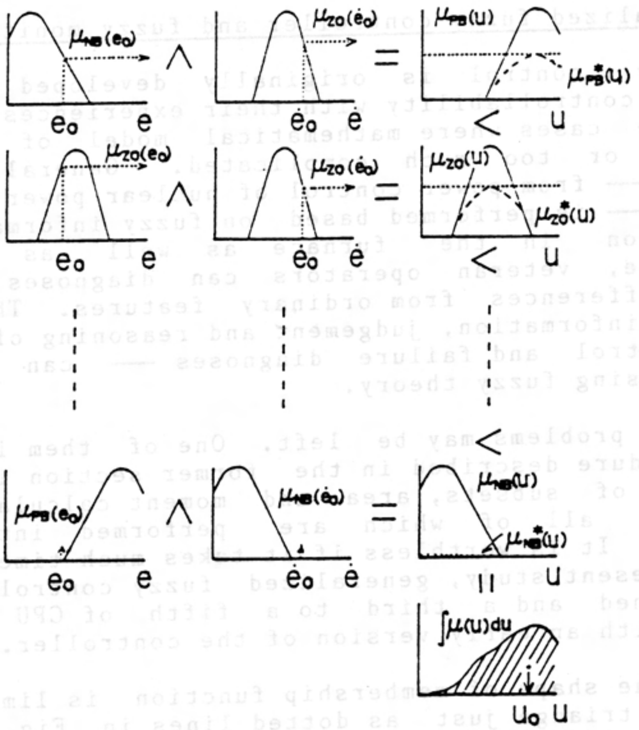
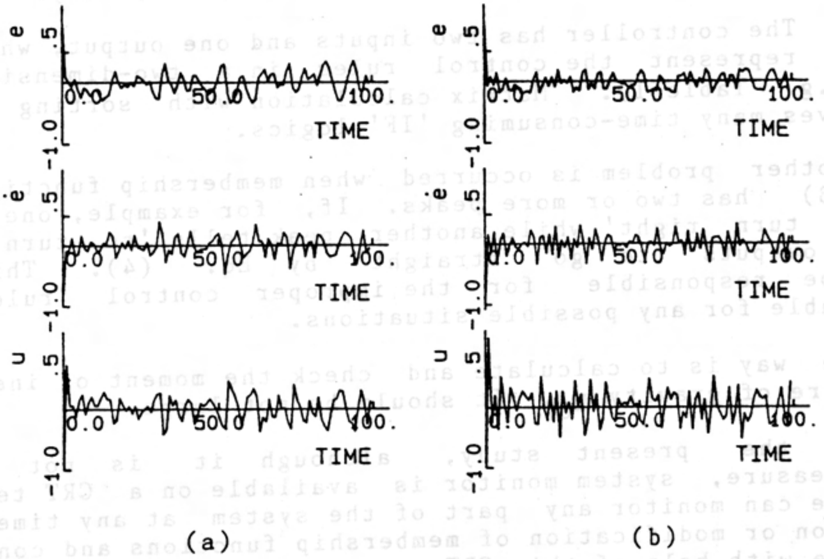


Figure 5. Procedure of fuzzy reasoning



(a)

(b)

Figure 6. Comparison between fuzzy and PD control

4.3 Generalized fuzzy controller and fuzzy monitor

Fuzzy control is originally developed by learning human superior controllability with their experiences or perceptions even for those cases where mathematical model of the process is not available or too much complicated. Generally speaking, plant control —— from power control of nuclear power plant to flavouring of stew —— is performed based on fuzzy information such as colour distribution in the furnace as well as monitoring meters. Furthermore, veteran operators can diagnoses plant failures by slight differences from ordinary features. These procedures —— gathering information, judgement and reasoning of the present state, plant control and failure diagnoses —— can be replacable by a computer using fuzzy theory.

Some problems may be left. One of them is calculation time. The procedure described in the former section includes product and summation of subsets, area and moment calculation of membership functions, all of which are performed intuitively by human operators. It is worthless if it takes much time in this procedure. In the present study, generalized fuzzy controller described below was designed and a third to a fifth of CPU time was achieved compared with an early version of the controller.

1) The shape of membership function is limited to a trapezium or a triange just as dotted lines in Fig. 3. The membership function is originally a fuzzy representation of a concept, so there arises little difference by this limitation. No more than two concepts overlie on any points. By these limitation calculation of crossing points and area becomes very simple and setting of membership functions becomes very easy.

2) The controller has two inputs and one output, which enables to represent the control rules in a two-dimensional matrix (e.g. Table 1). Matrix calculation with sorting techniques saves many time-consuming 'IF' logics.

Another problem is occurred when membership function obtained by Eq.(3) has two or more peaks. If, for example, one peak tells us 'to turn right' while another peak tells 'to turn left', the system outputs 'to go straight' by Eq. (4). This problem must be responsible for the improper control rules, but is unavoidable for any possible situations.

One way is to calculate and check the moment of inertia among the centre of gravity $\underline{u}_0$. It should be not large.

In the present study, although it is not a direct countermeasure, system monitor is available on a CRT terminal, on which we can monitor any part of the system at any time. Indeed, alteration or modification of membership functions and control rules were done with help of this CRT monitor during the study.

5. DESCRIPTION OF EACH SUBSYSTEM

5.1 Avoidance manoeuvres subsystem

This is the most important part in the whole system, where the system watches the radar and, if necessary, sends commands when and how we should avoid the threatening ship.

In the actual system we should prepare the subsystem of detection, where the system picks up threatening ship(s). This has been already realized in Automatic Radar Plotting Aids (ARPA), so we do not treat it. The inputs to this subsystem are relative position(s) of threatening ship(s).

Several criteria are proposed to judge if the own ship should take avoidance manoeuvres or not from the relative position of a threatening ship[2]. The common variables appeared in these criteria are distance of closest point of approach (DCPA) and time of closest point of approach (TCPA). The judgement of human operators also deeply concerns on these two values[3].

In the present study, collision risk (CR) is obtained from DCPA and TCPA by fuzzy reasoning. Membership functions and control rules for reasoning are shown in Fig. 7 and Table 2 respectively. The starts of avoidance manoeuvres is decided when CR reaches to a certain values, for example 0.70.

The manner of avoidance manoeuvres is roughtly set as shown in Fig. 8, regarding International Rules of the Nautical Road. In Fig. 8, the ordinate is the current ordered course of the own ship, the origin is the closest point of approach (CPA) and the own ship is currently on the negative part of the ordinate as shown in the figure. Type 0 is the case of overtaking, where right turn manoeuvre will be chosen when a threatening ship crosses the 'dangerous triangle', which is defined more detail in Fig. 9. When a threatening ship is in Type I or II region (the boundary of regions is not necessary to be strictly defined), the system will track the target ship and calculates CR continuously. Once CR reaches to 0.70, the system orders to turn right for Type I and to turn left and at the same time to reduce speed for Type II. The own ship is burdened for these three Types, but for cases of Types III and IV, she is privileged, so she needs not change her course. However, the system continues to check CR even for these cases, and if CR grows up to 0.85, the system judges that the treatening ship has no will to avoid or doesn't detect the own ship.

Avoidance manoeuvres by changing the course are modelled as follows, referring the actual operations (see Fig. 10).

(A) Course changing

At least 30° is taken to transmit the will of avoidance to the target ship. Then, the system calculates collision risk of after TCPA time, keeping the current course (defined $\widetilde{CR}$), and increases course change until $\widetilde{CR}$ will be less or equal to 0.70.

