# SIMULATION OF AUTOMATIC SHIP NAVIGATION AND VESSEL TRAFFICS
## (2nd Report)A Knowledge-based System Applied to an Automatic Navigation*[1]

By

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**Abstract**

A modeling of judgment and decision-making in ship operations is performed as a fundamental study for the development of an automatic ship navigation system. A prototype of knowledge based system for intelligent tasks of ship operators onboard is built. A simulation model for the judgment proposed, which is a hybrid of the knowledge based system and FORTRAN programming, is applied to the simulation of automatic ship navigation. It is shown that a collision avoidance algorithm works quite well and has a wide range of application under the supervision of the knowledge based system. Computer simulations for the navigation in Tokyo Bay and in emergency show reasonable and satisfactory results. A development of the new and flexible prototype and a practical application of the hybrid model for the judgment and decision-making seems to be quite promising.

Modification and extension of the simulation system SISANAM after publication of the 1st report are described in appendix.

## 1. INTRODUCTION

Sea traffic is highly congested in narrow waterways, ports and harbors. Marine safety in such navigation area is kept by skillful operations of captains or pilots as well as various measures for the sea area. Recent progresses in an artificial intelligence technology will realize a highly skillful operation performed by an automatic navigation system.

A ship navigation is performed through the following sequence, i. e. surveillance of the navigation area, detection of targets, identification of collision or stranding risks, judgment and decision-making for the operation and control command for ship handling. An advanced control system onboard has already been applied in practice from the viewpoint of automation. A marine radar has sufficient accuracy for the

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* Received on September 2, 1989

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[1]similar content is presented in CAMS'89[1)]

present purpose and radar data processing in navigation aids like ARPA[2] is plenty of useful functions. But the judgment and decision-making process depends on human ability as before. Even for experienced ship operators ship handling in congested sea area is a difficult task and brings them extreme mental tension. It is because of variety of conditions, ambiguity of informations especially on the intent and movement of target ships, and poor ship controllability.

When a ship sails alone in the sea area, only the functions of optimal routing and ability of tracking the route are required for the automatic navigation system. A collision avoidance maneuver should be taken according to the rules and the regulations when the ship encounters to other ships. Understanding and judgment of the situation, and finding out suitable ways of maneuver require expertise and empirical skill on ship operation. If a suitable way is selected, the collision avoidance maneuver is easily performed by setting new reference course to be tracked. Therefore modeling of the judgment and decision-making process is essential and the programming of the corresponding algorithm is a keystone of a fully automatic ship navigation.

Recent advances in an artificial intelligence technology offer new methodology to the ill-defined problem such as judgment and decision-making on which a conventional approach is not so effective.

A conceptual design for the automatic ship navigation is performed by the authors[2)3)]. In the design, multistage judgment process and decision-making process by means of a knowledge based system are used. A fundamental performance of the system is examined through a computer simulation. The simulation system is designed and constructed for realizing various ship's situation such as geographic conditions and sea traffic.

In this paper algorithm for collision avoidance and functions of the knowledge based system are highlighted. Realistic simulation for the automatic navigation system in the emergency as well as an ordinary navigation in congested sea area are performed.

## 2. KNOWLEDGE BASED-SYSTEM

Various kinds of knowledge based system are proposed and applied in practice. The feature of each system depends on the style of knowledge representation and the way of inference. *Production rule system*, where knowledges are expressed as the form of *If __Then __Rule*, is the most popular and called *Expert System*. It is possible to build an expert system in a short term by available ready-made AI tools. An inference system and powerful user's interface are provided in the tool, and only the expertise is expected to customize in the knowledge base. The operating system and the inference engine have functions of the inference control, truth maintenance, management of fact data base and etc.. The user's interface system

[2]Automatic Radar Plotting Aids

offers explanation of the reasoning and inference process, graphic expression of the results and input/output device.

For ship operation a knowledge based system is expected to be effective on judgment and collection of information in the ambiguous situations of target ship's behavior. Another application is the decision-making of the ship maneuver in an unco-ordinated situation where so many complicated factors are involved and many possible solutions exist[3)4)].

In this study AI tool named *ART* is used for the prototyping of the knowledge based-system[5)]. *ART* is named after automatic reasoning tools by *the Inference Co. U. S. A.*. It is one of representative 'AI tools in 2nd Generation', which comprise tools and functions of the 1st Generation and have better performance and human interface. At first *ART* is developed on LISP machine, which is a special computer for knowledge processing. Now there are various versions available for main frame computers, minicomputers and personal computers. *ART* is plenty of useful functions in knowledge processing, but only fundamental functions of *production rule system (If __Then __Rules)* and *frame* expressions are applied to this study.

## 3. AUTOMATIC SHIP NAVIGATION SYSTEM

There are three main functions required for the navigation; sensing, judgment and operation. Each function has various contents, i. e., the sensing contents measurement of nature conditions, surveillance of the navigation area and reception of various informations from other ship and land facility by radio communication and etc.. The judgment contains collision and stranding avoidance and achievement of the other missions, and the operation contains ship control and announcement to other ships and land facilities.

Usually a ship control consists of a rudder control for heading angle and lateral shift, and propulsion engine control for ship speed. Principally the rudder control for the automatic navigation system in near future seems to be an extension of an existing auto-pilot system. On the other hand, a nonlinear control is inevitable to have better performance in speed control because of a poor controllability by a propeller. Advanced controls such as an optimal bang bang control and a fuzzy logic control for ship speed are proposed by Shimizu[6)].

A conceptual design for the automatic ship navigation system is performed according to the analysis of the navigation mentioned above. The structure of the system should be a hierarchical one, which is useful from the viewpoint of system safety, i. e., redundancy and robustness can be easily taken into the system.

