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PROCEEDINGS

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TENTH
SHIP CONTROL
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SYMPOSIUM

DIXIÈME
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DES NAVIRES

OCTOBER
25-29
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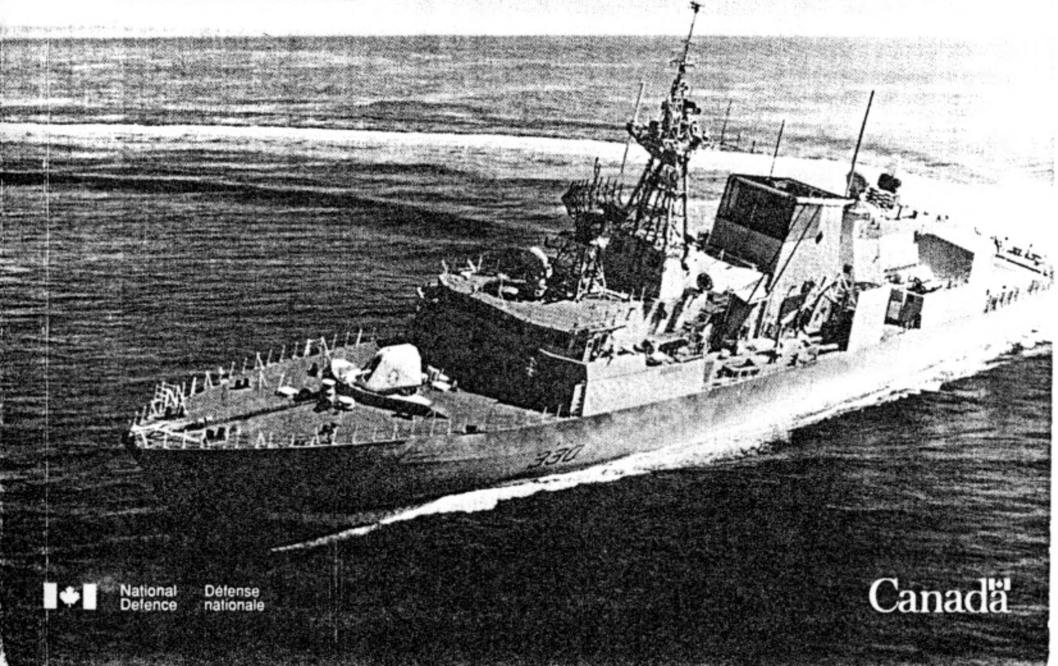
1993



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KNOWLEDGE-BASED AUTOMATIC NAVIGATION SYSTEM FOR HARBOUR MANOEUVRING

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1. ABSTRACT

Automatic navigation system called "SAFES" is revised more suitable for the harbour and congested waterway navigation. The system has almost all the functions necessary for the path planning, normal operation and collision avoidance against other ships or the waterways. The system is also combined with vessel traffic simulation system, where realistic traffic flow can be generated according to the given statistical data. Using the system a case study is done to demonstrate the possibility to apply for the safety assessment of a waterway. Two alternative plans are visually evaluated after certain hours of traffic simulation.

At the same time another system for automatic berthing control using neural network is introduced. Three layer neural network is configured and error back propagation method is used for parameter learning. The network configuration as well as some additional knowledge-base are discussed through simulation of various situations. It is verified the system with the final configuration is quite robust against ship position, direction or wind disturbance.

2. INTRODUCTION

Nowadays the safety assessment of ship navigation, especially that of crude oil tankers are of urgent and update concern. IMO (International Maritime Organization) has made a regulation of so-called double-hull tankers after the oil spill of Exxon Valdez in 1989. However, it is not an active solution, but a passive one. There should be another or rather important consideration.

The author is developing automatic navigation system since 1985 and some of the results were presented in the previous symposia (eighth and ninth). In the eighth symposium, the fundamental functions of collision avoidance are proposed using fuzzy reasoning and control[1]. In the ninth symposium, it is expanded to multi-target and for congested waterways using an expert system approach[2].

The system is further developed suitable for safety assessment of harbour manoeuvring. Automatic navigation subsystem is supervised by knowledge-based system, where execution of each command is done by fuzzy control or reasoning. The system can solve almost all situations before approaching to a harbour. From the entrance to a port or a pier, automatic berthing subsystem will guide the ship to the point just before the berth. For this execution, knowledge-based neural network control system is designed.

3. "SAFES" — SYSTEM FOR SAFETY NAVIGATION

3.1 Review of previous works

The Ship Auto-navigation Fuzzy Expert System (SAFES) is developed as a general tool to solve multi-own-ship and multi-target navigation problem with automatic collision avoidance manoeuvres.

The system is supervised by an expert system, in which some fuzzy reasoning and control are used in LHS and/or RHS of rules. OPS83 is used as a tool for expert system. In OPS83 so-called working memory and definition of elements play an important role. 'Ship' element is an element or a data structure which contains all the data concerning to each ship except information about target ships or banks. These data are separately hold in 'target' element, as originally proposed by Koyama and Jin[3]. So in the working memory, there are 'ship' elements with the same number of ships in the gaming area and certain number of 'target' elements as well as some other necessary elements.

The fundamental feature for a target ship is fully described in [1] and the general strategy for the multi-target ships is roughly described in [2], but as some functions are added for the harbour manoeuvres, it may be summarized again as follows.

3.2 Revised system description

a. Navigation path planning

Navigation path planning is done based on the given points called path points (PP) to be passed. These points are normally selected at the turning points, but in the harbour or narrow waterways, some more additional points are chosen[2]. The path is planned normally directing to the next path point (PP) to be passed, but near the turning point, fuzzy reasoning system will work to chose the appropriate course defined by the next two PP's as follows[1].

$$\psi_I = \psi_1 + RD*(\psi_2 - \psi_1) \qquad (1)$$

where

Ψ_I: order of course

Ψ_1: course of the shortest path to the next PP

Ψ_2: course of the shortest path to the second next PP

RD: reference degree to the second next PP (0<= RD <= 1)

RD is same with CDH called in [1] and obtained in the same way just as CR describing below.

b. Collision avoidance

The collision avoidance manoeuvre is one of the oldest but still hottest topics in this field. The author has defined the fear of collision reasoned from TCPA (time to the closest point of approach) and DCPA (distance of the closest point of approach) using fuzzy theory[1]. In a narrow waterway, the values in the definition of each membership function should be tuned according to the waterway under considering[2]. Minimum distance to be avoided from other ships and similar values may be possible factors to determine it, but there are no explicit rule yet.