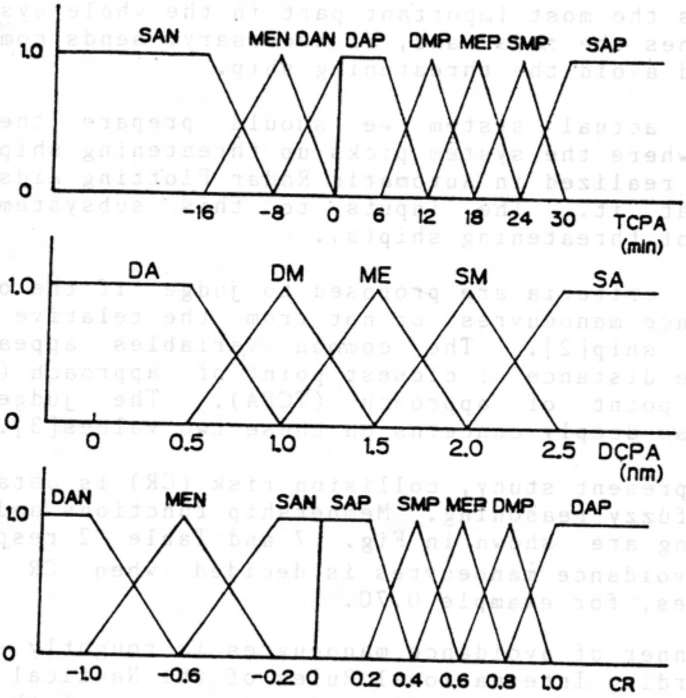


Figure 7. Membership functions for collision risk reasoning

Table 2. Control rules for collision risk reasoning

		TCPA							
		SAN	MEN	DAN	DAP	DMP	MEP	SMP	SAP
DCPA	DA	SAN	MEN	DAN	DAP	DMP	MEP	SMP	SAP
	DM	SAN	SAN	MEN	DMP	MEP	SMP	SAP	SAP
	ME	SAN	SAN	SAN	MEP	SMP	SAP	SAP	SAP
	SM	SAN	SAN	SAN	SMP	SAP	SAP	SAP	SAP
	SA	SAN	SAN	SAN	SAP	SAP	SAP	SAP	SAP

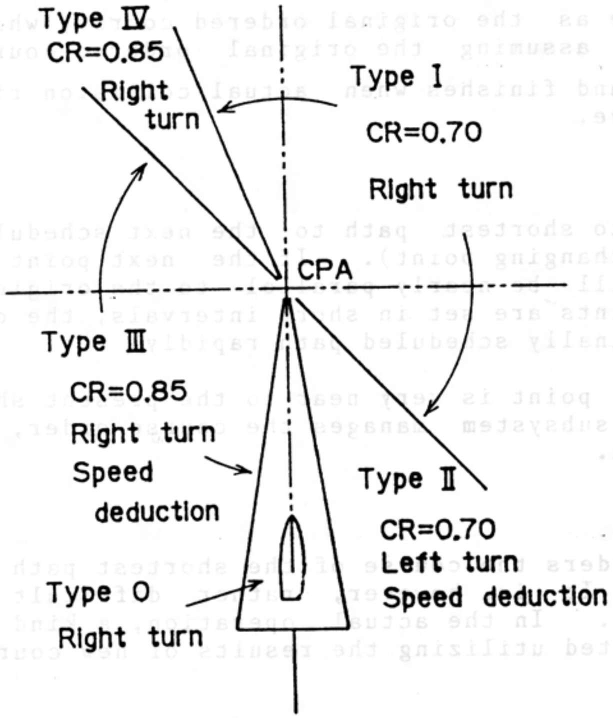


Figure 8. Pattern definitions of collision avoidance manoeuvres

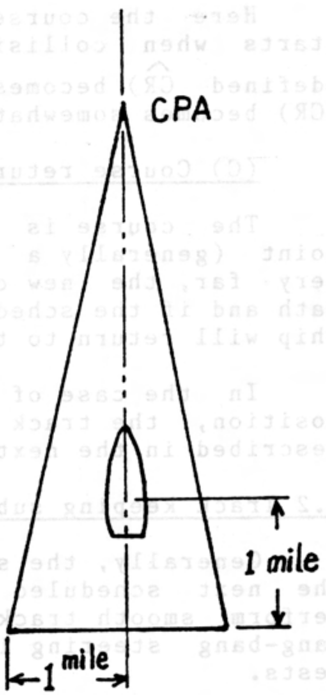


Figure 9. Region of overtaking

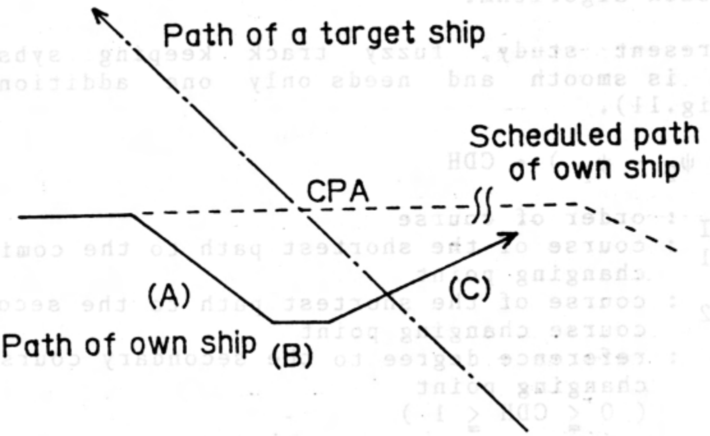


Figure 10. Path of collision avoidance manoeuvres

(B) Parallel shift

Here the course is same as the original ordered course, which starts when collision risk assuming the original ordered course (defined $\widehat{CR}$) becomes 0.70 and finishes when actual collision risk (CR) becomes somewhat negative.

(C) Course return

The course is chosen to shortest path to the next scheduled point (generally a course changing point). If the next point is very far, the new course will be nearly parallel to the original path and if the scheduled points are set in short intervals, the own ship will return to the originally scheduled path rapidly.

In the case of the next point is very near to the present ship position, the track keeping subsystem manages the course order, as described in the next section.

5.2 Track keeping subsystem

Generally, the system orders the course of the shortest path to the next scheduled point. It is, however, rather difficult to perform smooth track keeping. In the actual operation, a kind of bang-bang steering is conducted utilizing the results of new course tests.

Koyama et al.[4] use the similar method installed for computer simulation, but the timing of start of first steering is not determined automatically.

Amerongen et al.[5] have developed track keeping system using model reference adaptive control, and Norrbin et al.[6] proposed a very simple feedback algorithm.

In the present study, fuzzy track keeping sybsystem is designed, which is smooth and needs only one additional simple algorithm (see Fig.11).

$$\psi_I = \psi_1 + (\psi_2 - \psi_1) \cdot \mathrm{CDH} \qquad (5)$$

where
ψ_I : order of course
ψ_1 : course of the shortest path to the coming course changing point
ψ_2 : course of the shortest path to the secondary course changing point
CDH : reference degree to the secondary course changing point ($0 \leqq \mathrm{CDH} \leqq 1$)

For reasoning of CDH, similar approach of avoidance manoeuvres subsystem is involved. Let the course changing point be assumed as a target ship, CDH is obtained from DCPA and TCPA to the course changing point. Membership functions and control rules are shown in Fig. 12 and Table 3 respectively.