The system is roughly divided into five parts; a supervising part, a data acquisition part, a data processing part, a communication part and a command part for ship control. Each part consists of some subsystems as shown in Fig. 1. The supervising subsystem controls the internal data which are to be processed and referred by other subsystems, and possesses backup functions of them in order to increase the robustness and to widen the working range of the system.

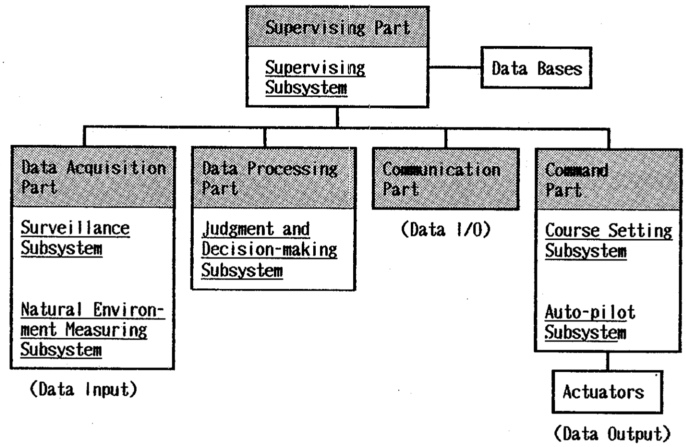


**Fig. 1** Structure of Automatic Navigation System

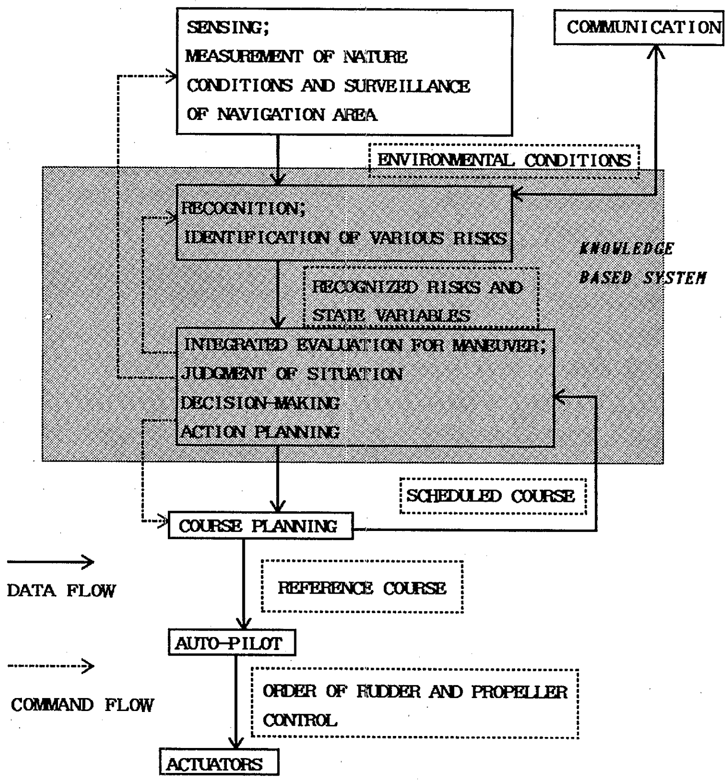


**Fig. 2** Flow Diagram of Judgement and Dicision-making for Collision Avoidance

A parallel execution of element processes in the subsystem is another merit of the hierarchical system. This is essential to the real time system, because it enables an effective utility of onboard computer system and a high performance of the navigation system. Advanced judgment and decision-making functions by means of a knowledge based system, which takes longer time than other processes, should be executed as a background job.

A collision avoidance ability is the most important in the navigation, especially within the congested region. The collision avoidance maneuver can be also realized in the hierarchical system shown in Fig. 1. A flow chart of data and processes for the collision avoidance is shown in Fig. 2, in which sequential processes are performed according to the indicated flow. The advanced processing of the knowledge based system is performed in the background which is shown as a hatched region.

The surveillance subsystem gathers informations on the positions, velocities of own ship and other ships, and intent of other ship with the aid of the communication subsystem. The judgment and decision-making subsystem classifies the level of the collision danger with other ship according to the informations, and recognizes various risks and their emergency. It is difficult to get a simple solution for the collision avoidance maneuver in the case of multiple encounters. A possible safety course in a narrower range and shorter prediction span is searched and decided if no safety course is found. The obtained course is set to the auto-pilot subsystem, which gives control commands to the actuators such as a propeller revolution and a rudder angle.

The judgment and decision-making ability is required to solve difficulties for ship operations. Identification of risks is performed at the first stage. Integrated evaluation of various risks and other informations, finding out suitable way of maneuver and decision-making are carried out for the succeeding stages. The integrated evaluation requires several kinds of data bases such as digital charts, rules and regulations etc.. Multistage judgment process and decision-making process by means of a knowledge based system are useful for an automatic ship navigation system.

As it is important to make cooperative maneuvers, especially in the case of multiple ship encounters, all the ships should be operated according to the same navigation standards and the mutual understanding confirmed by communication. The way of communication for ship operators is limited to flags, light signals and VHF radio. Transponder and secondary surveillance RADAR, which are standard equipment of airplanes, are not available. Therefore judgment and expertise to supplement are expected in the information processor. Moreover situation and conditions change dynamically as the nature of mobile control, and the real time judgment and treatment are required. The rules and regulations are necessary as the standard of action also taken into the decision-making process. Data bases of the rules, regulations and nature conditions etc. are required for the appropriate decision in each stage of judgment and decision-making. In the automatic navigation system, the knowledge based system gives consultations of the data bases to each stage from the background.