Another point to be considered is the scale effect. There should be the difference on the fear of collision between a large ship and a small one. The following non-dimensionalization proposed by Hirano et al. [4] is employed for TCPA and DCPA for this reason. The fear of collision (same with the term collision risk or with the symbol CR used in [1]) is then reasoned from TCPA' and DCPA' instead of TCPA and DCPA. Membership function of CR and RD, and control rules to reason CR and RD are same with those in [1].

$$TCPA' = TCPA \frac{V_r}{L} \qquad (2)$$

$$DCPA' = \frac{DCPA}{L} \qquad (3)$$

where

TCPA: Time to the CPA (closest point of approach) (sec)

DCPA: Distance of the CPA (m)

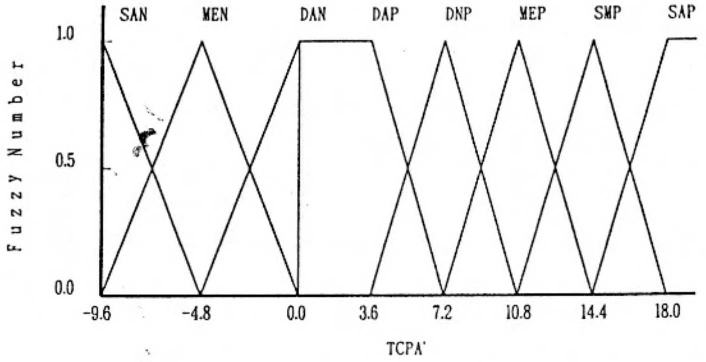
V_r: Relative velocity between own ship and the target (m/sec)

L: Ship length (of own ship) (m)

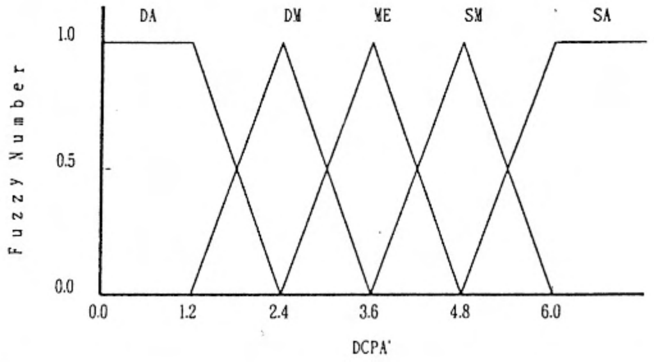
A definition of TCPA' and DCPA' for CR is shown in Figures 1 and 2, and that for RD is shown in Figures 3 and 4 respectively. In the case of RD, ship speed V is used instead of V_r in Eq.(2).

c. Avoidance from other ships

The fear of collision thus defined is reasoned all the time (every 1 second) between all other targets within a certain distance from the own ship. In "SAFES", 30 times of each ship length is adopted for the diameter of the check circle. If the fear of collision is less than a certain value (0.7 is chosen in "SAFES"), the target element will be removed from the working memory.



igure 1: *Membership function of TCPA' for CR.*



igure 2: *Membership function of DCPA' for CR.*

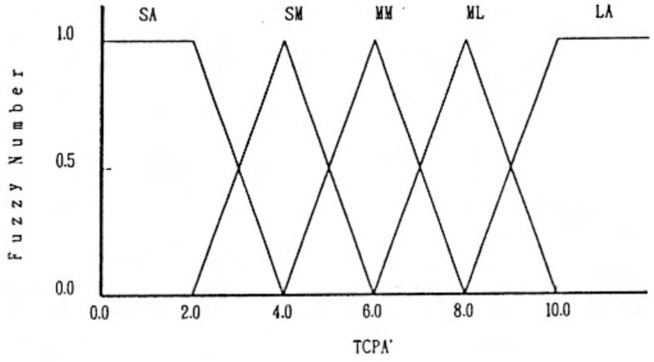


Figure 3: Membership function of TCPA' for RD.

For each moment every ship will judge her decision regarding the remaining 'target' elements. There should be also 'target' element(s) between waterway boundary(-ies). Conflict rules against these 'targets' will be resolved based on the degree of the fear of collision. The most dangerous 'target' should be first avoided. However, the avoidance manoeuvre may involve new fear of collision between another ship or waterway boundary. Cooperative avoidance manoeuvre is proposed by Jin and Koyama [5]. If the communication between all ships or the complete VTS (Vessel Traffic Service) is available, this method will be, of course, most efficient. Kose et al. [6] have proposed avoidance planning method, where each ship will make the short term avoidance manoeuvre plan estimating the target ship's behaviour. However, there is no general and common rule to find out a unique path to be avoided. In "SAFES", the following sequence of rules is checked for each 'ship', if the 'target' requires her action.

(1) Find out the most dangerous 'target' in the working memory.
(2) If the own ship is privileged, mark this 'target' and continue her normal voyage.
(3) If the fear of collision (<u>CR</u>) is over 0.9, or if $0.7 \leq CR < 0.9$ and the own ship is burdened, she will take the following actions.
(4) Assume the primary avoidance action for the 'target', and reason the fear of collision among other 'ships' under the assumed manoeuvre. The 'target' created through this procedure is defined as 'act-target'. The primary action is defined according to the direction of the target ship as defined in [1].
(5) If the most dangerous 'act-target' for the assumed action is also dangerous, the assumed action with reducing her speed half of the primary action speed will be adopted. There should be a chain of

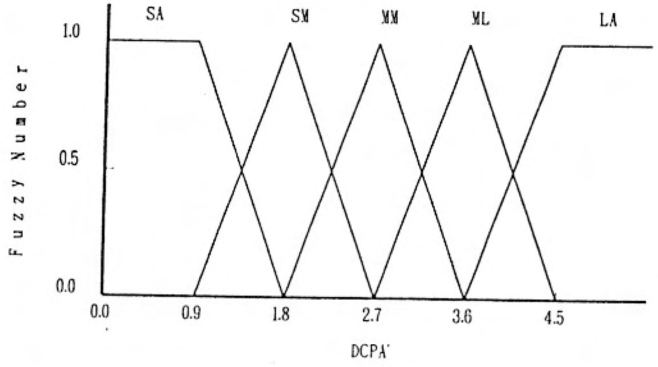


Figure 4: Membership function of DCPA' for RD.

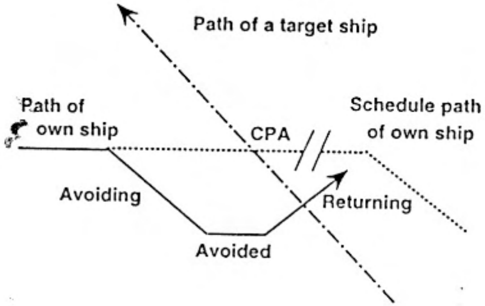


Figure 5: Definition of collision avoidance manoeuvres in general.

alternative actions further, but in the present study two alternatives are regarded satisfactory. It may be changed case by case. For the purpose of the safety assessment, moderate or average skill of the modelled captain will be suitable.

(6) Then select the most appropriate action for the 'target' through the above procedure for the actual manoeuvre. Of course, if the situation is more complicated and congested, the selected action may not succeed, but in "SAFES" such a situation is regarded as an ill-designed waterway or never-acceptable traffic and point out the occurrence of the casualty. In an automatic system installed in a ship, an alarm may request human assistance.