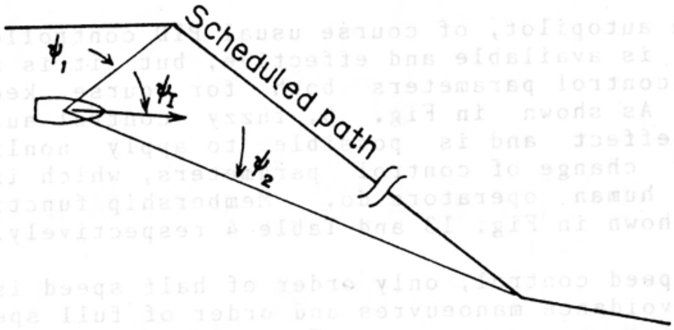


Figure 11. Course command near a course changing point

Table 3. Control rules for course changing algorithm

		TCPA				
		SA	SM	MM	ML	LA
DCPA	SA	LA	ML	MM	SM	ZE
	SM	ML	MM	SM	ZE	ZE
	MM	MM	SM	ZE	ZE	ZE
	ML	SM	ZE	ZE	ZE	ZE
	LA	ZE	ZE	ZE	ZE	ZE

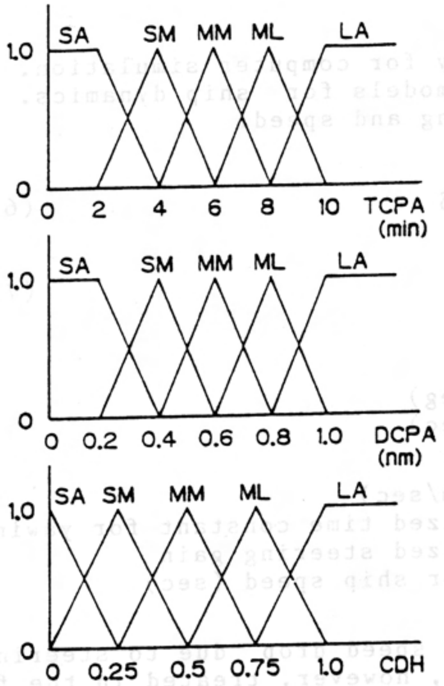


Figure 12. Membership functions for course changing algorithm

5.3 Steering and engine control subsystem

For an autopilot, of course usual PID controller or an adaptive controller is available and effective, but it is not profitable to use same control parameters both for course keeping and course changing. As shown in Fig. 6, fuzzy control autopilot has some filtering effect and is possible to apply nonlinear smooth but linear-like change of control parameters, which is maybe the same manner as human operators do. Membership functions and control rules are shown in Fig. 13 and Table 4 respectively.

For speed control, only order of half speed is deliveried when starting avoidance manoeuvres and order of full speed is deliveried when ordering course return in Types II and III of Fig. 8. Neither the setting of propeller revolution, nor the selection of speed itself is considered in the present study.

5.4 System monitoring subsystem

Operators can monitor informations concerning to the own ship and the threatening ship(s), and input/output states of each subsystem or fuzzy controller, as described in <u>4.3</u>.

5.5 Ship dynamics subsystem

This subsystem is prepared only for computer simulation. It is not necessary to provide strict models for ship dynamics. First order models are used both for yawing and speed:

$$T' \left(\frac{L}{V} \right) \ddot{\psi} + \dot{\psi} = K' \left(\frac{V}{L} \right) \delta \qquad (6)$$

$$T_V \dot{V} + V = V^* \qquad (7)$$

where ψ : yaw angle (deg)
δ : rudder angle (deg)
V : ship speed (m/sec)
L : ship length (m)
V^* : ordered speed (m/sec)
T' : non-dimensionalized time constant for yawing
K' : non-dimensionalized steering gain
T_V : time constant for ship speed (sec)

Dynamics of a steering gear and speed drop due to steering and yawing are ignored, which should be, however, treated in the future work.

The target ship sails only straight or on a zig-zag course at a constant speed.

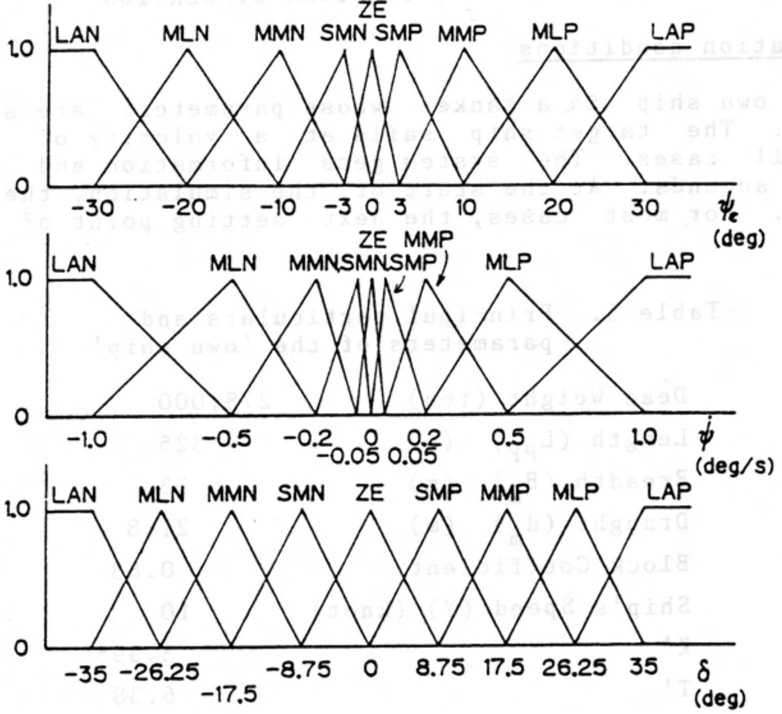


Figure 13. Membership functions for fuzzy control autopilot

Table 4. Control rules for fuzzy control autopilot

		HEADING ERROR								
		LAN	MLN	MMN	SMN	ZE	SMP	MMP	MLP	LAP
	LAN				MLP	LAP	LAP			
D	MLN				MMP	MLP	LAP			
	MMN	MMN	SMN	ZE	SMP	MMP	MLP	LAP	LAP	LAP
P	SMN	MLN	MMN	SMN	ZE	SMP	MMP	MLP	LAP	LAP
	ZE	LAN	MLN	MMN	SMN	ZE	SMP	MMP	MLP	LAP
H	SMP	LAN	LAN	MLN	MMN	SMN	ZE	SMP	MMP	MLP
	MMP	LAN	LAN	LAN	MLN	MMN	SMN	ZE	SMP	MMP
I	MLP				LAN	MLN	MMN			
	LAP				LAN	LAN	MLN			

6. VALIDATION OF THE SYSTEM BY COMPUTER SIMULATION

6.1 Simulation conditions

The own ship is a tanker whose parameters are summarized in Table 5. The target ship sails at a velocity of 10 knots for almost all cases. The system gets information and sends orders every 10 seconds. At the start of the simulation, the own ship is at (0,0). For most cases, the next setting point of the path is (15,0).

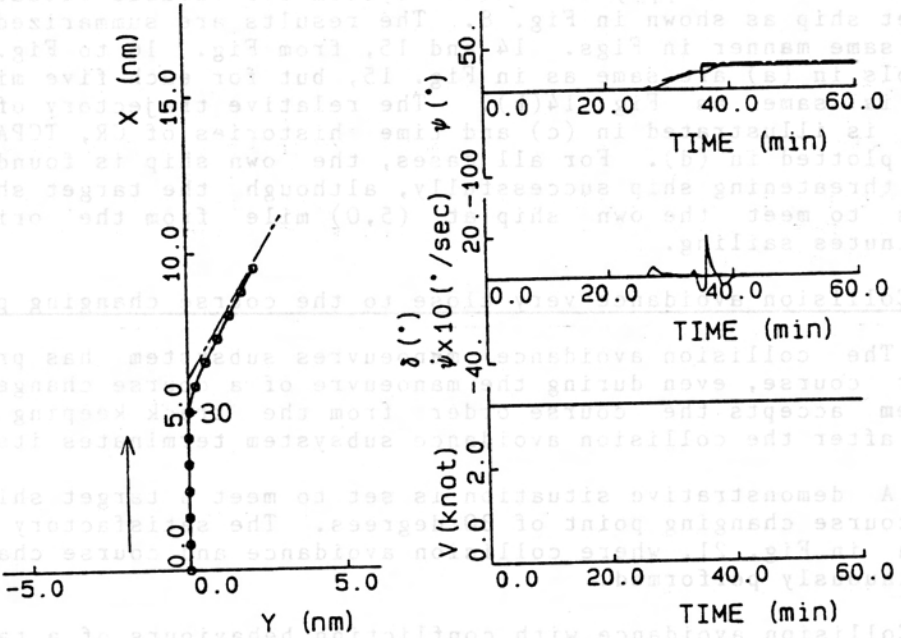
Table 5. Principal particulars and parameters of the 'own ship'