## 4. MODELING OF JUDGMENT AND DECISION-MAKING PROCESS

An ocean going vessel is a complete system like a small society, and there are various kinds of tasks onboard. A special ability for the management is required to perform these tasks timely by a minimum numbers of personnels. Once a sequence of jobs in any kind of task is analyzed and a way of control is formulated, the automatic system easily performs an optimal control. The most difficult and essential in the task management and ship operation is the judgment of the situation when the full automation is realized.

The total judgment process by human seems to have multiple levels. The top level process judges the global matters and checks the consistency from the macroscopic viewpoint. It makes principal decision and offers guidelines for the judgment in the lower level. The lower level judgment, on the other hand, judges matters and situation for a restricted region, and makes decision in detail. Generally a process of judgment and decision-making can be modeled as the following sequence seen in Fig. 3.

After examination of informations collected, the real state of the situation is estimated. This is the stage of the judgment and understanding of the situation. Sometimes the estimation is information itself or state of the situation desired in future. The estimation is defined by the amount and accuracy of information, the way of inference etc., and it depends on an amount of experiences and knowledge of the ship operator or system designer. Secondly, it is determined what to do and what not to do in the situation based on the aim, principle and strategy of the system. This is the stage of decision-making. In this stage the experience and knowledge are also utilized. Thirdly the best plan and optimum procedure are made out if it is required. This is the stage of planning. Lastly commands for the actions are ordered just on the time necessary according to the action plan.

Usually these stages are repeated iteratively, and sometimes they are repeated like a trial and error manner in assumption before the actual judgment or decision is obtained. When interactions or conflicts have happened during the process, another knowledge for the resolution is recalled and applied. The iteration loop can be in the upper level as well as in the same level.

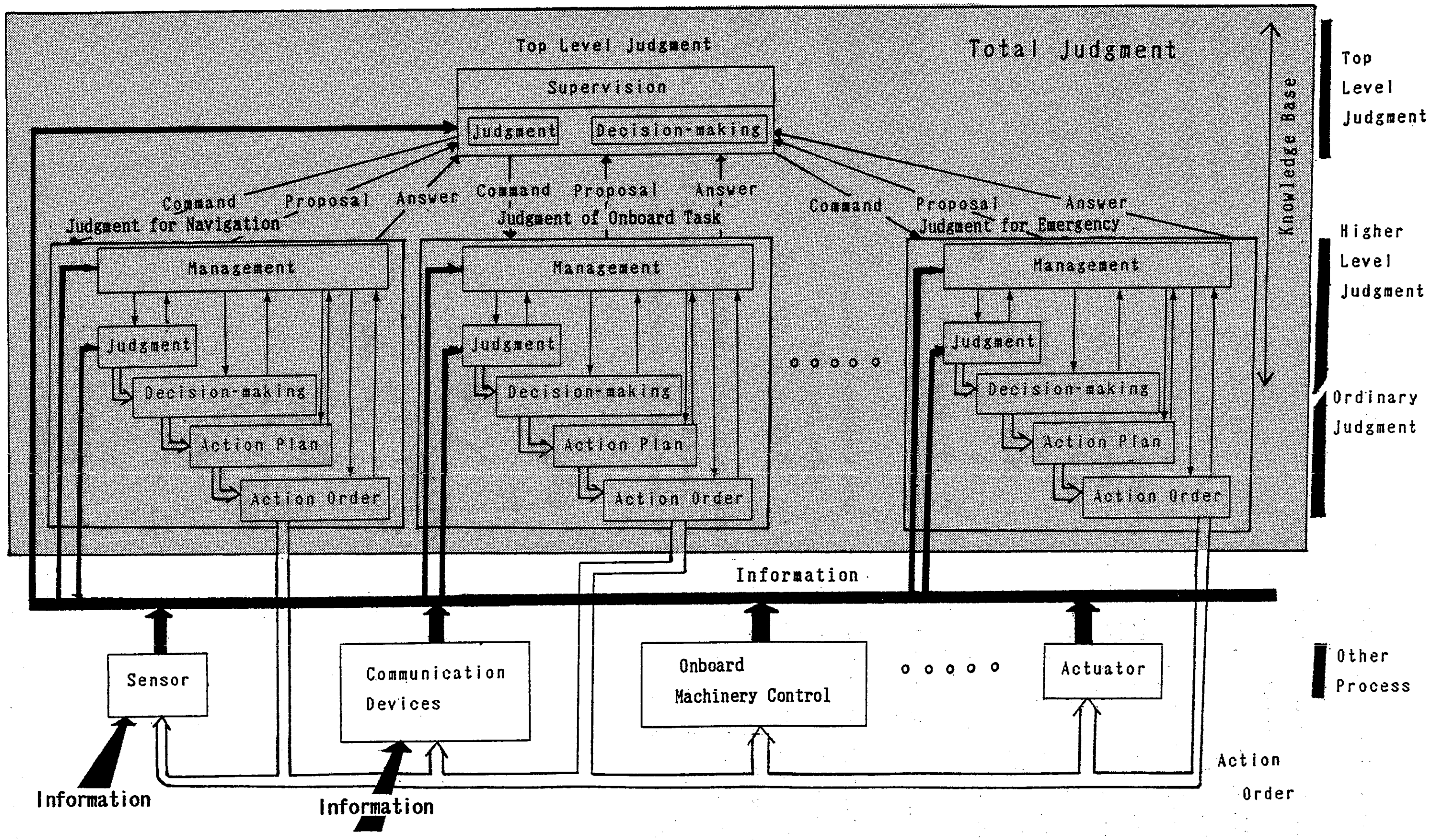


**Fig. 3** Structure of Judgement and Dicision-making Process

## 5. COMPUTER MODEL OF JUDGMENT FOR SHIP NAVIGATION

A new computer model for the judgment and decision-making process in ship operation is proposed. It performs several kinds of tasks. It is composed of a hierarchical structure and hybrid of different styles in algorithm presentation and programming. The top and higher level of the hierarchy take roles of understanding and judgment for working situation and make a plan and guidelines of the tasks. The lower level corresponds to the judgment in narrower range of the tasks. In the level, the tasks are performed as a sequence.