(7) Even during the "avoiding action" as shown in Figure 5, 'target' is always created for the target ship and others. There may be a new 'target' to be avoided first, or a case where the action for the 'target' is inadequate. In the latter case, incremental course change angle is added until the fear of collision of 'tcpa-target' (defined as CR in [1]) will be less or equal to 0.7. The 'tcpa-target' is a 'target' between the own ship with the present avoiding course and the target ship with the same course at <u>TCPA</u> time ahead.

(8) At the same time 'para-target' is created to judge the timing of changing to the "parallel manoeuvre". It is defined for the own ship, assuming that she changes her course to the "parallel manoeuvre" at this moment. If the fear of collision of 'para-target' which is defined as CR in [1] is less or equal to 0.7, actual "parallel manoeuvre" will be taken. These 'tcpa-target' and 'para-target' are globally called as 'if-targets' in [2] and 'act-target' and 'target' created between 'false-ship' described below may be also included into them.

(9) The "parallel manoeuvre" will shift to the "returning manoeuvre", when the fear of collision of the 'target' will be negative as defined in [1].

d. Avoidance from waterway boundaries

The 'false-ship' concept [2] is still adopted for the ships sailing within the waterway boundaries. The waterway boundary is replaced with 'false-ships', which are located on the cross point with the own ship's heading line with the boundary and on the cross point with the own ship's lateral line (vertical with the heading line) with the boundary respectively. The fear of collision obtained by this 'false-ship' is defined as (bank collision risk). However, the following points are modified or added.

(1) There are several 'false-ships' in a general polyline waterway, but the 'false-ship' is redefined to hold the most dangerous <u>BCR</u>.

(2) For those ships who don't care of the waterways, the 'false-ship' is not created. It will be necessary, when a small ship is crossing the waterway. Figure 6 shows such a situation.

(3) Do not overtake a 'target', which is overtaking the other, but reduce her speed to follow the 'target'.

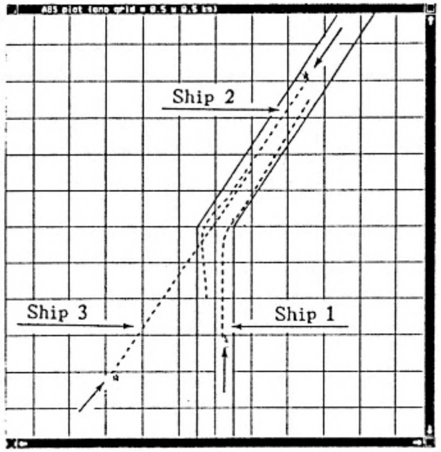


Figure 6: Sailing ships within and crossing a waterway.

The additional course and engine control is necessary near a bent point of the given waterway and <u>BCR</u> obtained under the assumption the speed and the course do not change, is not suitable there. Hence, new concept of fear of collision near a bent point in a waterway is defined. The concept called <u>VBCR</u> (virtual bank collision risk) is used for it. If the ship is near from the bent point, <u>VBCR</u> is obtained assuming the ship is at the next PP directing to the second next PP. <u>RD</u> (reference degree to the second next PP) is used to judge how the ship is near from the bent point of the waterway. <u>VCR</u> (virtual collision risk) should be also obtained for other ships at the bent point, which will be used instead of CR near the bent point, but in the present version of "SAFES", it is not implemented.

The rules regarding BCR and VBCR are included in the avoidance action part, but it is sophisticated to describe here. Principle is to reduce speed, for any occurrence of fear of collision against the waterway boundary.

e. *Autopilot*

Fuzzy autopilot [1] is still effective. The membership functions of course deviation, rate of turn and rudder angle, and the control table defined in [1] work satisfactory even in the harbour and congested waterways, because it is designed with nonlinear gain suitable both for course keeping and course changing.

f. *Engine control*

This function is already described in [1]. For some encounter conditions with a target, the avoidance manoeuvre should be accompanied with speed reduction. Besides, for the multi-target situation, some additional rules described above may require the engine control. Especially in the narrow and bent waterways, engine control will be often used to avoid other ships or waterway boundaries.

4. SAFETY ASSESSMENT USING "SAFES"

4.1 Application area of "SAFES"

The author was scoping the application area of "SAFES" as shown in Figure 7[7]. In the figure, "ACAS" is the core system developed in [1]. The system was already applied for the safety assessment of narrow and bent waterways[2] and marine traffic simulation[7]. The possibility to develop an intelligent simulator was also discussed, though it is not realized yet[8].

He has also pointed out the necessity of ship manoeuvring simulation including a navigator's model when a new waterway or harbour is designed as well as the conventional methods[9]. Safety assessment of a waterway or a harbour should not be done only by ship and waterway configurations, nor by a case study using full-mission ship handling simulator. Although it will take much time to be accepted and actually used, "SAFES" or similar system may be one of the solutions for it.

4.2 Combination with vessel traffic simulation system "SMARTS"

A vessel traffic simulation system called "SMARTS"(each-Ship-with-captain MARine Traffic Simulation system)[7] can be also implemented into "SAFES". In the previous paper[2], a short introduction of the system with a sample result is shown. The system is a kind of Monte Carlo simulation system applied for marine traffic with capability of collision avoidance.

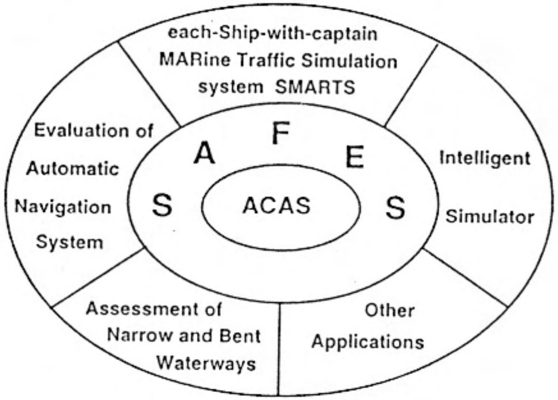


Figure 7: Applications of "SAFES".

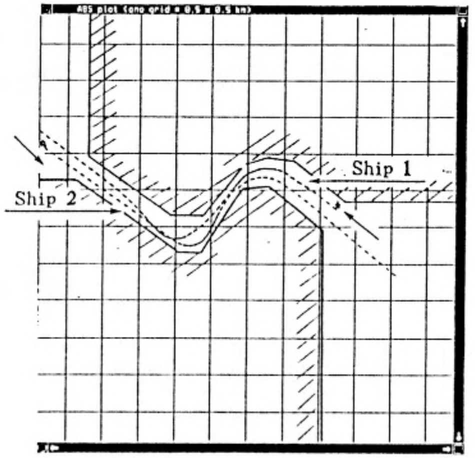


Figure 8 Simulation results of two-way traffic route (meeting).

