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# PASSAGE PLANNING SYSTEM FOR SMALL INLAND VESSELS BASED ON STANDARD PARADIGMS AND MANEUVERS OF EXPERTS

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Abstract: The authors has developed the passage planning system for small inland vessels. In this paper, algorithms, models and simulator studies on the passage planning system are discussed. The proposed passage planning system consists of following three sub systems; 1) Route planning system, 2) Maneuver planning system and 3) Real-time maneuvering information support system. Simulations of the passage planning system show that the system can generate the good passage plan automatically. Simulator studies by navigators using the real-time maneuvering information support system based on the passage planning system also shows the good tracking performance.

## 1. INTRODUCTION

When a large vessel enters and leaves a port, a pilotage by a pilot is provided to the vessel with a legal basis. This pilotage keeps the safety operation of the vessel and contributes the safety and effective port operation. But in Japan, almost 10 or more times as many as the number of legal piloted vessels have accessed ports. Almost all of them are small inland vessels which have no legal basis on not only pilotage but also VTS: Vessel Traffic Service and AIS: Automatic Identification System. Many marine accidents on the small inland vessels had been occurred in and around Japanese ports. From a viewpoint of safety port operation and efficient traffic management, maneuvering assistance for whole vessels, including small inland vessels, should be provided.

If real-time information of an appropriate planned passage, like a pilotage, for each small inland vessel is provided to the vessel, her operator can maneuver the vessel more safely and without any delay. In order to realize this real-time maneuvering information support system based on the appropriate planned passage for a small inland vessel, the authors has tried to develop the passage planning system [3,4,5,6]. In this paper, system configuration of the passage planning system, algorithms and models, which were developed and used in the system, are introduced. Simulations and simulator studies, which were executed in order to verify the passage planning system, were also reported.

## 2. STANDARD PASSAGE PLANNING PARADIGM

The paradigm of passage planning by expert and skillful mariners are investigated by questionnaire surveys, passage planning experiments and simulator studies. Expert captains have many experiences to maneuver vessels. Pilots have not only many experiences to maneuver vessels but also much priori knowledge on the target port and area. A passage planning for a vessel in a water area should be produced based on these priori experiences and knowledge. A passage plan has to include a route plan and a maneuvering plan. The standard passage planning consists of two sub-plannings. One is route planning and the other is maneuver planning.

### (1) Planning a route

A route from the origin to the destination should be planned in according with planning guidelines, such as UKC, distance off, recommended and legal passage, etc. This route is a chain of elemental passages. Each elemental passage is defined by its course, width and length of its Safe Water. For planning a route, the priori knowledge on the target water area is necessary.

### (2) Planning maneuvers

A maneuvering plan is to maneuver a vessel along with the planned course and speed. Maneuvers of vessels are classified into some kinds of elemental maneuvers, such as course alteration, turning, stopping, etc. This maneuvering plan should be composed of a chain of elemental maneuvers and maneuvering orders. For planning maneuvers, the priori knowledge on maneuverabilty characteristics of the vessel is needed.

Based on the above-mentioned standard passage planning paradigm of expert and skillful mariners, the passage planning system should consist of the route planning system, the maneuver planning system and the real-time maneuvering information support system, as shown in Figure 1.

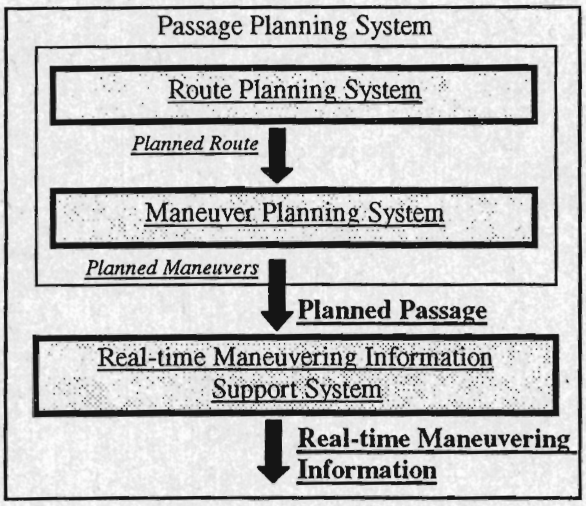


Fig.-1 System Configuration of the passage planning system

## 3. ROUTE PLANNING SYSTEM

A rational method to plan routes was found by investigating standard methods and guidelines on route planning. This rational route planning methods consists of following 4 steps.

*1st Step:* *Definition of the topographical constraints, the init and the goal*
The No-Go Areas should be defined based on a database of topographical constraints on the target water area. Figure 2 shows an example of the defined No-Go Areas.

*2nd Step:* *Planning the shortest path*
Using the Visibility Graph method [7], a shortest path from the init to the goal through the free area except the No-Go Area should be found. Figure 3 shows an example of the found shortest path.

*3rd Step:* *Planning a chain of elemental Safe Waters*
In order to maximize the clearance between the ship and the No-Go areas, elemental Safe Waters along the shortest path should be found. Figure 4 shows an example of the chained elemental Safe Waters.

*4th Step:* *Planning a chain of elemental passages and the route*
In order to keep the continuity of the passages, elemental Safe Waters should be transformed into elemental passages. The route, which keeps the enough clearance to the No-Go Area like as the Voronoi diagram method [7], should be planned. Figure 5 shows an example of the chained elemental passages and the planned route.