An automatic navigation in a congested sea area is performed by the already described procedure. There are three kinds of judgment in the procedure discussed here. The first is a judgment and identification of the collision risk, and the second is a finding out of a suitable way of action. The last is the general judgment of the situation for navigation. The former two algorithms are programmed in FORTRAN and a knowledge based system is applied to the last.

### 5. 1 Judgment for Collision Risk and Collision Avoidance Maneuver

So-called CPA[3] analysis based on simple geometric calculation, the prediction of relative course and movement of the target ships are obtained and the risk of collision is calculated in the program.

Collision risk $\varepsilon$ is defined for the encounter condition to a single target ship. For a multiple encounter condition, total collision risk is defined as functions of risks for every target ships involved. The functions are depended on the principle and the

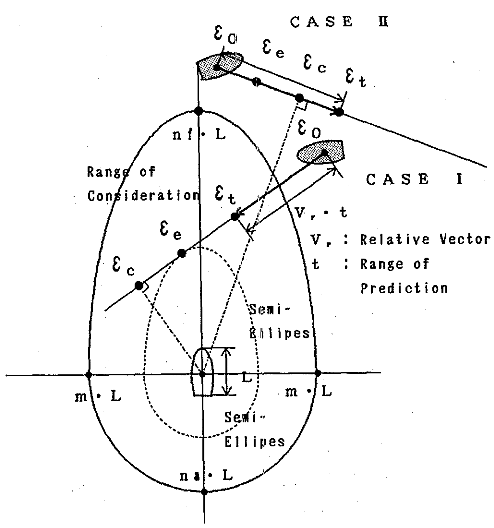


**Fig. 4** Collision Risk $\varepsilon$

[3]Closest Point of Approach

way of collision avoidance maneuver of the ship. For example, maximum value of risks, weighted additional relations of risks for all ships, or value for the smallest TCPA ship or the nearest ship etc can be the total collision risk. In the simulation performed by SISANAM model for collision avoidance, the total collision risk has not established yet, and the functional relations differ for versions of models.

In Fig. 4, explanation of collision risk $\varepsilon$ for a single encounter condition is shown. The collision risk $\varepsilon$ is defined after a concept of blockage region for ship navigation in traffic flow. It is obtained by the observation of marine traffic and applied to a bumper model. The shape of the blockage is modeled as a combination of semi-ellipses. The collision risk is defined as followed.

$\varepsilon = 1 - (RD/RB)$

RD : Relative distance to the target ship in the elliptic coordinate

RB : The size of the blockage region defined in the elliptic coordinate

When $\varepsilon$ shows a positive value, the target ship is or will be in the blockage region and there is a risk of collision to the target ship. The larger value of $\varepsilon$, the higher the risk level is. There are four collision risk values defined for each target ship ($\varepsilon_o$, $\varepsilon_t$, $\varepsilon_e$, $\varepsilon_c$). $\varepsilon_o$ is the collision risk value at present position. $\varepsilon_t$ is the one at the relative position, where the target ship will reach after some time interval. During the time, collision avoidance is taken into account. $\varepsilon_t$ is the value at the position where the shortest relative distance to the target ship in the semi-elliptic coordinate is measured. $\varepsilon_c$ is the value at the CPA position. If the TCPA of a target ship is negative value, $\varepsilon_o$ would be used as the collision risk $\varepsilon$ for the target ship. If the TCPA is larger than the range to consider about collision avoidance, $\varepsilon_t$ would be used as $\varepsilon$. And another condition, maximum value is used as $\varepsilon$. In CASE I, in Fig. 9, TCPA is larger than the time range to consider to collision avoidance, so $\varepsilon_t$ is adopted as $\varepsilon$. And in CASE II, the TCPA is in the range of consideration, $\varepsilon_c$ (maximum value of the four)becomes $\varepsilon$.

The judgment process selects a suitable plan for the maneuver, taking the encounter situation and other surrounding conditions into account. Of course, privilege and burden in the marine traffic regulation are considered in the plan.

Usually a simple algorithm for collision avoidance is not available for the congested area. Because multiple encounter occurs quite often, a more complex and sophisticated algorithm is required. Adopting hierarchical structure in the judgment process, and letting the knowledge based system to tune parameters of the algorithms in the top level as a role of supervision and management, the same simple algorithm is available for the congested area.

### 5. 2 General Judgment by a Knowledge based System

A practical modeling of the judgment and decision-making process shown in Fig. 3 is proposed on the analogy of the human judgment. The feature of the model is its hierarchical structure and application of knowledge based system in the top and higher levels of the process.

The top level judgment responds to informations from the lower level judgment and other information as well, and performs in the global or macroscopic view by knowledge in the knowledge base. The knowledge is expressed as production rules. Inference based upon the *IF __THEN __RULE* is performed by ready-made inference engine. General judgment and understanding of the situation, and decision-making are the two major subject of the top level judgment process.

The top level judgment performs final judgment and decision-making for the whole voyage plan and actions. The judgment, however, will not give command of action directly but supervision only. Usually it shows the results of judgment and understanding for the situation or gives guidelines for action.

The supervising function is realized in two ways. One is an explicit supervision in the form of command to the lower level, which is realized as the assertion of Fact in the knowledge base. The other is implicit supervision which indirectly affects to the whole of the knowledge base by means of special Fact handling named Control Fact. The higher level judgment, which includes the management of the judgment process in the lower level and some judgment and decision-making in the level, is also a knowledge based system. The ordinary judgment has a role of judgment and decision-making after a well defined sequential procedure, and orders the processes of action by commands. The knowledge based system works one of an asynchronous processes in the multi-process type simulation system.