From certain gates in the gaming area, ships will arrive based on Poisson distribution of the given arriving interval. The ship sizes are also distributed according to the statistic data. Some mother ships are provided for each class(small, middle and large), and small variations on ship speed and manoeuvring characteristics are added from the mother ships.

The sample result suggests us the possibility to be used for the safety assessment or casualty simulation of a given waterway, but there still need some improvements such as

(1) Precise manoeuvring motion
(2) Path planning
(3) Prevention of double overtaking
(4) Detection and action for waterway boundaries

Now as these features are fully implemented in "SAFES", these two systems are unified into one system.

4.3 Simulation result using expanded "SAFES"

The unified system is applied for the same waterway used in [2]. The detail of the waterway, background and conditions are described in [2] and the same situation is assumed here.

Figure 8 is an example result used to check the features of revised "SAFES". Collision avoidance, waterway boundary detection and speed reduction near the curved points are all done satisfactory than those of the previous version[2].

The traffic flow simulation is then done at the same waterway. The ship speed is 6.2 knots average and arriving time interval is 15 min. for both westbound and eastbound traffics.

Figure 9 is the case for two-way traffic scheme and Figure 10 is the case for one-way traffic scheme. In the figures, the large window shows all traces at 1 minute interval, while the lower-left window shows the present state of all ships in the gaming area. The lower-right window shows the positions of the casualties, where each circle denotes the position of nearmiss (CR is greater than 0.9) and each cross denotes the position of overran on the boundary.

Although there are some unnatural movements in the figures, other movements seem to be realistic and acceptable. It is also unbelievable to find there are only four ships in Figure 9 and no ship in Figure 10 which ran aground in 5 hours. Comparing two figures, it is also clear that the lane separation is quite effective to reduce dangerous meeting encounters.

The system will be useful to check the following factors.

(1) Traffic density
(2) Kind of ships, ship speed and dynamics
(3) Skill of navigators or evaluation of automatic system

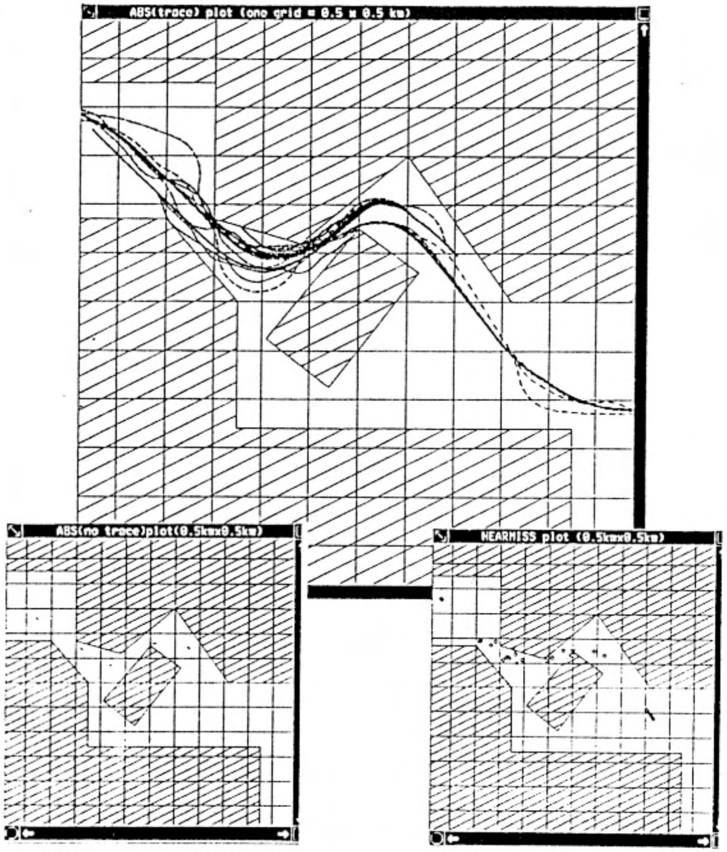


Figure 9: Simulation results of two-way traffic scheme.

5. AUTOMATIC BERTHING SYSTEM USING NEURAL NETWORK

5.1 Overview of the automatic berthing system

Another system newly developed for the harbour manoeuvring is automatic berthing system[10,11]. The system is developed, aiming to connect with "SAFES", but at this moment it is an independent system developed on a PC.

Three layer neural network is designed similar to that of Yamato et al.[12], but slightly changed as shown in Figure 11, where coordinate system

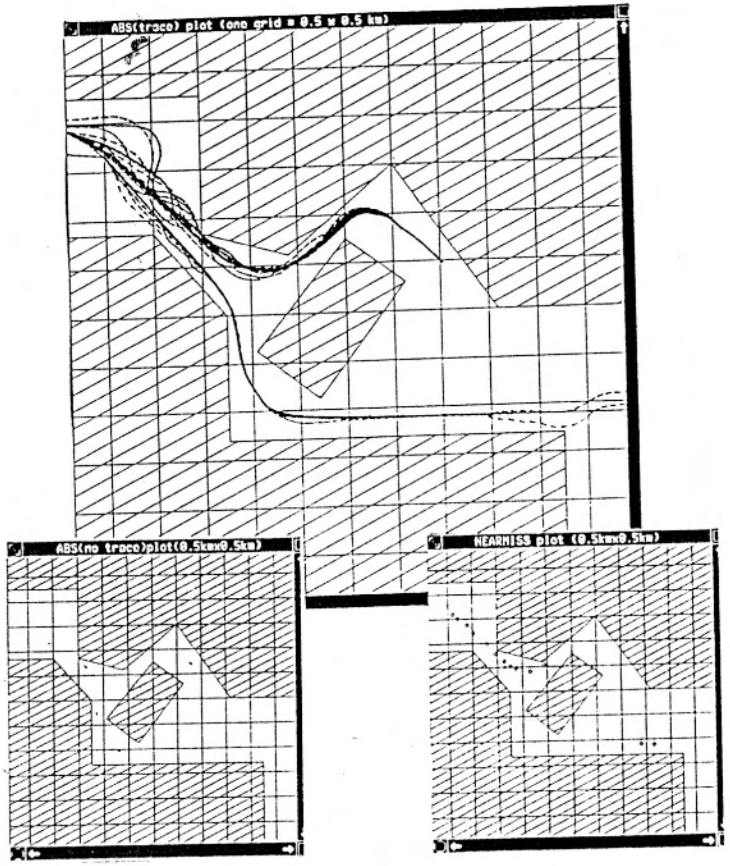


Figure 10: Simulation results of one-way traffic scheme.

and variables are defined as shown in Figures 12 and 13. The difference between Yamato et al.[12] is adding x and y in input neurons and deleting wind velocity and direction from the inputs. Error back propagation method is used for learning parameters. In this study berthing up to near the berth (Phase 1 defined by Yamato et al.[12]) is treated. Patterns shown in Figure 14 are used for creation of teaching data and a sample teaching data is shown in Figure 15 (circles show the sampled data). The same tanker of 154,000 ton as well as the same mathematical model proposed by Kose et al.[13] are used.