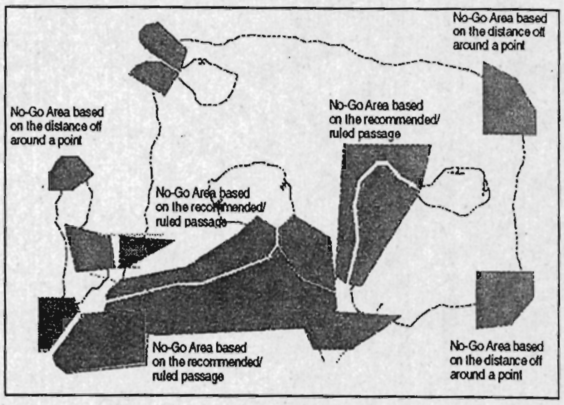


Fig. 2 The No-Go Area based on the topographical constraints, such as water depth, distance off areas around points and recommended/ruled passages

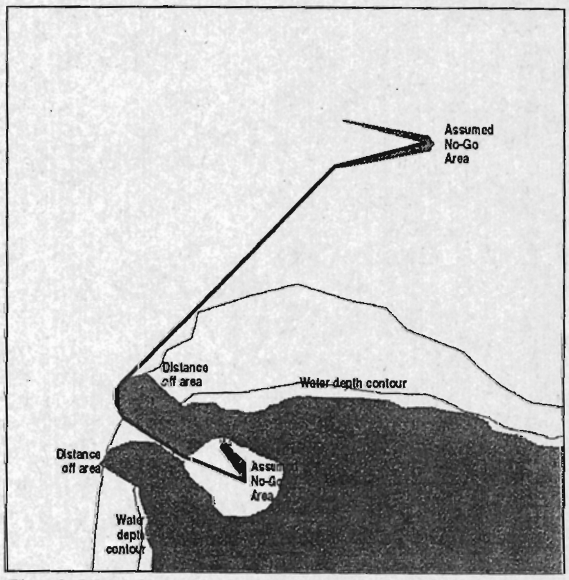


Fig. 3 The shortest path planned under the No-Go Area constraint which consists of the water depth contour, distance off areas and assumed No-Go Areas

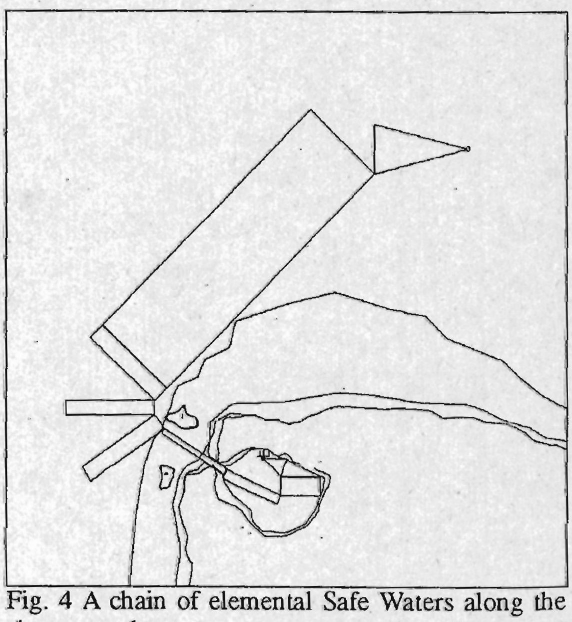

Fig. 4 A chain of elemental Safe Waters along the shortest path

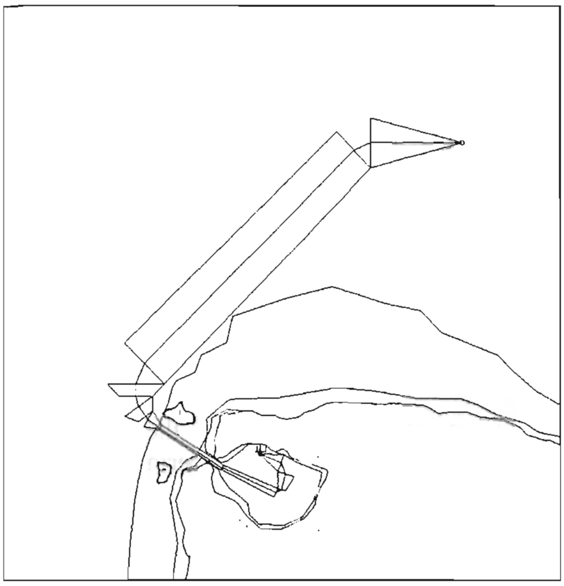

Fig. 5 A chain of elemental passages and the route

Photo 1 GT499 inland vessel

## 4. MANEUVER PLANNING SYSTEM BASED ON THE MODELS OF STANDARD MANEUVERS

Planning maneuvers should be based on the standard maneuvers by expert and skillful mariners. In order to find the standard maneuvers by expert and skillful mariners, questionnaire surveys and simulator studies on deceleration, course alteration and stopping maneuvers were executed. Through these surveys and experiments, standard maneuvers of GT499 inland vessels on deceleration, course alteration and stopping were found. A photo and a principal particulars of the typical GT499 inland vessel, which is the target ship on this study, are shown in Photo1 and Table 1.