Dead Weight (ton)	278,000
Length (L_{PP}) (m)	325
Breadth (B_m) (m)	53
Draught (d_m) (m)	21.8
Block Coefficient	0.83
Ship's Speed (V) (knot)	10
K'	3.395
T'	6.38
T_v (sec)	500

6.2 Validation of each subsystem

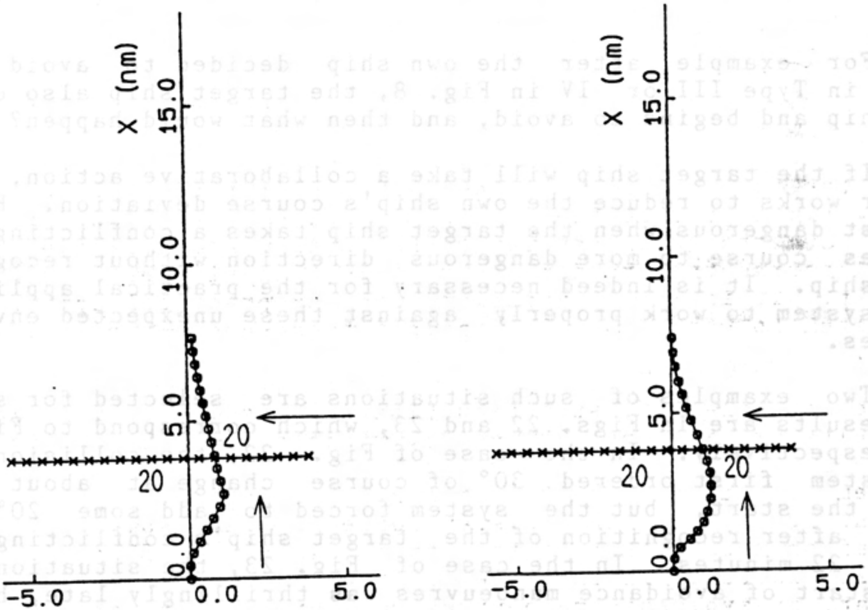
Track keeping subsystem is tested as shown in Fig. 14. In the figure, (a) is the trajectory where one-dot chain line represents scheduled path and the solid line does the actual ship path with her positions of every five minutes marked by circles. Numbers aside the marks are time in minute. In the same figure, (b) is the time histories of heading angles (— · — : scheduled, — — : ordered and —— : actual), rudder angle (——) and rate of turn (x10, — —) and ship speed (— — : ordered and —— : actual) from the top to the bottom in order. The smooth change of heading and the smooth approach to the new path are observed.

Avoidance manoeuvres subsystem is confirmed to work properly in comparison with human behaviour as shown in Fig. 15. In the figure, where the position of the own ship is marked by circles and that of the target ship is done by crosses both for every two minutes, (a) is the result of the automatic collision avoidance system and (b) is that of a veteran officer of 26 years' carrier, which was carried out at SR-151 Ship Handling Simulator of Osaka University. On the case of (b), the own ship is a VLCC tanker of 390 m L_{PP} with unstable loop of 4°, so the trajectory is rather fat. However, the starting point of avoidance manoeuvres, DCPA and the timing of return to the original path are all very similar. Therefore, we may conclude that the settings of each fuzzy controller are reasonable and reliable.



(a) (b)

Figure 14. Simulation of scheduled path navigation



(a) (b)

Figure 15. Simulation of collision avoidance manoeuvres by fuzzy control in comparison with human behaviour

Now we can apply the whole system for various situations of a target ship as shown in Fig. 8. The results are summarized, just as the same manner in Figs. 14 and 15, from Fig. 16 to Fig. 20. The symbols in (a) are same as in Fig. 15, but for each five minutes and (b) is same as Fig. 14(b). The relative trajectory of a target ship is illustrated in (c) and time histories of CR, TCPA and DCPA are plotted in (d). For all cases, the own ship is found to avoid the threatening ship successfully, although the target ship is set so as to meet the own ship at (5,0) mile from the origin after 30 minutes sailing.

6.3 Collision avoidance very close to the course changing point

The collision avoidance manoeuvres subsystem has priority to order course, even during the manoeuvre of a course change, and the system accepts the course order from the track keeping subsystem just after the collision avoidance subsystem terminates its mission.

A demonstrative situation is set to meet a target ship just at the course changing point of 30 degrees. The satisfactory result is shown in Fig. 21, where collision avoidance and course changing are continuously performed.

6.4 Collision avoidance with conflicting behaviours of a target ship

The system is always watching the target ship, even during the mission is undertook by collision avoidance subsystem. Therefore, it is possible to follow the conflicting behaviours of the target ship.

For example, after the own ship decided to avoid the target ship in Type III or IV in Fig. 8, the target ship also detects the own ship and begins to avoid, and then what would happen?

If the target ship will take a collaborative action, the system rather works to reduce the own ship's course deviation. However, it is most dangerous when the target ship takes a conflicting action or changes course to more dangerous direction without recognizing the own ship. It is indeed necessary for the practical applications of the system to work properly against these unexpected environmental changes.

Two examples of such situations are selected for simulation. The results are in Figs. 22 and 23, which correspond to Figs. 17 and 19 respectively. In the case of Fig. 22, the collision avoidance subsystem first ordered 30° of course change at about 15 minutes from the start, but the system forced to add some 20° to course order after recognition of the target ship's conflicting action at about 22 minutes. In the case of Fig. 23, the situation is worse. The start of avoidance manoeuvres was thrillingly late, because the own ship is privileged, and still she was under reducing her speed. It must be a kind of panic, if it occurs in the real navigation. The system made a cool decision of increasing course change gradually from about 45° to 90° and waited until the target ship has passed. The miss distance is rather shorter than that of Figs. 17 and 19, but can be acceptable, considering the emergent situation.

7. CONCLUSIONS

As a first stage of integrated navigation system, an automatic collision avoidance system is designed using fuzzy reasoning and fuzzy control. Computer simulation is done to confirm the validation of the system for various two-vessel encounter situations.

All parts of the system are verified to work satisfactory even for complicated meeting condition and with conflicting actions of a target ship.

There are, however, further problems to be solved for the practical applications: accurate detection and recognition from the radar signal, effects of sensor errors in radars or position sensors and human interfaces etc.

The proposed system provides one way to replace the officer-helmsman-autopilot link by a computer. Furthermore, it is expected to be applicable for more complicated situations by connecting with an expert system.

ACKNOWLEDGEMENTS

The author is grateful to Mr. A. Kouzuki of Mitsubishi Heavy Industries, Ltd., who was a master course student of Osaka University during this work, for his contributions and collaborations.

REFERENCES

(1) L.A. Zadeh, "Fuzzy Sets", Information and Control, Vol.8, 1965, p.338.
(2) H. Imazu and A.M. Sugisaki, "A Theoretical Analysis of Collision Risk for Vessel", Third International Symposium on Ship Operation Automation (ISSOA-79), Tokyo, Nov., 1979, p.190.
(3) H. Kobayashi, "The Man-Machine System and the Ship's Heading Control", The Second IAIN International Congress, Sussex, Sep., 1980.
(4) T. Koyama and K. Shimizu, "Fundamentals of Automatic Harbour Manoeuvring", Seventh Ship Control Systems Symposium, Bath, Sep., 1984, Vol.3, p.123.
(5) J. van Amerongen and E.F.A. Land, "An Adaptive Autopilot for Trackkeeping", ISSOA-79, Tokyo, Nov., 1979, p.99.
(6) N.H. Norrbin and S. Göransson, "A Study of the Safety of Two-way Traffic in a Panama Canal Bend", Fifth Ship Control Systems Symposium, Annapolis, Oct., 1978, Vol.3, p.K1-3.