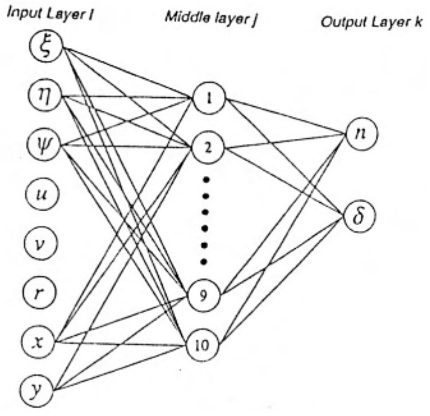


Figure 11: Three layer neural network for berthing control.

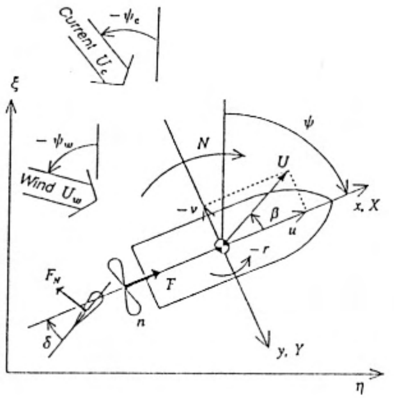


Figure 12: Coordinate system in general.

5.2 Simulation results

Before configuring this network, the following points are investigated through simulation.

a. *Three teaching patterns*

Three patterns from Figure 14 are the same as those of Yamato et al.[12]. They are (5L, 4L),Ψ=-60(deg), (5L, 2L),Ψ=-30(deg) and (5L, 0.3L),Ψ=0(deg). The notation is defined as x,y ,heading angle at the starting

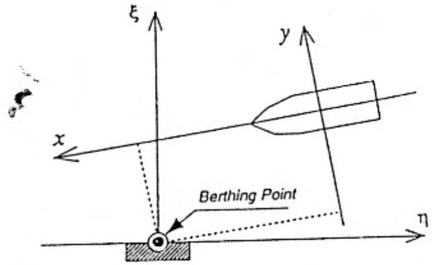


Figure 13: Coordinate system of berthing.

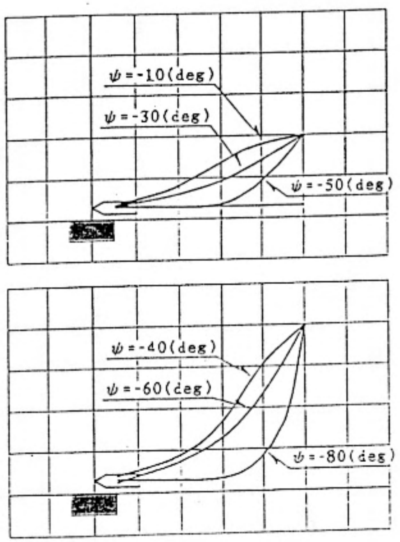
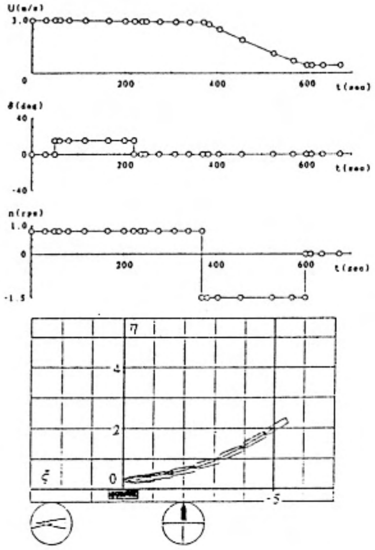


Figure 14: Patterns of teaching data.

point. The results are summarized in Figure 16. It works well for those patterns same as teaching data, but doesn't for the other patterns which have different heading angles from the teaching data.

b. Seven teaching patterns

The results providing seven teaching patterns (Figure 14) are shown in Figure 17. It is improved, but some patterns still have difficulties. This shows that increasing teaching patterns improves the performance, but not always. This may be caused by the nonlinearity of teaching data.



(5L, 2L), ψ=-30(deg)

Figure 15: An example of given teaching data.

c. Eight input neurons

Therefore, two inputs of x and y are further added as shown in Figure 11. The results are shown in Figure 18. It is rather improved. However, before just berthing (final stage of Phase 1), some misjudges are observed.

d. Adding simple knowledge-base

At the final stage of Phase 1, simple knowledge-base shown in Table 1 is adopted. The results shown in Figure 19 are quite satisfactory. Hence, patterns which don't start from the same points as those of teaching data are also tested. The results shown in Figure 20 look fairly well.

e. Effect of wind

Finally, wind effect is checked. Wind velocity is constant (10m/sec), but wind direction is changed. The results are shown in Figure 21. It is found the neural network compensates the wind effect very smoothly and naturally.

5.3 Evaluation of the system

As shown above, final configuration of the neural network with simple knowledge-base works very well for almost all possible cases only getting seven patterns and 171 sets of points as teaching data. The system is very robust against wind effect and manual disturbances of rudder or propeller command. While Yamato et al.[14] have proposed expert system approach