Table 1 Principal particulars of GT499 inland vessel

| | | |
|---|---|---|
| Gross Tonnage | 498 T | |
| Length p.p. | 70.00 m | |
| Breadth | 11.80 m | |
| Depth | 7.20 m | |
| draft | 3.78 m | |
| MCR | 2400 ps x 260 RPM | |
| NOR | 2050 ps x 240 RPM | |
| Bow Thruster | 203 ps x 2.03 t | |
| Stern Thruster | 162 ps x 1.52 t | |
| RATING | RPM | SPEED(kt) |
| Navigation Full | 240 | 12.4 |
| Full Ahead | 240 | 12.4 |
| Half Ahead | 180 | 9.3 |
| Slow Ahead | 120 | 6.2 |
| Dead Slow Ahead | 60 | 3.1 |

### 4.1 Standard deceleration maneuvers

The result of a questionnaire to experts on deceleration maneuvers is shown in Fig. 6. On basis of this result, a model of standard deceleration maneuvers was developed. It is well known that the speed response of the ship motion to a telegraph order, such as the half down and the slow down orders, is approximated to a first order differential equation (1) and (2) as shown by the following.

$$m\frac{dv(t)}{dt}+c\cdot v(t)=k\cdot n(t) \quad \text{---(1)}$$

$v(t)$ : Ship Speed [m/s], $n(t)$ : RPS of Engine,

$$T_P\frac{dv(t)}{dt}+v(t)=K_P\cdot n(t) \quad \text{---(2)}$$

$$T_P={}^{m}/_{c},\ K_P={}^{k}/_{c}$$

Constants of the above equations, which are m: mass, c: resistance factor and k: thrust factor, can be estimated from the principal particulars of the ship.

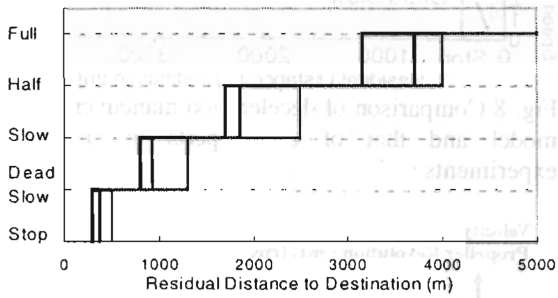


Fig. 6 Results of a questionnaire to the experts on deceleration maneuvers

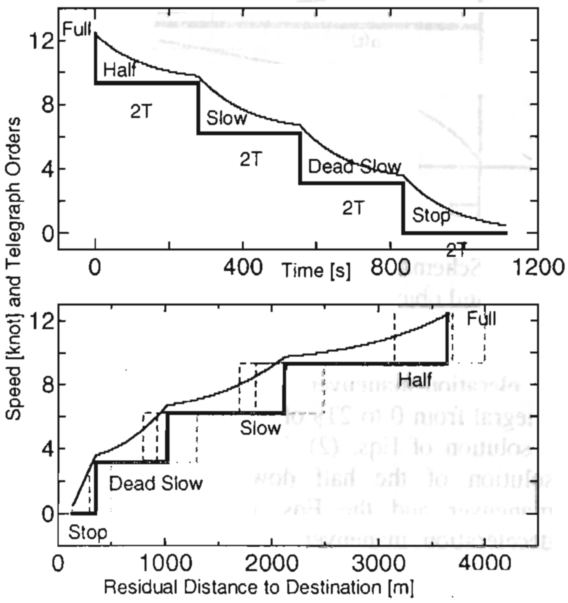


Fig. 7 Model of deceleration maneuvers by the experts

As some numerical calculation on this equation, it was found that a series of deceleration telegraph orders, which composed the standard deceleration maneuvers, had been executed at each twice the time of constant $T_P$ of the Eqs. (2). The standard deceleration orders based on this model and their simulated responses are shown in Fig. 7. A thick solid line, a thin solid line and dotted lines in the figure show a series of the standard deceleration orders, the simulated response and results of the questionnaire. Residual distances to the destination at each telegraph order were roughly coincided with results of the questionnaire. A verification of the model was executed using a ship-handling simulator. Fig. 8 shows a comparison of maneuvers of the model with the experts. A thick black solid line and thin gray solid lines show the model and the experts. This developed deceleration maneuver model was in agreement with the maneuvers of experts.

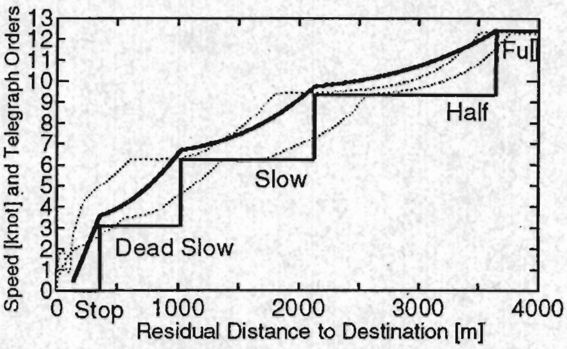


Fig. 8 Comparison of deceleration maneuver of the model and that of the experts in simulator experiments