Rules in knowledge base is classified in two categories. One is rules for system management of judgment, such as data handling with other simulation processes programmed in LISP or FORTRAN, timing management and flow control of the interface. Other is rules for the expression of the knowledge in the real world. According to the modeling of judgment ship navigation and decision-making shown in Fig. 3, rules for the knowledge in the real world are classified with four groups.

Of course it is possible to build up either whole process of judgment from primitive to the top, or whole of the simulation system as a knowledge based system[4)7)]. Different style of system design is chosen here in order to realize a real time simulation system in a large scaled multi-process system. A lot of existing software programs in FORTRAN are utilized, and CGI[4] system on advanced graphic workstations in the computer network is built up easily by means of the hybrid style.

### 5. 3 Hierarchy in Knowledge based System

It is not procedures but knowledges that are expressed and programmed in the knowledge based system. The flexibility is a remarkable feature and an advantage of the knowledge based system which has plenty of possibility in new practical domain and offers much freedom for the system design.

In some cases needless freedom for a well defined problem spoils an easiness in the system design. A knowledge based system is designed after the hierarchical modeling of the judgment process but different from the viewpoint of system freedom.

A Control Fact system is introduced after the two stand points. One is management in the kind of task and another is control for the level of the situation.

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[4]Computer Generated Imagery

Remarks for Chinese Characters used in the Rule

1 Trouble
2 Kind
3 Level of situation
4 Order-decreasing speed
5 Order-diagnosis
6 Declare trouble
7 Order-navigation
8 Getting out of route

```
(defrule 故障[1]JUDGE_TROUBLE1 ""
  (declare (salience 1000))
    (request ?a ?b koshou)
      (or (種別[2] ?a all ) (種別[2] ?a f))
      (抑制[3] ?a ?)
        (test (= (judge_trouble ?a) 1))
=>
  (assert (減速指令[4] ?a))
  (assert (故障診断指示[5] ?a)))
```

```
(defrule 故障宣言[6] ""  ------------------- one of RULE of supervise
  (declare (salience 1000))--------------- priority of RULE
    (request ?a ?b koshou)---------①----- system mng. FACT      IF
       ?f<-(種別[2] ?a all)------------②--- control     FACT
      ?f2<-(抑制[3] ?a ?)--------------②--- control     FACT      Part
         (code ?a  ?l&:(> ?l 1))-------③- condition   FACT
  =>
  (printout t t "?a= " ?a)---------①----- for monitor
  (retract ?f ?f2)-------------------②---  ) recreate
     (assert (種別[2] ?a f))-----------②---  } control             THEN
     (assert (抑制[3] ?a 2))-----------②---  )  FACTS
     (assert (航行指令[7] ?a 航路離脱[8])) ③-direction out          Part
     (assert (koshou ?a)))------------ ③-create condition
                                          FACT(trouble)
```

```
(defrule 故障[1]JUDGE_TROUBLE2 ""
  (declare (salience 1000))
     (request ?a ?b koshou)
     ?f1<-(種別[2] ?a f)
     ?f2<-(抑制[3] ?a ?)
(test (= (judge_trouble ?a) 0))
       ?f3<-(koshou ?a)
  =>
  (printout t t "?a= " ?a)
  (retract ?f1 ?f2 ?f3)
     (assert (koshou-end ?a))
     (assert (種別[2] ?a all))
     (assert (抑制[3] ?a 9   )) )
```

Remarks for layers in the Rule

① 1st.layer:system management
② 2nd.layer:Control FACT
③ 3rd.layer:Ordinary condition of action

**Fig. 5** Examples of Rules in Knowledge Base

Level of the situation has essential meaning but kind of task is only for the convenience of the system management and system design.

These control facts are governed by the top level judgment process. The top level judgment can select the kind of work or restrict the judgment in lower level by the management of the Control Fact. In other words the total inference is affected and controlled by the final judgment and understanding of the top level judgment process for the ship situation.

Each rule of the production system has three layered context in its IF __part as shown in Fig. 5. The first is conditions for the system management, the second for the Control Fact, i. e., for the control of inference by higher level through the control fact management, and the last is for ordinary conditions of knowledge expression.

The layers are indicated in Fig. 5 as the numbers 1, 2 and 3 for the statement line in the rule. As seen in Fig. 5 Chinese characters and Japanese are used for the knowledge base, which offers efficiency and easiness in the management of the knowledge based system for Japanese people. For convenience of English speaking people, translations are shown in Fig. 5.

By this way ordinary knowledge based system designed by segment according to the kind, is put in the hierarchy and unified. As the results the knowledge based system has wider range of validity. The hierarchy is also helpful for the management and handling of the total system.

## 6. RESULTS OF COMPUTER SIMULATION AND DISCUSSION

A data centered and scenario driven type of computer simulation system is built[8)9)]. It is easy to carry out simulation in various kind of condition by the system. Typical results of simulation for the automatic navigation system are shown here.

In entering a congested port, the automatic navigation system should take various tasks such as communication with a vessel traffics management center and a pilot center, embarkation of a pilot and collision and stranding avoidance maneuvers. For the test of the total performance of the system, a simulation scenario shown in Feg. 6 is effective, in which various tasks are included as the events on navigation. This is a scenario of the entering Tokyo Bay. Navigations of other ships are also realized just as the ship of mainly concerned and to be tested, but it is possible to use simplified models according to the purpose of the simulation.

### 6. 1 Fundamental Results for Collision Avoidance

The collision avoidance algorithm is formulated for the fundamental single encounter conditions such as shown in Fig. 7. They are meeting, crossing, overtaking and overtaken conditions. The same algorithm is applied to the both ships in the simulation.