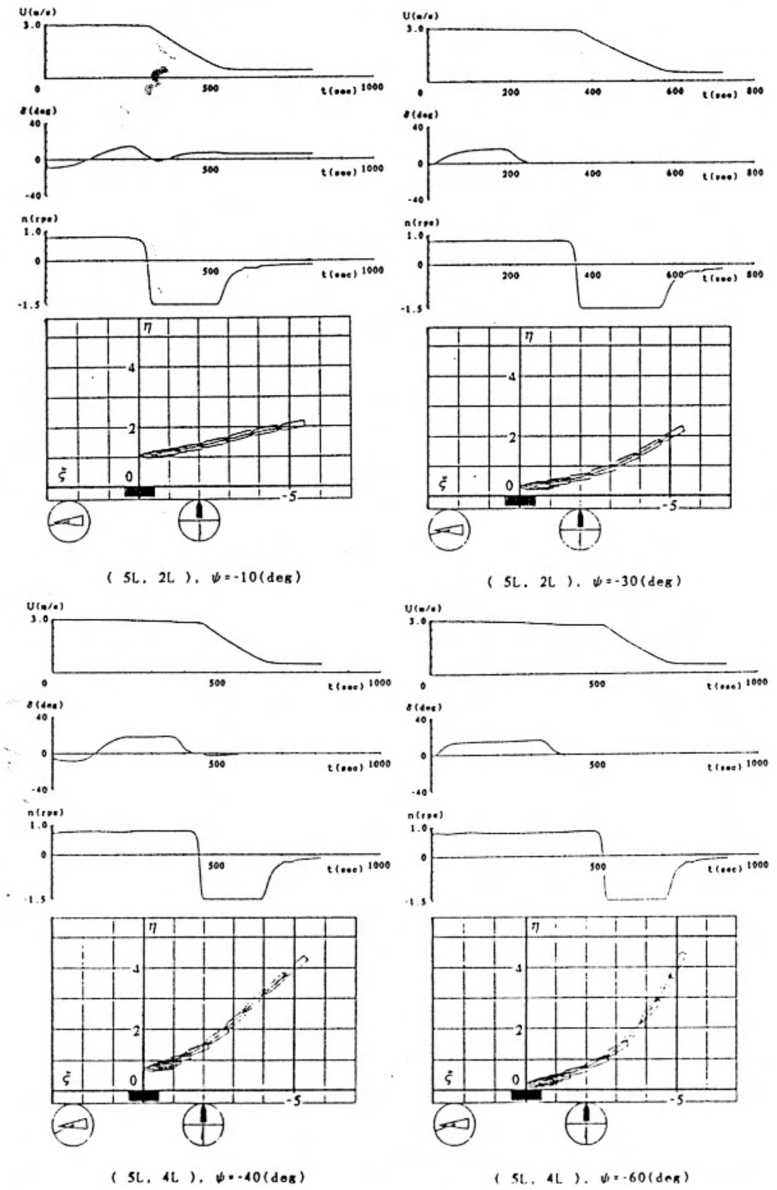


Figure 16: Simulation results for learned data from three teaching patterns.

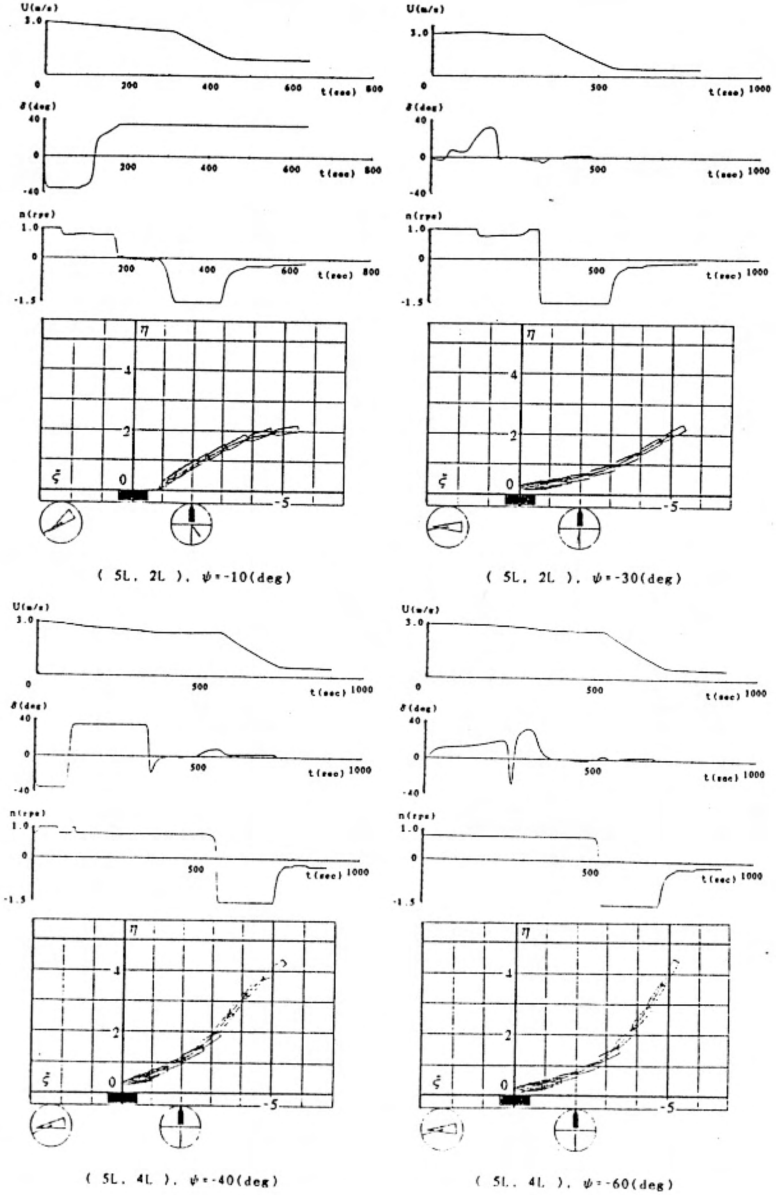
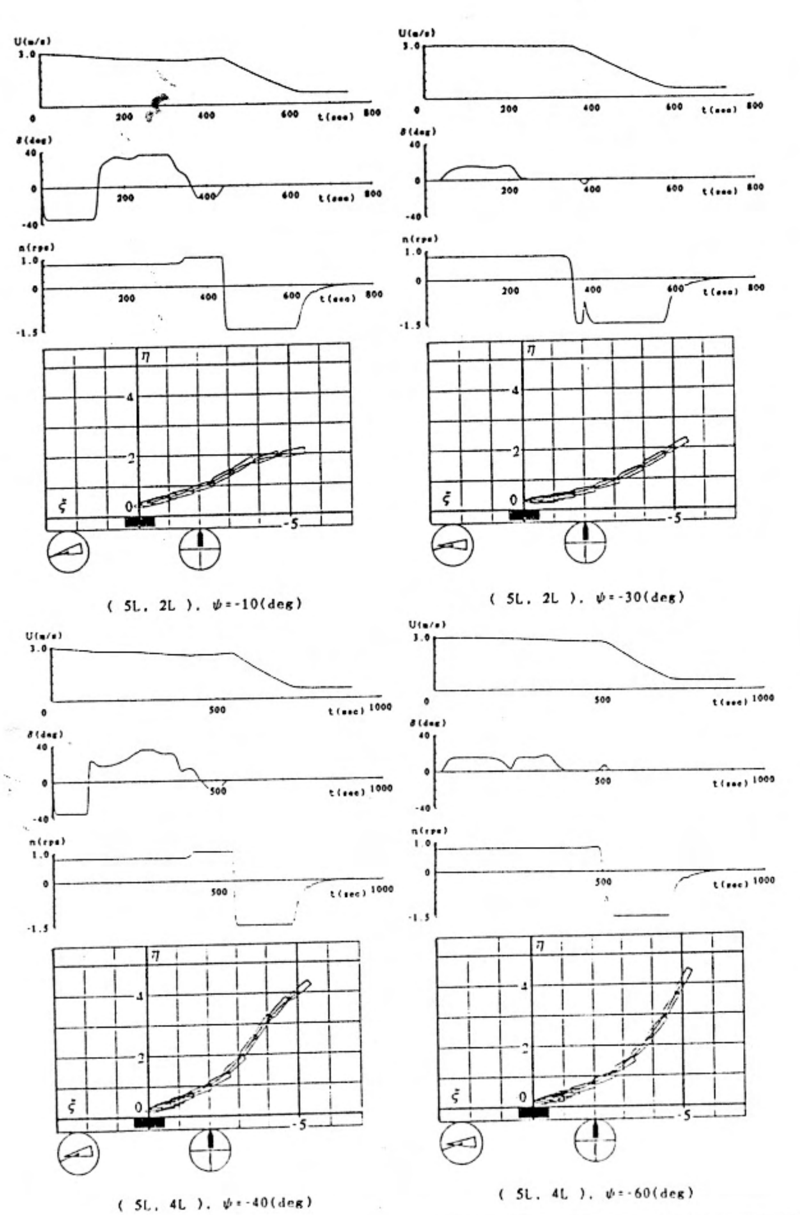


Figure 17: Simulation results for learned data from seven teaching patterns.