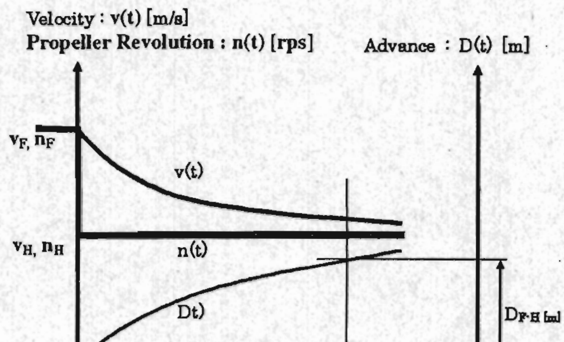


Fig. 9 Schematic relation among the advance, current speed and object speed

As shown in Fig. 9, the advance of the standard deceleration maneuver can be found by the definite integral from 0 to $2T_P$ of vessel speed: v(t), which is a solution of Eqs. (2). The following Eqs. (3) is a solution of the half down standard deceleration maneuver and the Eqs. (4) is of the graduated deceleration maneuver from the full ahead to the dead slow ahead.

$$D_{F-H} = \int_0^{2T_P} v(t)dt = T_P K_P (0.865 n_F + 1.135 n_H) \quad \text{---(3)}$$

$$D_{F-D} = T_P K_P (0.865 n_F + 2 n_H + 2 n_S + 1.135 n_D) \quad \text{---(4)}$$

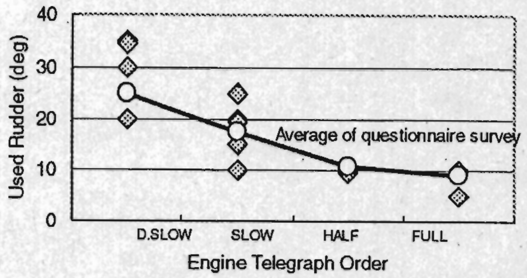


Fig. 10 Rudder angles used by the experts for course alterations in simulator experiments

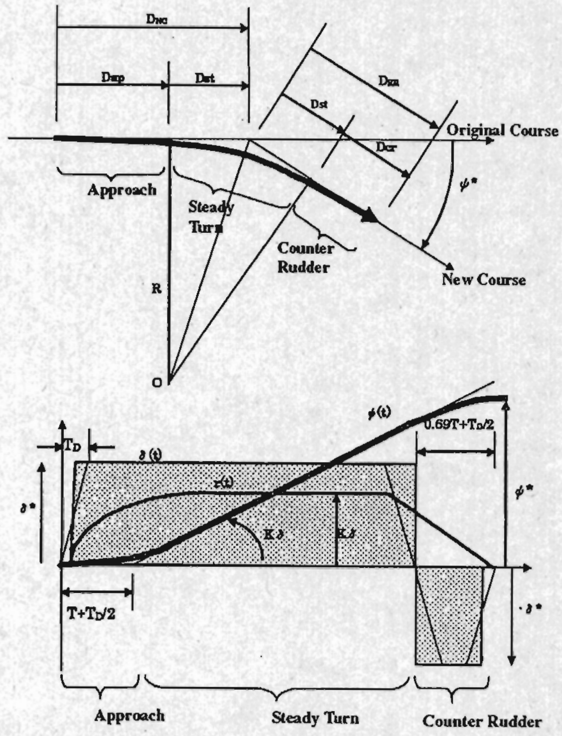


Fig. 11 Schematic definition of the standard steering to alter course and relation among trajectory, yaw rate, yaw angle and rudder angle

### 4.2 Standard course alteration maneuvers

The result of a questionnaire to experts on ordinary rudder angles of course alterations and used rudder angles in simulator experiments of experts are shown in Fig. 10. This distribution of used rudder angles were coincided with the ordinary rudder angles of the questionnaire. It becomes clear that the standard course alteration maneuver is composed of maneuvers using the rudder angle depending on the telegraph position.

As shown in Fig. 11, the distance from the stating point of the course alteration to the way point can be found by solving the following Eqs. (5). In same way, the distance to the ending point can be found by the

Eqs. (6). In these equations, $T_D$ is the delay of the steering gear, T' and K' are non-dimensional maneuverabilty characteristics of the vessel and others are defined in Fig. 11.

$$D_{NC} = \frac{T_D}{2} v(t) + T'L + \frac{L}{K'\delta'_{rad}} \tan\frac{\psi'}{2} \qquad \text{---(5)}$$

$$D_{RR} = \frac{T_D}{2} v(t) + 0.69T'L + \frac{L}{K'\delta'_{rad}} \tan\frac{\psi'}{2} \qquad \text{---(6)}$$

4.3 Standard stopping maneuvers

By the questionnaire surveys to experts on stopping maneuvers, it became clear that the standard stopping maneuvers consists of a series of two maneuvers. First one is a deceleration maneuver with a stop order along the straight course. The other is a stopping maneuver with a slow astern order at 1.5L short of the target point. As same as Eqs. (3) and (4), the advance for the standard stopping maneuver is found as following equation (7).

$$D_{STOP} = 1.5L + 0.865 T_P K_P n_D \qquad \text{---(7)}$$

## 5. SIMULATION OF THE PASSAGE PLANNING SYSTEM

Simulations based on the above-mentioned passage planning system were executed. Planning a passage for a GT499 inland vessel from the origin/start in an open sea to the destination/goal, where is in front of a berth, were simulated. Simulation results are shown in Fig.12 - Fig.17. The origin/start is at the lower left and the destination/goal is at the upper right in the water area.