Both ships are burdened in the case of meeting. But not necessarily the both take collision avoidance maneuver as seen in the results. This is possible in

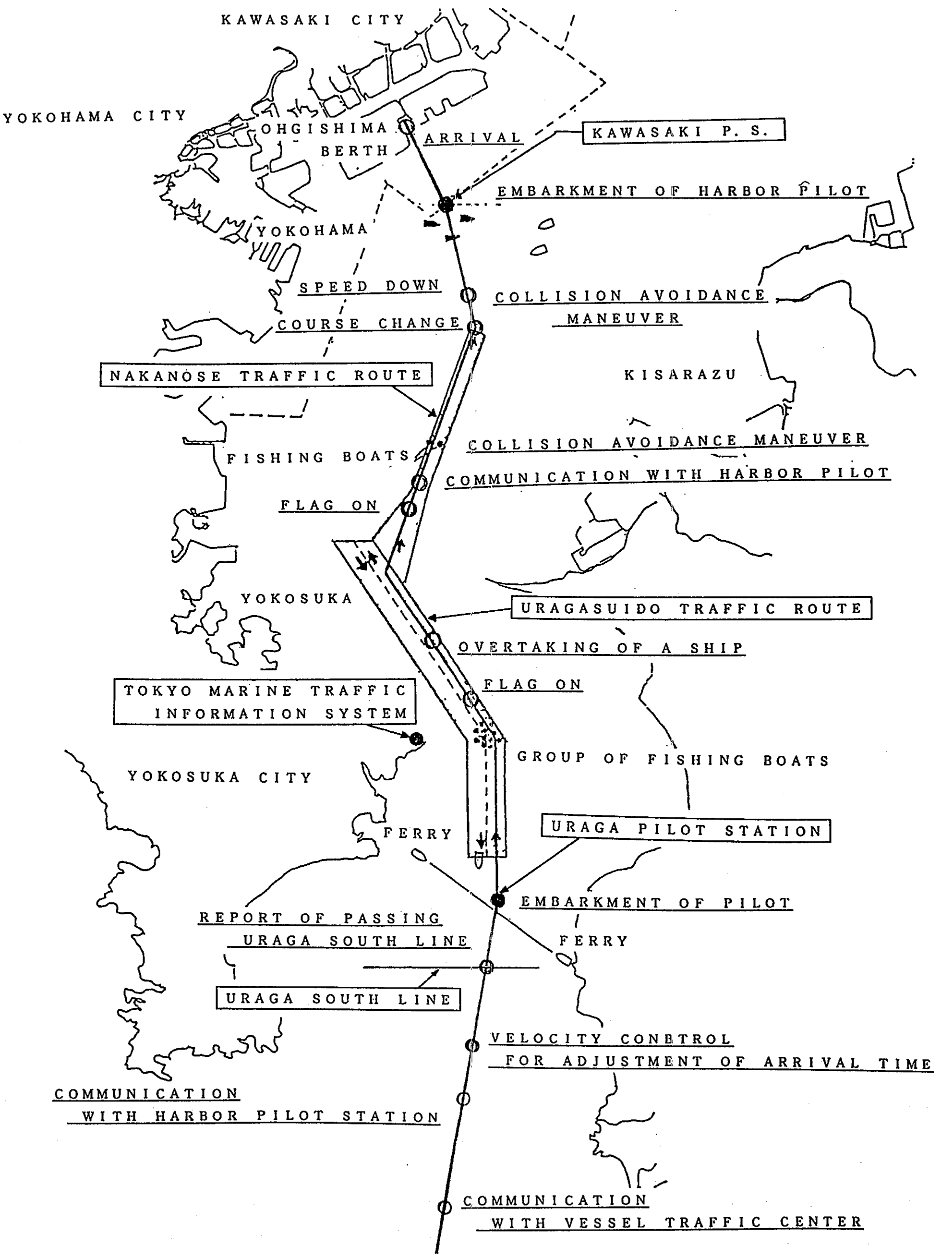



**Fig. 6** Simulation Scenario for Navigation in Tokyo Bay

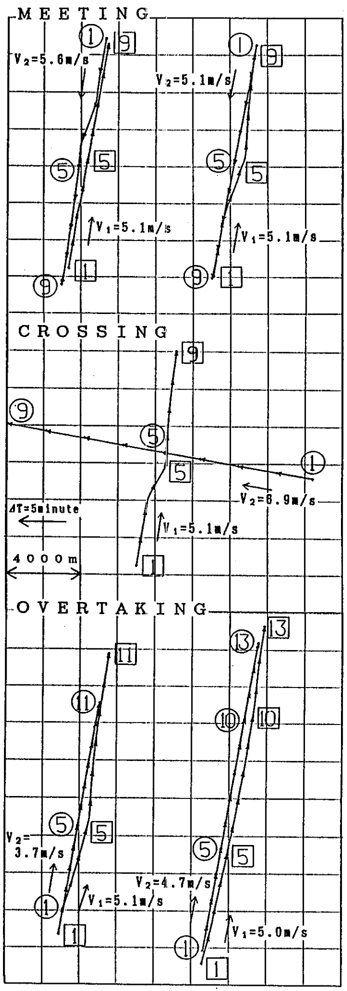



**Fig. 7** Ship Trajectories in Fundamental Encounter Conditions

practice, but will not happen in the simulation with the same algorithm and the same condition for the same ship if a single process calculation is achieved. In the case of crossing, burdened ship takes collision avoidance maneuver to the right and the privileged goes straight. If the burdened suppresses the algorithm and goes straight, the privileged will avoid. Because the privileged ship also obeys the same algorithm except the smaller radius of the dangerous circle than the burdened. Overtaking in a small speed deference takes a long time to complete. If other restriction or cooperation between the ships exists the knowledge based system tunes the parameters to the situation and the different results will be obtained.