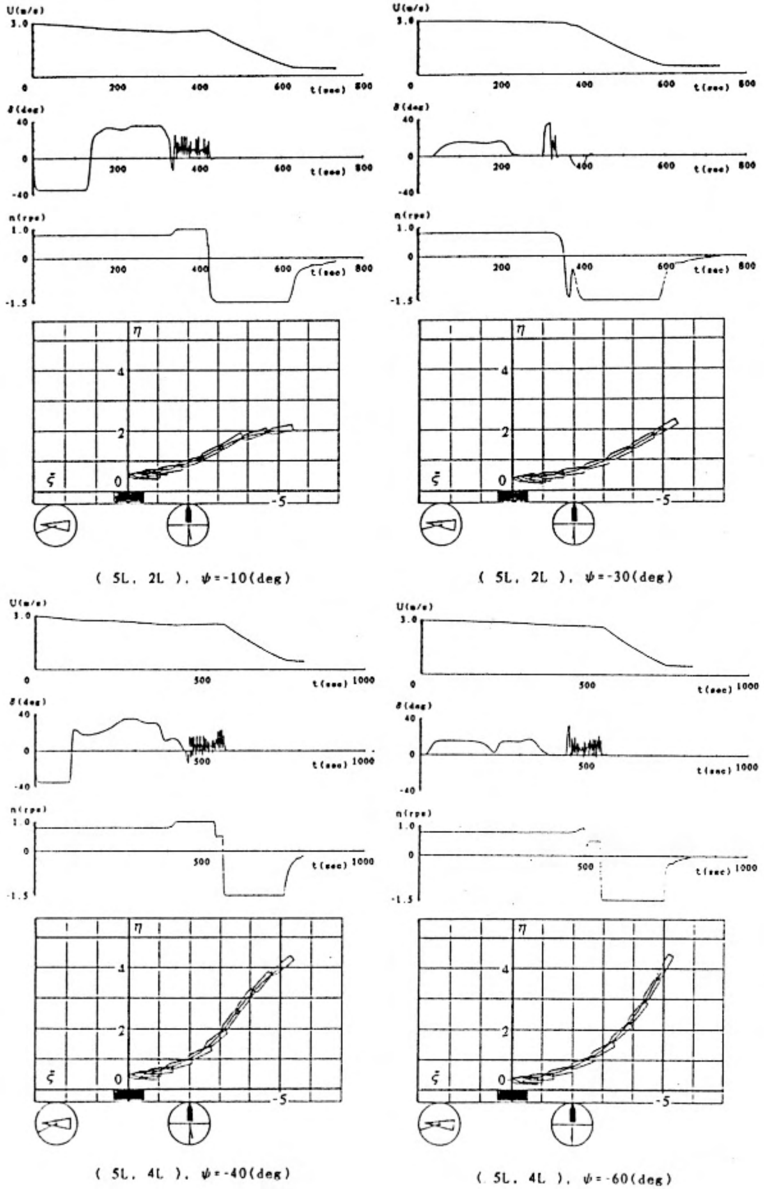
(5L, 2L), ψ=-10(deg)

(5L, 2L), ψ=-30(deg)

(5L, 4L), ψ=-40(deg)

(5L, 4L), ψ=-60(deg)

Figure 18: Simulation results for learned data from seven teaching patterns with eight input neurons.



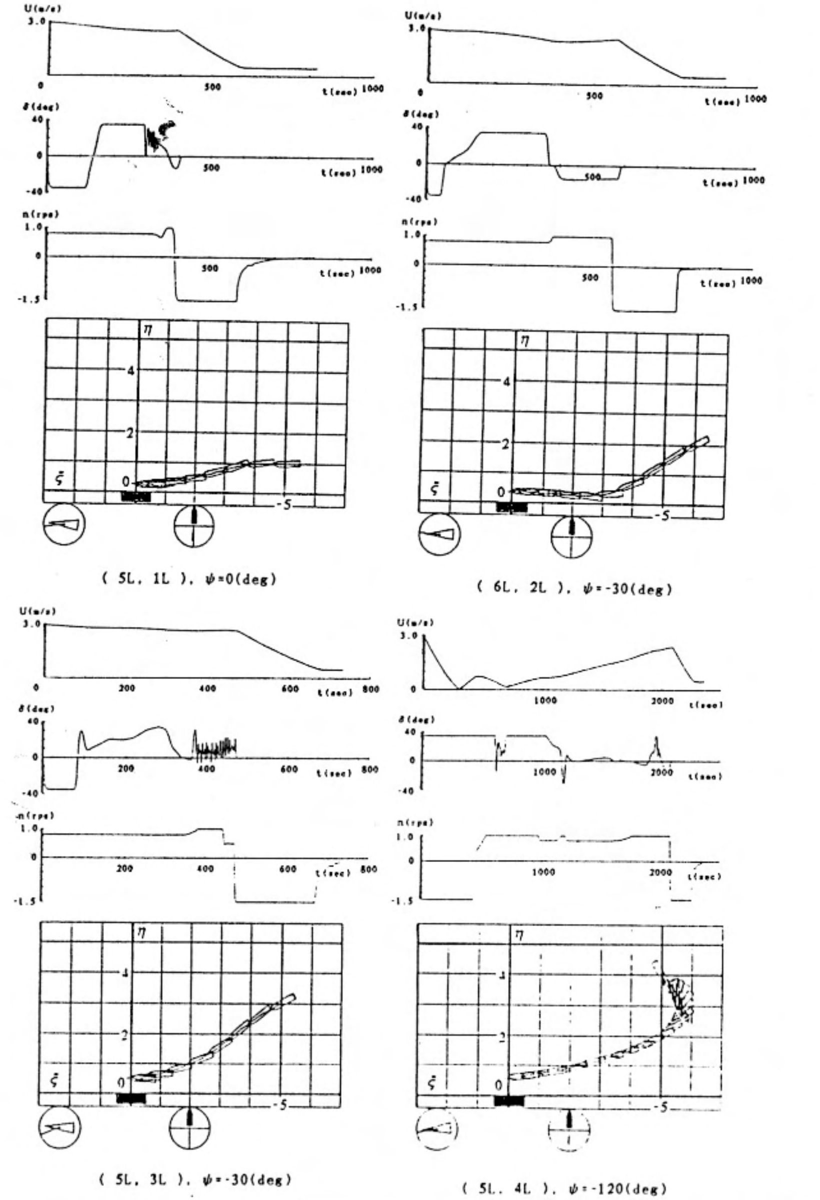
(5L, 2L), ψ=-10(deg)

(5L, 2L), ψ=-30(deg)

(5L, 4L), ψ=-40(deg)

(5L, 4L), ψ=-60(deg)

Figure 19: Simulation results for learned data from seven teaching patterns with eight input neurons and knowledge-base.