*(1) Finding a shortest path under topographical, legal and other restrictions*

In the target water area, there are many No-Go areas, which are defined by the water depth contour lines of the chart, based on the UKC: under keel clearance of the vessel. Paths from the origin to the destination should avoid No-Go areas. Some paths were found and the shortest path of them was selected, as shown by the line in Fig.12. But there are often some recommended passages, legal based passages and other restricted areas in and around ports in addition to a restriction of the UKC. Re-finding another shortest path through the recommended entrance passage from the origin to the destination was done, because there is a recommended passage in the target water area. Finally the modified shortest path through the recommended passages was selected, as shown by the line in Fig.13.

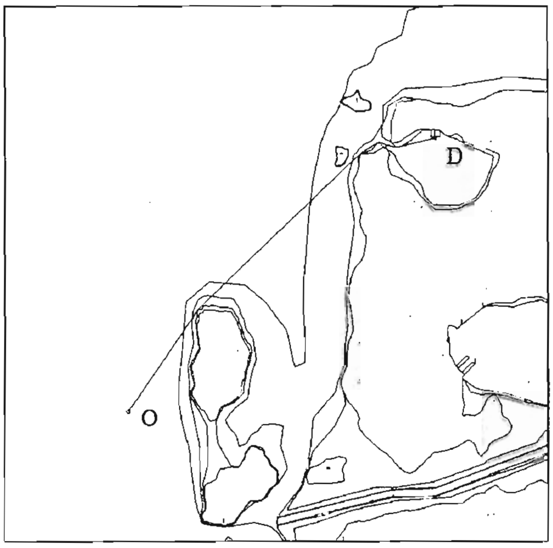


Fig. 12 The shortest path under the UKC constraints

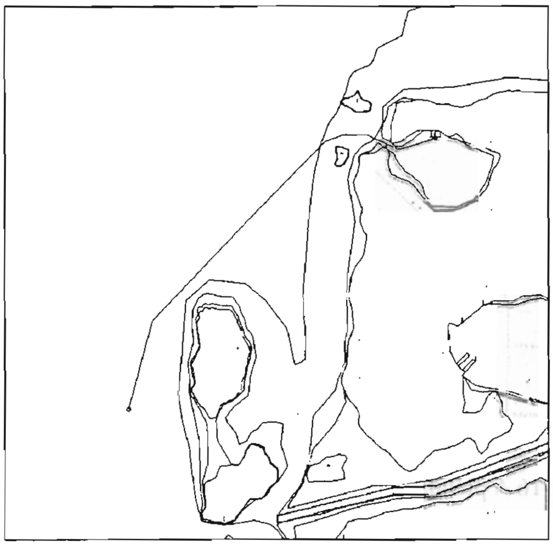

Fig. 13 The modified shortest path through the recommended passages under the No-Go Area constraints