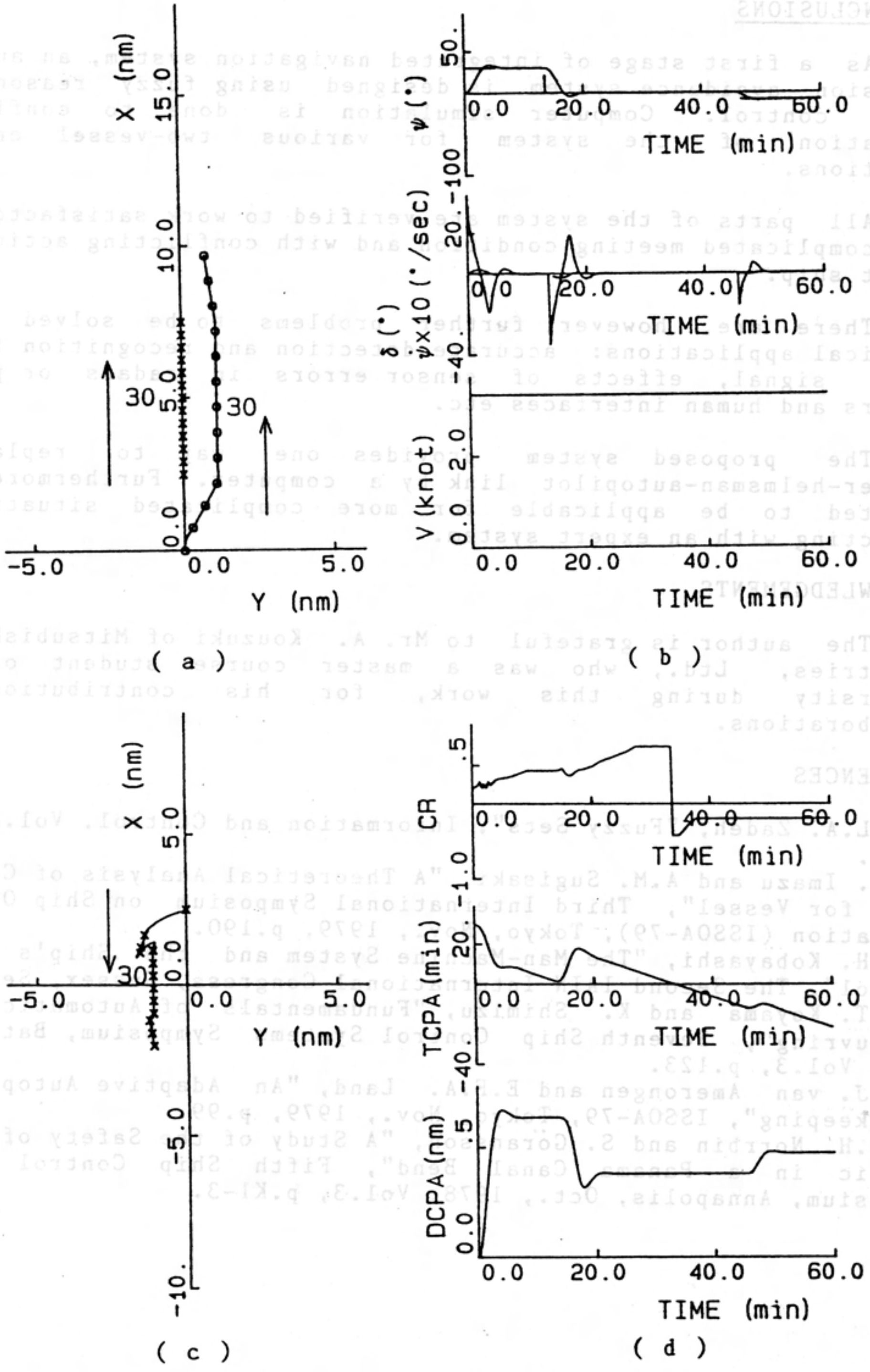
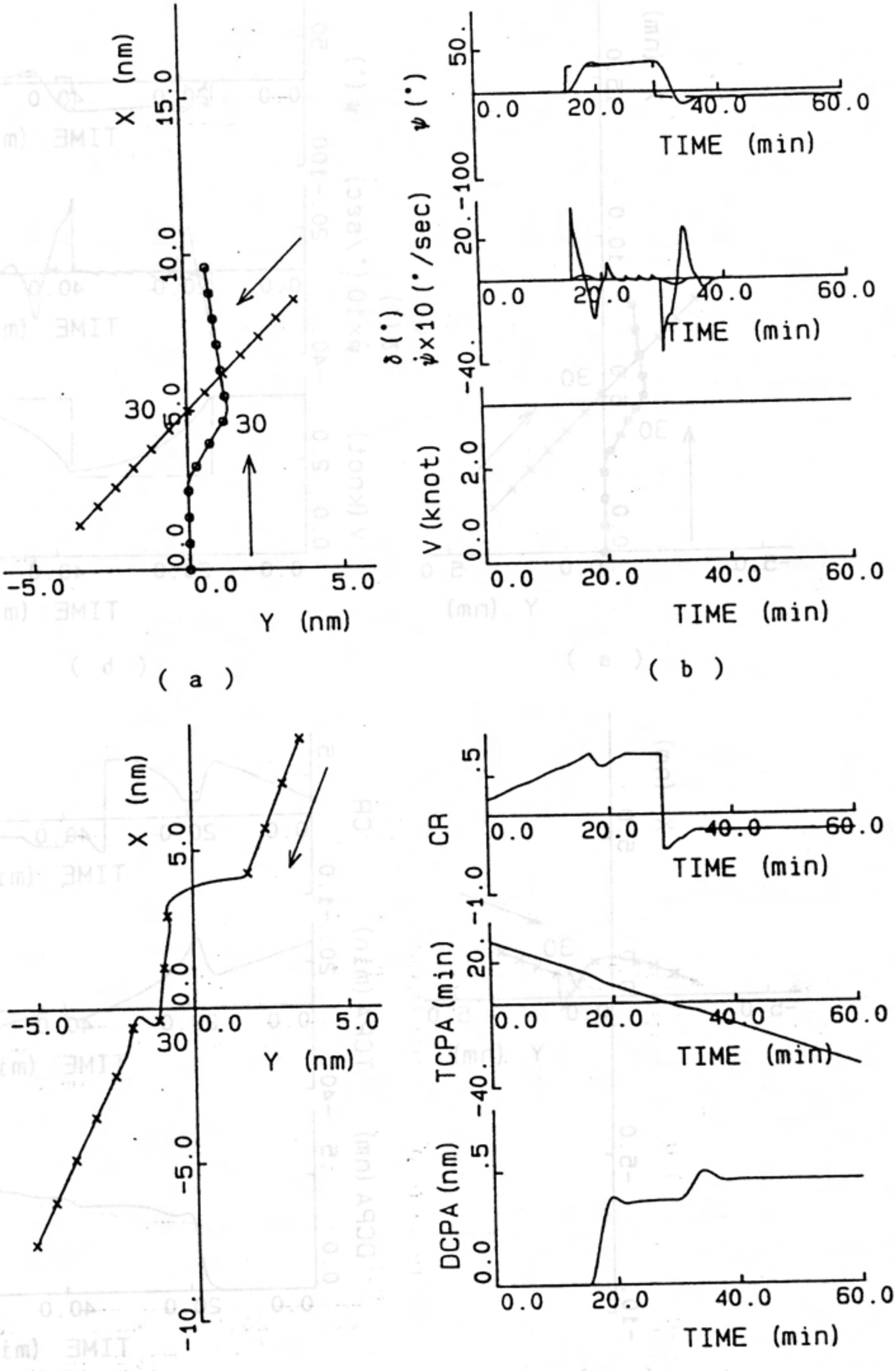