The parameters of the algorithm such as a radius of dangerous circle and duration of prediction and etc., which are adjusted dynamically by the knowledge

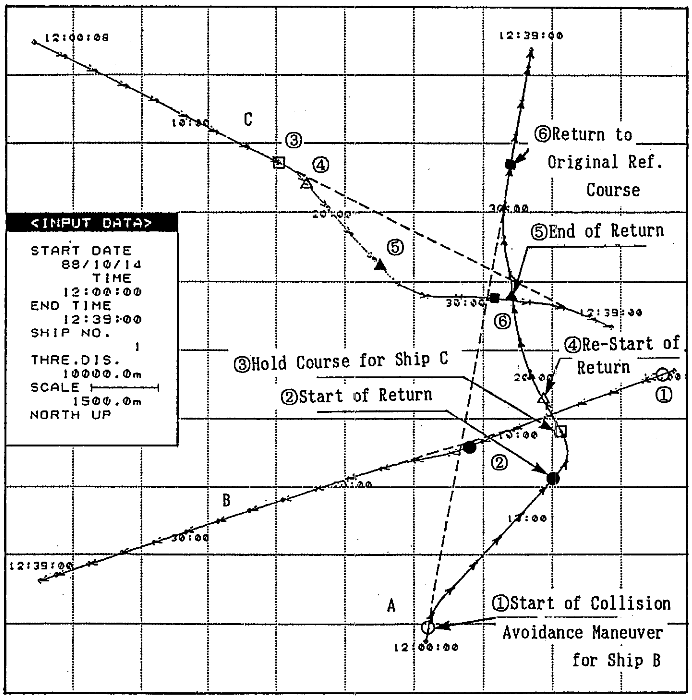



**Fig.** 8 Ship Trajectories in Multiple Encounter

based system during the simulation, are kept constant in these cases because the situations are simple enough. Collision avoidance are performed by the course change without speed alteration because of the same reason.

Figs. 8 and 9 show results of collision avoidance with the same algorithm of three ships in encounter. It is seen by the figure that traces of all ships traces are quite reasonable and keep safe from collisions. Broken lines in Fig. 8 are their reference course and solid lines are ship trajectories. In Fig. 9, CPA values, collision risk $\varepsilon$, ordered course direction and rudder angle of Ship A are shown as the time histories. In this case of encounter, Ship A is burdened to Ship B and privileged to Ship C according to the marine traffic regulation. Ship A changed its course to the right at time 1 in order to avoid collision with Ship B. At time 2 Ship B passed and collision risk $\xi$ disappeared as seen in Fig. 9, and then Ship A started to return to the original course, but at time 3 collision risk $\varepsilon$ for Ship C exceeded the criteria. As Ship A is privileged to Ship C, Ship A stopped returning and hold its course until time 4. The judgment process judged that the collision avoidance was over at time 5, and it ordered to do the navigation along the original course.

The process of the judgment for ship situation, and ship behavior can be seen by the time histories in Fig. 9

Examining these simulation results obtained, an evaluation of the collision avoidance ability is performed.

Typical patterns of ship encounter are prepared in the data basis of the simula-

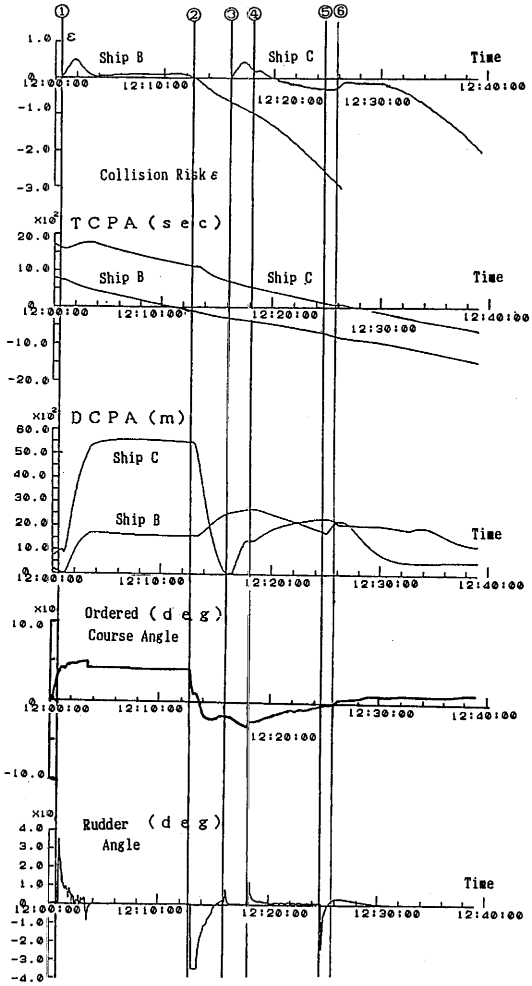



**Fig. 9** Time Histories of Ship Behavior in Multiple Encounter Condition

tion system, and a slight modification of the simulation scenario brings different encounter pattern. Therefore various situation for simulation is realized easily. The performance of collision avoidance maneuver should be confirmed by the systematic series of computer simulation tests. Parameters in the algorithms for the collision avoidance are also tuned by the trial and error and the way of tuning and its results are stored as important know-how in the knowledge base.