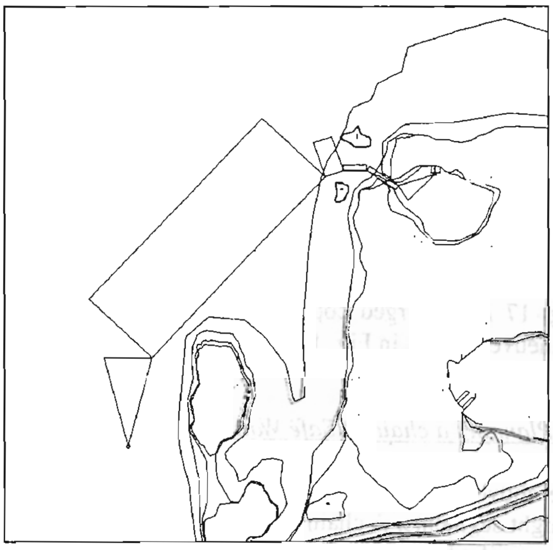

Fig. 14 A chain of the Safe Waters along the shortest path

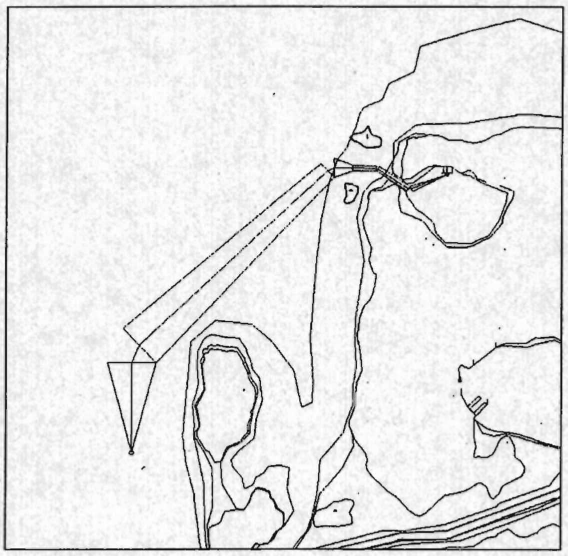

Fig. 15 A chain of elemental passages and the route

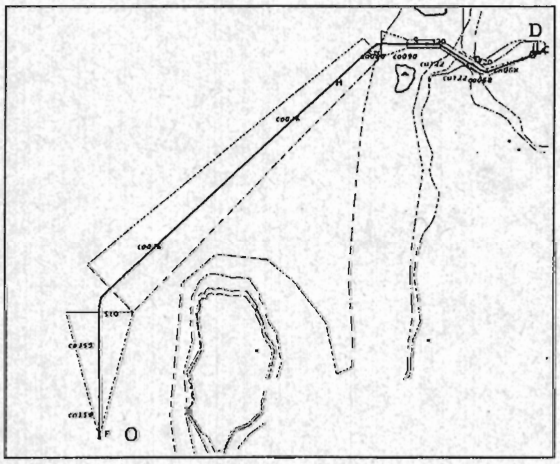

Fig. 16 A planned maneuvers

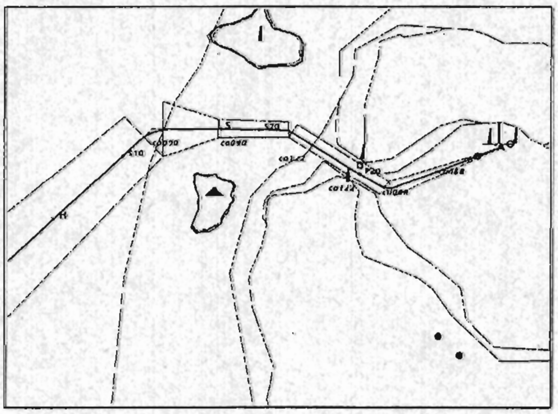

Fig. 17 An enlarged copy of a part of the planned maneuver shown in Fig. 16.

*(2) Planning a chain of Safe Waters*

The above modified shortest path is only a chain of straight segments. A chain of continuous areas, along the modified shortest path, with margins of safety should be created. The area with the enough navigable width as a margin of safety is an elemental Safe Water. To keep safety margins of passages, the maximum navigable width of each Safe Water was searched. A chain of Safe Waters, which is shown in Fig.14, was obtained.

*(3) Planning a chain of elemental passages*

In order to keep continuity of two passages and prevent a long way of passages, width of the outlet of the passage were set equivalent to width of the inlet of the next. A chain of continuous elemental passages was obtained. A route based on this chain of elemental passages, which keeps center of each passage, was proposed. Fig.15 shows the obtained elemental passages with a proposed route.

*(4) Planning a chain of elemental maneuvers*

According to the above-mentioned standard maneuvers, wheel over positions, rudder orders, telegraph orders and their positions were fixed on the above proposed route. Fig.16 shows a chain of elemental maneuvers and maneuvering orders which was proposed finally. Fig. 17 is an enlarged copy of a part of the planned maneuvers shown in Fig. 16.

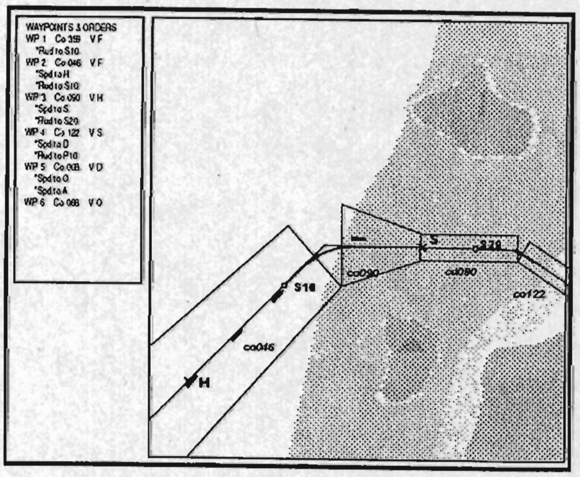

Fig. 18 Display image of the real-time maneuvering information support system

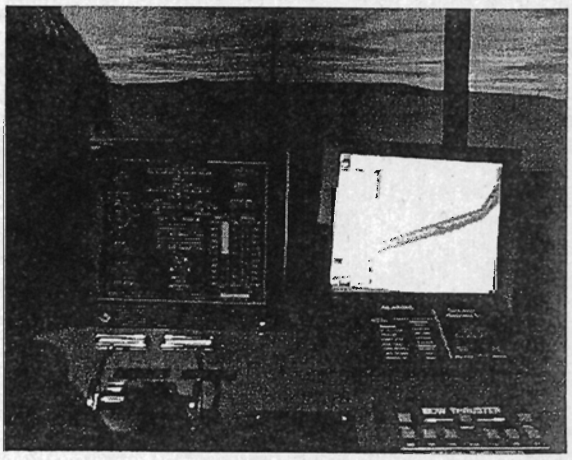

Photo 2 The real-time maneuvering information support system in the shiphandling simulator

## 6. REAL-TIME MANEUVERING INFORMATION SUPPORT SYSTEM BAESD ON THE PASSAGE PLANNING SYSTEM

The real-time maneuvering information support system based on the passage planning system was installed into the shiphandling simulator. A display image of the real-time maneuvering information support system is shown in Fig. 18. The system equipped in the shiphandling simulator is shown in Photo 2.

Using this real-time maneuvering information support system, the navigators can get her automatic planned passage, her current position, her current deviation from the current course, positions and distances of the way points and next maneuvering orders by means of a quick glance at the display of the system.