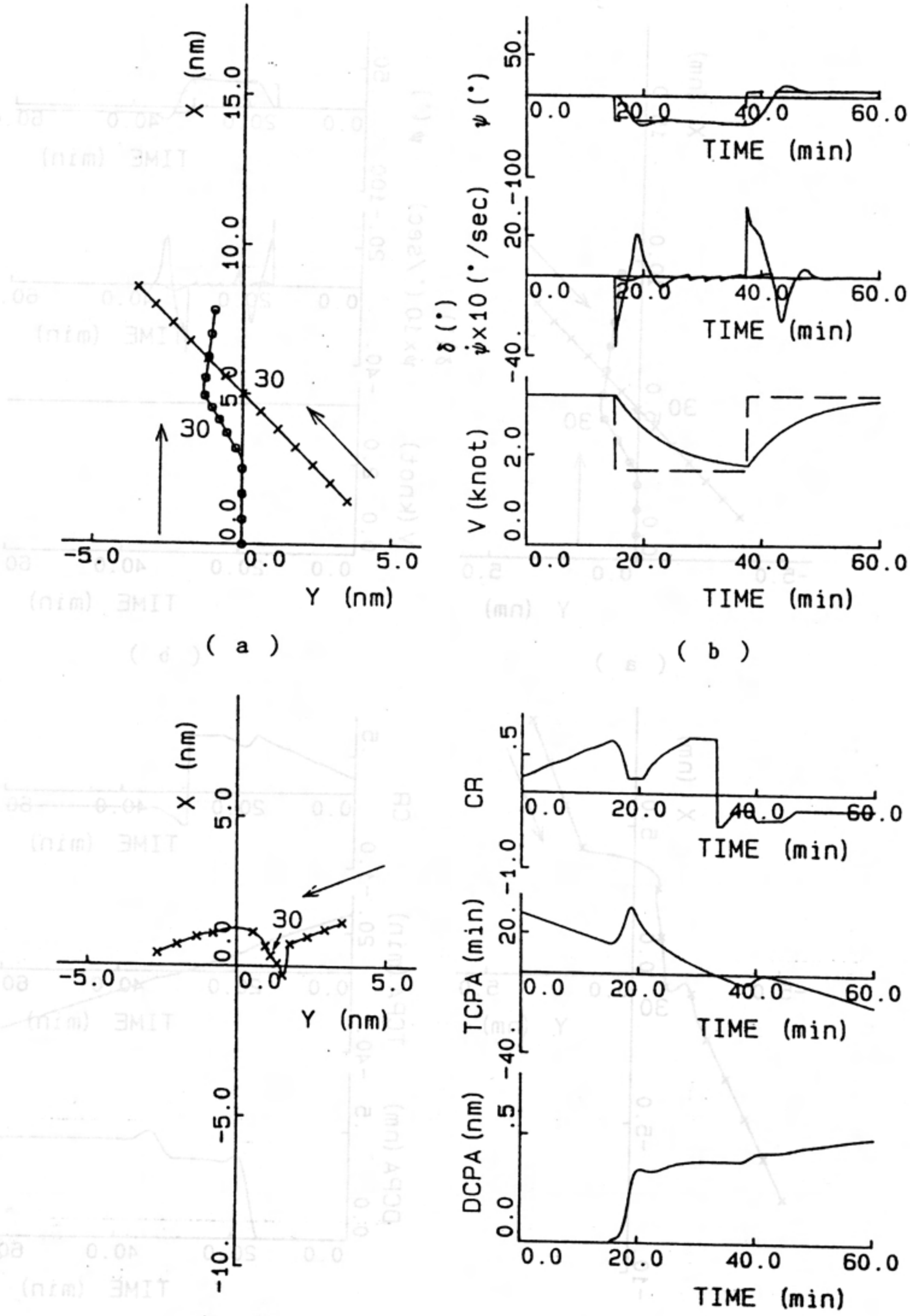
Figure 16. Simulation of collision avoidance manoeuvres by fuzzy control (Type 0)



(a) (b)

(c) (d)

Figure 17. Simulation of collision avoidance manoeuvres by fuzzy control (Type I)



(a) (b)

(c) (d)

Figure 18. Simulation of collision avoidance manoeuvres by fuzzy control (Type II)

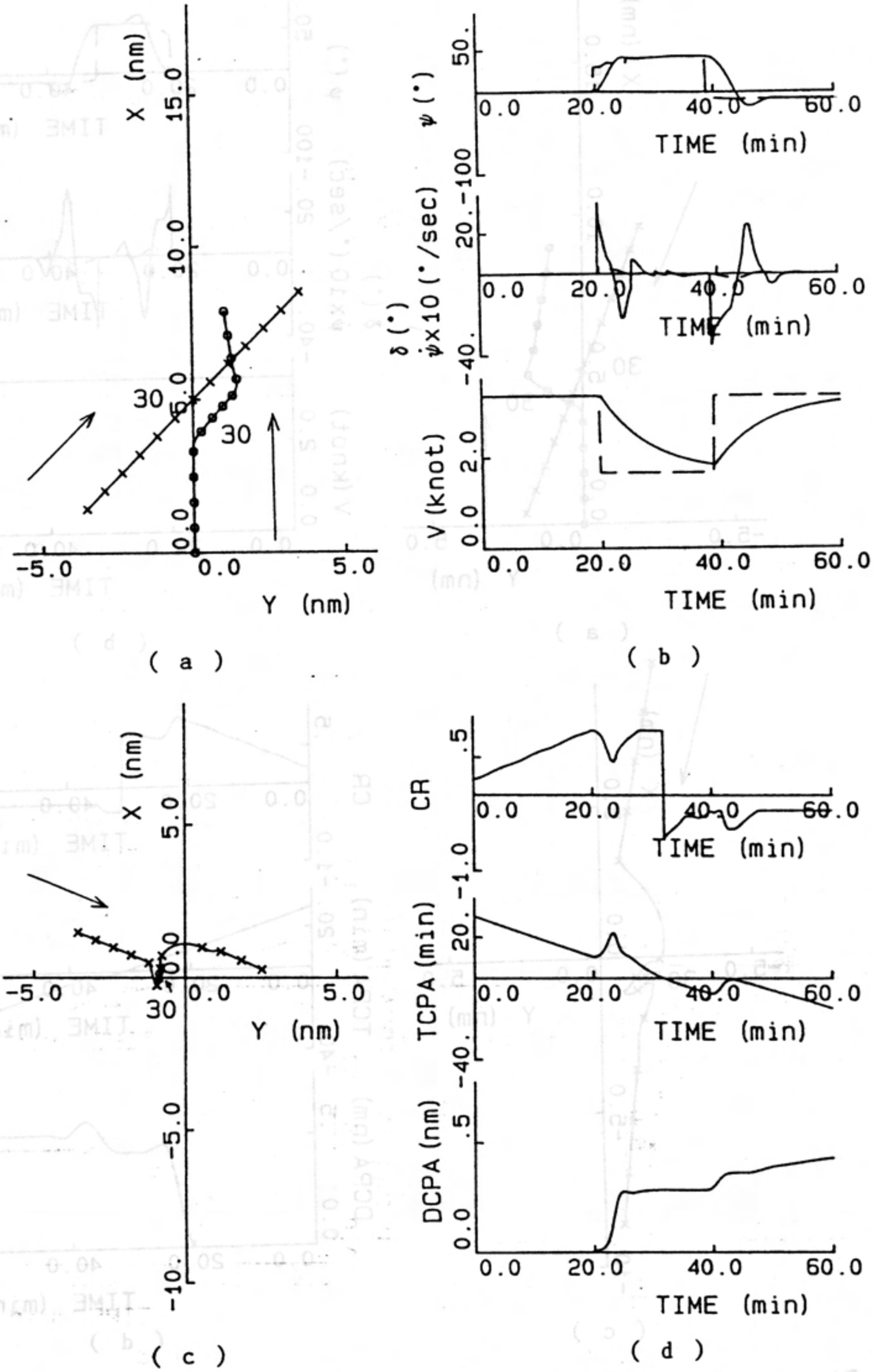


Figure 19. Simulation of collision avoidance manoeuvres by fuzzy control (Type III)