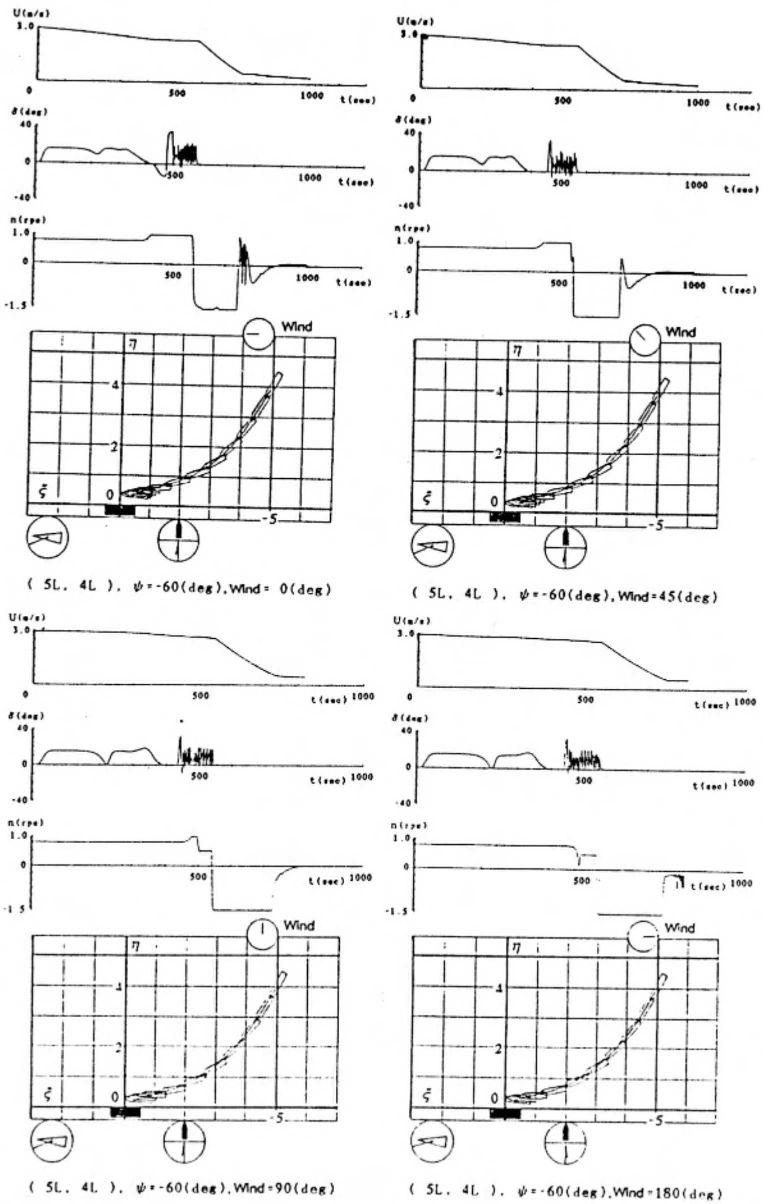
(5L, 1L), ψ=0(deg)

(6L, 2L), ψ=-30(deg)

(5L, 3L), ψ=-30(deg)

(5L, 4L), ψ=-120(deg)

Figure 20: Simulation results for learned data from seven teaching patterns with eight input neurons and knowledge-base (simulated patterns are not included in the given patterns).



(5L, 4L), ψ=-60(deg), Wind= 0(deg)

(5L, 4L), ψ=-60(deg), Wind=45(deg)

(5L, 4L), ψ=-60(deg), Wind=90(deg)

(5L, 4L), ψ=-60(deg), Wind=180(deg)

Figure 21: Simulation results for learned data from seven teaching patterns with eight input neurons and knowledge-base (effect of wind direction).

- Reversing ($n=-1.5$rps for the given ship)
  if $u>0.5$ m/s   at $x/L < 1.0$
- Take hard starboard (with boosting optional)
  if $\psi < -10$ deg   for $1.5 < x/L < 2.5$
- Take port ($\delta = -15$ deg) (with boosting, optional)
  if $r > 0.1$ deg/sec   for $1.5 < x/L < 2.5$

Table 1: Knowledge-base used for berthing at the final stage of Phase 1.

recently, neural network approach should be more investigated. Of course expert system approach may be easier for Phase 2 (from near the berth to the berth generally using side thrusters or tugs) operation, but in Phase 1 several preferences or variation of patterns are stored in each captain or pilot. This system will be flexible for any teaching data and easily customized by users. The system is workable on a PC, and may be installed into an on-board PC simulator.

6. CONCLUDING REMARKS — FUTURE GOAL OF "SAFES"

This paper is dealing with two systems concerning to the automation of harbour manoeuvring. The main system called "SAFES" is a general tool to solve multi-own and -target problems and can be used not only for automation of navigation, but also for the safety assessment of navigation. The other system is automatic berthing system using neural network. Combining these two systems, further automation system can be developed. However, we should always pay attention for the level of automation concerning to the human relation[15]. Otherwise, so-called "ironies of automation"[16] may involve more human actions and errors.

Some scope of future application of "SAFES" are already described but it had better conclude as follows.

(1) Automatic navigation system "SAFES" is expanded more suitable for the harbour and congested waterways.
(2) Safety assessment using "SAFES" combining marine traffic simulation system is introduced and this kind of assessment is promising.

(3) Neural network suitable for berthing control is discussed and designed. The system is found to be robust against position, direction and wind effect.
(4) The neural network berthing system is handy enough to be installed on a PC-based simulator and usable on-board.
(5) New applications will be expectable using these two systems.

The future works to be done will be summarized as follows.

(6) Implementation of mathematical model suitable for harbour manoeuvring into "SAFES"
(7) Development of the method for quantitative analysis of traffic evaluation
(8) Expansion of automatic berthing to Phase 2 (final stage of berthing)

7. ACKNOWLEDGEMENTS

The author would like to send his sincere gratitude to Prof. K. Kose of Hiroshima University for the admission of using the coefficients of a tanker model. He would also like to thank Mr. Y. Fujita and Mr. K. Kitera for their contributions to develop "SAFES" and automatic berthing system respectively, when they were undergraduate students of Osaka University.

His would lastly like to acknowledge Mr. A. C. Pijcke, former Director of CMO, the Netherlands, Mr. A. H. Nielsen, Director of DMI, Denmark, Mr. Y. Yamasaki, SDL, Japan and Lt(N) C. Zaidi, DGMEM/DMEE, Canada for their encouragements and supports for this work and presentation.

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