## 7. VERIFICATION OF THE PASSAGE PLANNING SYSTEM

### 7.1 On the passage plan

In order to verify the passage planning system, the plans generated by the system had been compared with the plans of expert mariners. Fig.19 shows the planned routes of three expert mariners and the system. The black thick line with passages is the automatic planned route of the system and the gray colored lines are the planned route of the experts. Fundamental difference between them is not found. Fig. 20 shows the chain of elemental maneuvers which was planned by the experts. Fig. 21 is the chain of elemental maneuvers which was automatically generated by the system. Comparing Fig. 20 with Fig. 21, their deceleration orders and their positions to order are almost same. The passage plans generated by the system is generally accepted by simulator testees as expert mariners.

### 7.2 On the system with the real-time maneuvering information support

In order to verify appropriateness of the generated plans and usefulness of the system, simulator experiments with the real-time maneuvering information support system were executed.

Fig.22 shows simulator experimental results, which are the tracks, the telegraph orders, the speed and the rudders, using the real-time maneuvering information support system. Fig. 23 is the simulator experimental results without the real-time maneuvering information support system. Comparing Fig. 22 with Fig. 23, it is clear that experimental results using the support system shows better tracking performances than that of no support system. There is no large rudder angle more 25 degrees in Fig. 22. But large rudder angles more than 25 degrees are found in Fig. 23.

The passage planning system with the real-time maneuvering information support system can provide effective and appropriate support for the navigator under operation. It is considered that the passage planning system with the real-time maneuvering information support system is useful to maneuver the vessel more safely.

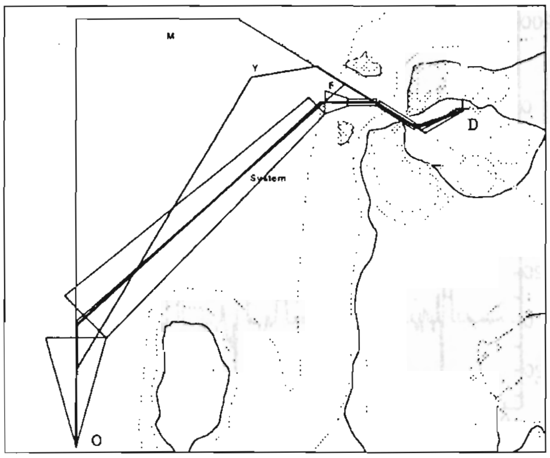


Fig. 19 Comparison of the routes of the experts and that of the passage planning system

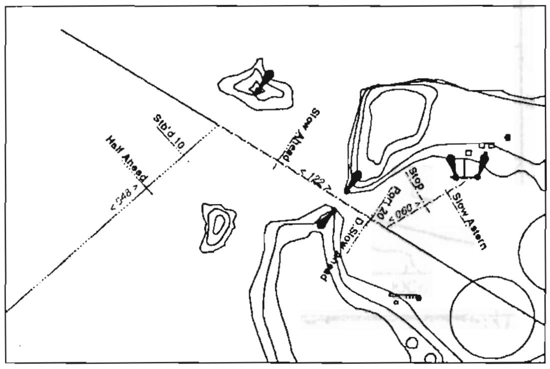

Fig. 20 Maneuvering plan of the expert "F"