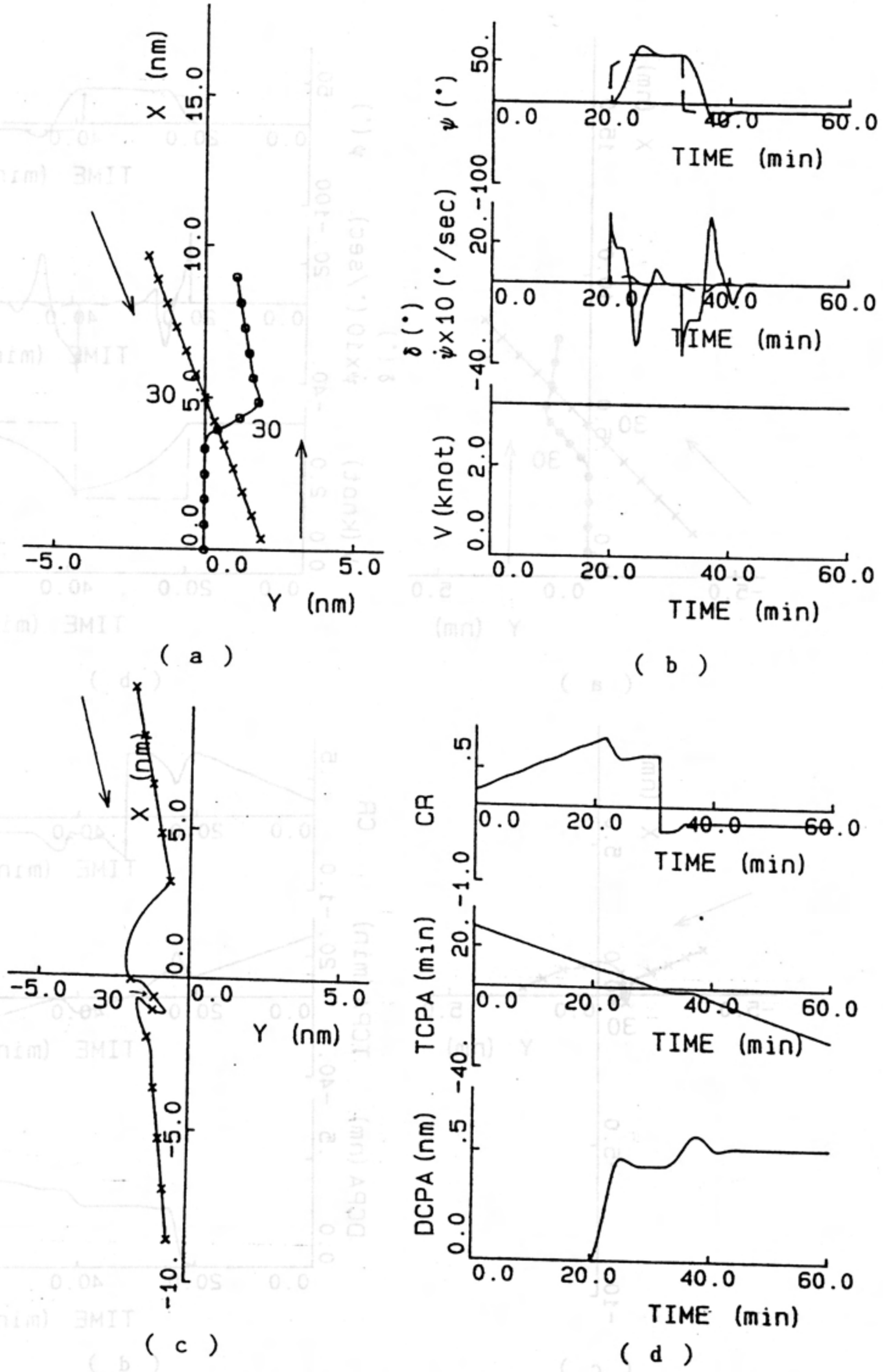
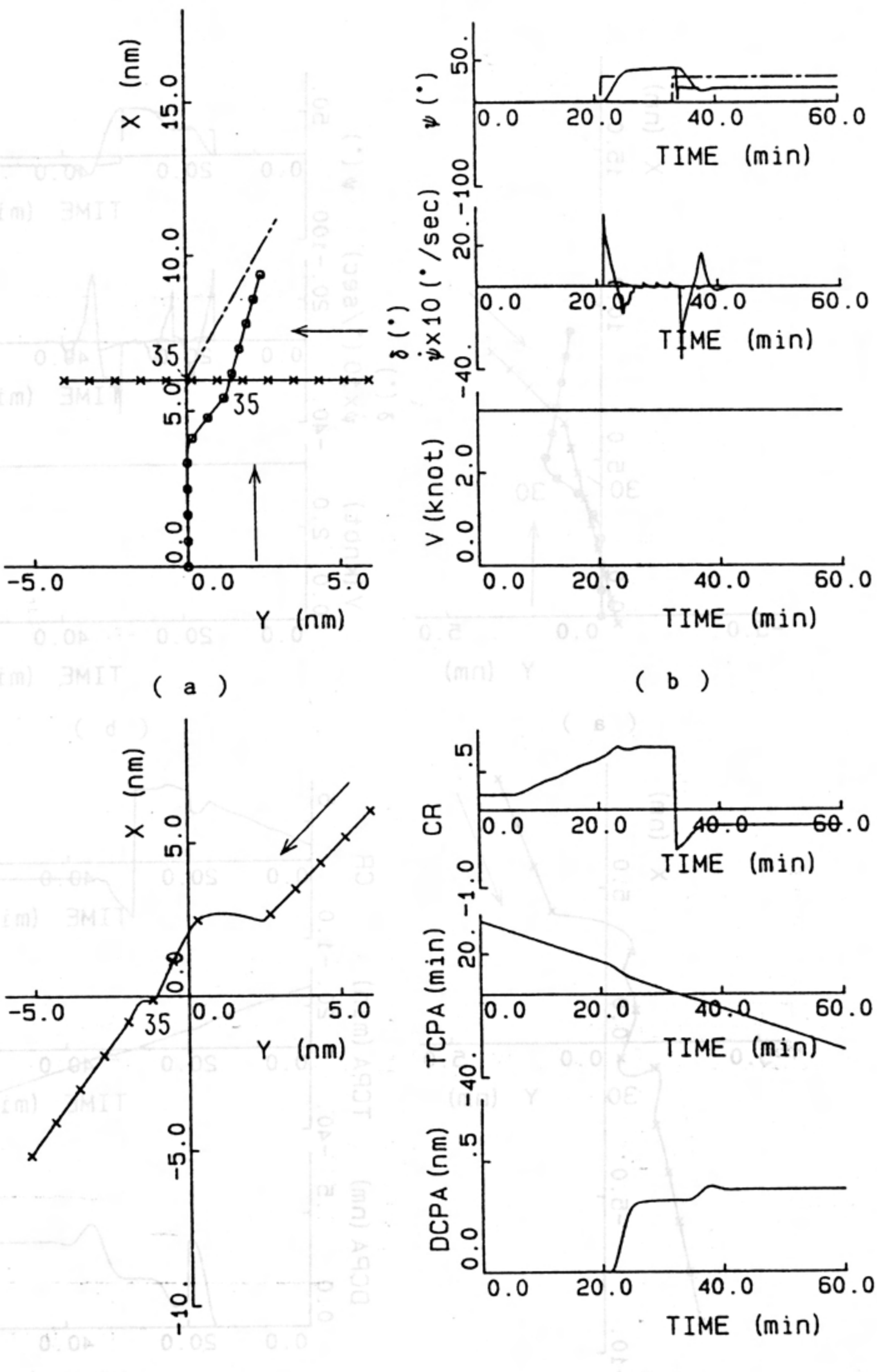


Figure 20. Simulation of collision avoidance manoeuvres by fuzzy control (Type IV)



(a) (b)

(c) (d)

Figure 21. Simulation of collision avoidance manoeuvres by fuzzy control (Type I; close to a course changing point)