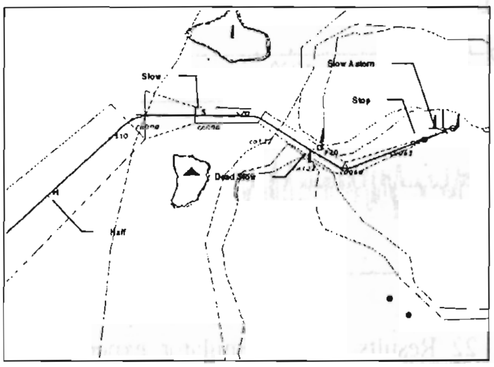

Fig. 21 Maneuvering plan of the passage planning system

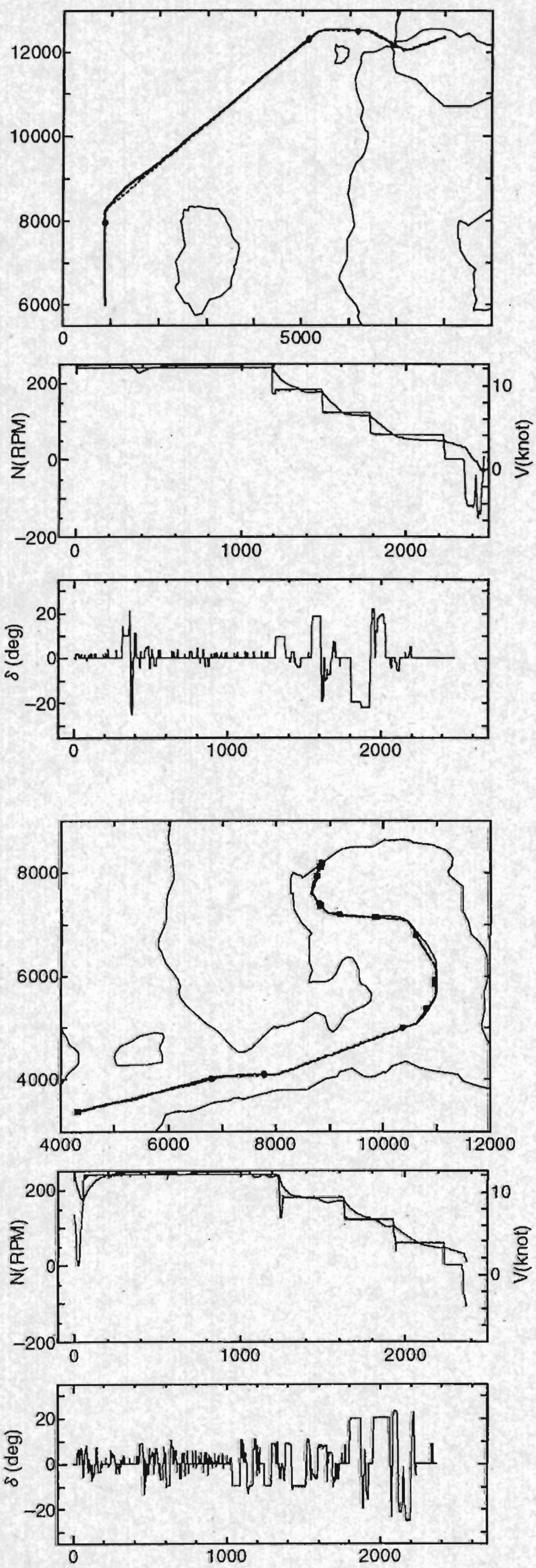


Fig. 22 Results of the simulator experiments with the support system by the less experienced operators

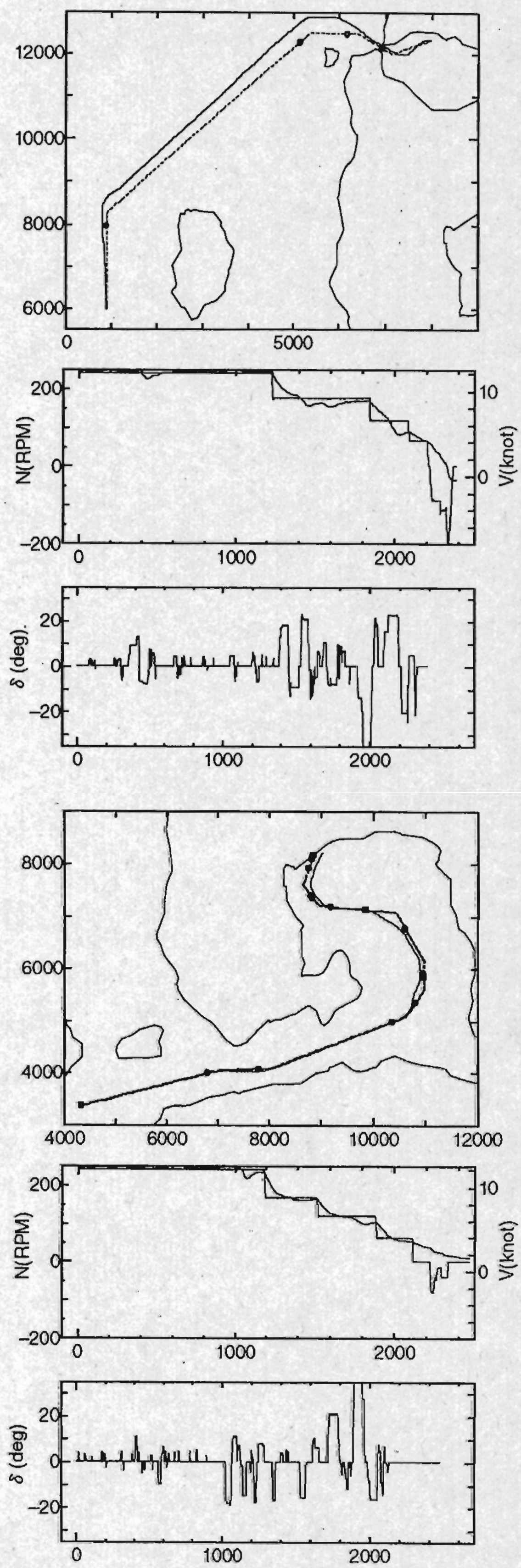


Fig. 23 Results of the simulator experiments without the support system by the less experienced operators

## 8. CONCLUSIONS

The authors concludes by listing important points of this study.

- The passage planning system, which is one of the countermeasures answering the requests of vessels and port operators, was proposed.
- Standard maneuvers, which a model of maneuvers by expert mariners, were investigated.
- Algorithms to generate the passage plan automatically were developed.
- Simulation results of the passage planning system show that the system can reproduce the passage plan which the expert mariners plan usually.
- Results of the simulator studies with the real-time maneuvering information support system based on the passage planning system shows the good tracking performance and the efficient maneuvers by the operator.
- By using the system, a large effect to increase safety and economical efficiency on port management is expected.

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## AUTHOR'S BIOGRAPHY

Makoto Endo studied Nautical Science at Tokyo University of Mercantile Marine. After working as a naval architect for 3 years, he has a place at the Nautical Department of Toyama National College of Maritime Technology as a professor since 1981. Since 2002, He is a chairman of Ship Handling Simulator Committee in Japan Institute of Navigation. He holds a Bachelor's degree and a Master degree in Navigation and a Doctoral degree in Engineering. His current research interests are safety evaluation of ship manoeuvrability, man-machine system analysis in ship handling and cooperative navigation system