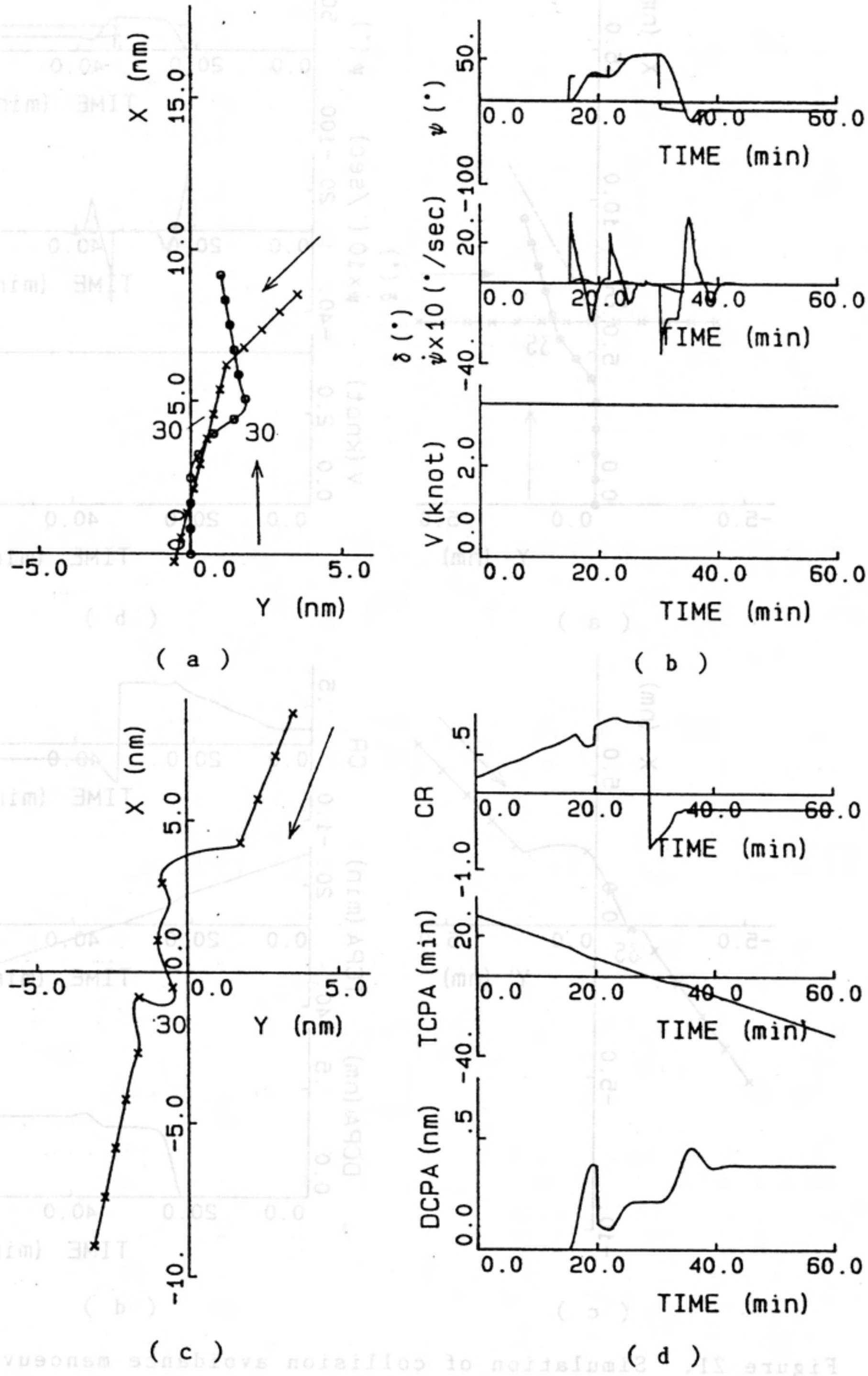
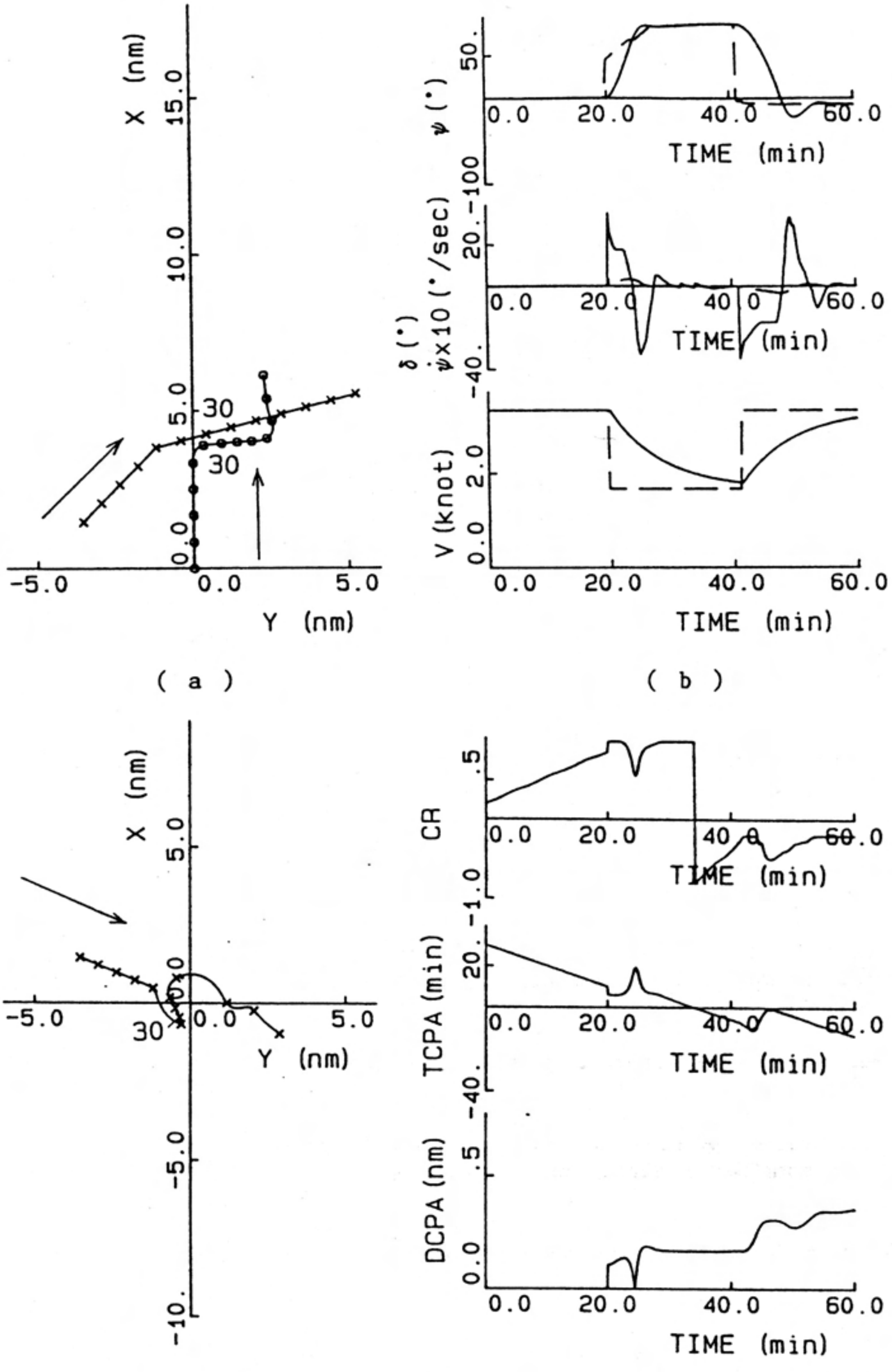


Figure 22. Simulation of collision avoidance manoeuvres by fuzzy control (Type I; with a conflicting behaviour of a target ship)



(a) (b)

(c) (d)

Figure 23. Simulation of collision avoidance manoeuvres by fuzzy control (Type III; with a conflicting behaviour of a target ship)