## 6. 2 Simulation of Navigation in Congested Area

Computer simulation in various realistic conditions are performed according to the scenario shown in Fig. 6. Figs. 10 and 11 show an example of the recorded results. They are ship trajectories and state and control variables of the ship to be

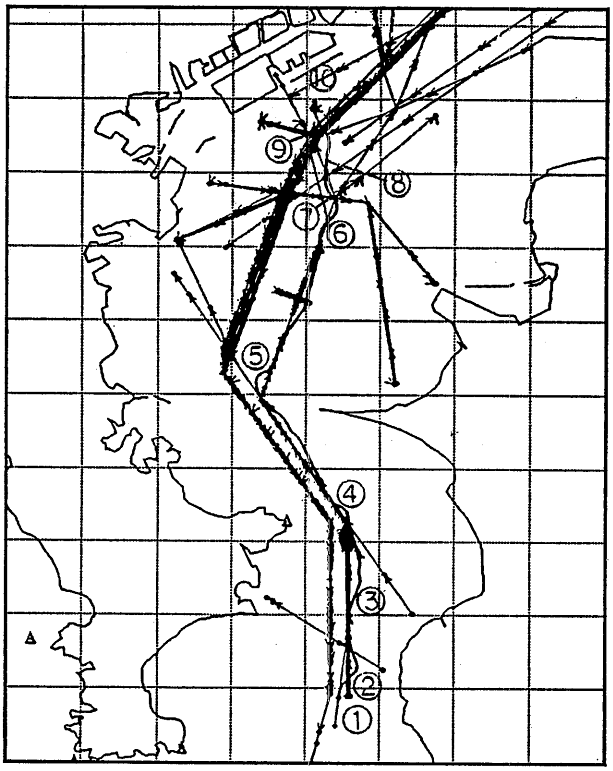


**Fig. 10** Simulation Results for Navigation in Tokyo Bay

tested. The reference course of the ship in the voyage plan is entering into Tokyo Bay through Uraga Suido Traffic Route and Nakanose Traffic Route and arriving to a berth in Ohgishima. The ship tracked its reference course and changed the planned course several times by the judgment for the collision avoidance. In this simulation, other ships followed their planned courses without collision avoidance maneuver unless the ship to be tested came near in a certain range and the simulation system switched their simulation models.

The state variables of the ship in Fig. 11 show how course tracking maneuvers are taken by changing a propeller revolution and a rudder angle. The resulting ship motion is calculated with the precise model which has sufficient accuracy for the evaluation of the collision avoidance maneuver.

In Fig. 12 another results of simulation for the last part of the same simulation scenario is shown. There are trajectories of nine ships running in the area near Ohgishima with the same algorithm for collision avoidance. Parameters in the algorithm for each ship, however, are tuned by the knowledge based system according to the encounter condition, traffic conditions of the navigation area such as traffic density, navigation condition, visibility of the area, whether the schedule of

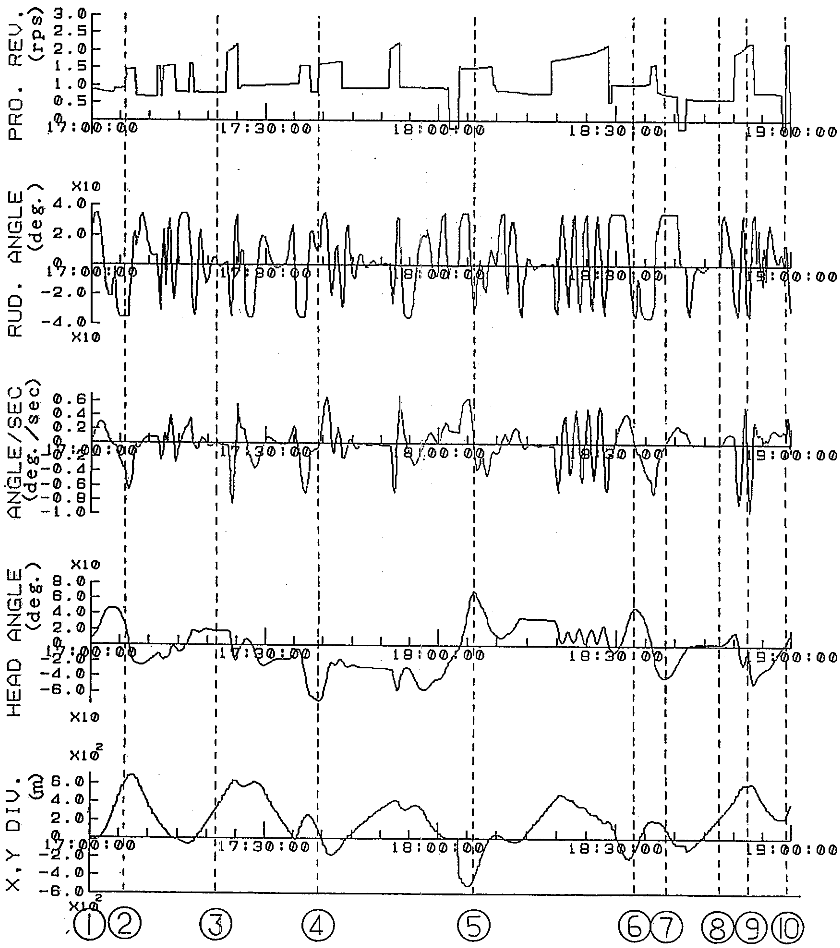



**Fig. 11** Time Histories of Tested Ship Behavior

the voyage is kept or not, whether the schedule is strict or not etc.. The results seem to be quite reasonable, and the judgment process seems to perform well both for algorithm and structure.

As various algorithms in the automatic ship navigation system can be tested according to the same scenario, simulations for parameter-tuning of the algorithms and confirmation of the marine safety of the automatic navigation system can be done.

## 6. 3 Simulation of Navigation in Emergency Condition

Figs. 13~15 show the results of simulation for the navigation in emergency condition. Time histories of state variables; ship velocity, course angle, rudder angle, revolution of propeller are shown in Fig. 13. Trajectories of ships are shown in Fig. 14 with corresponding marks to the time history of state variables for own

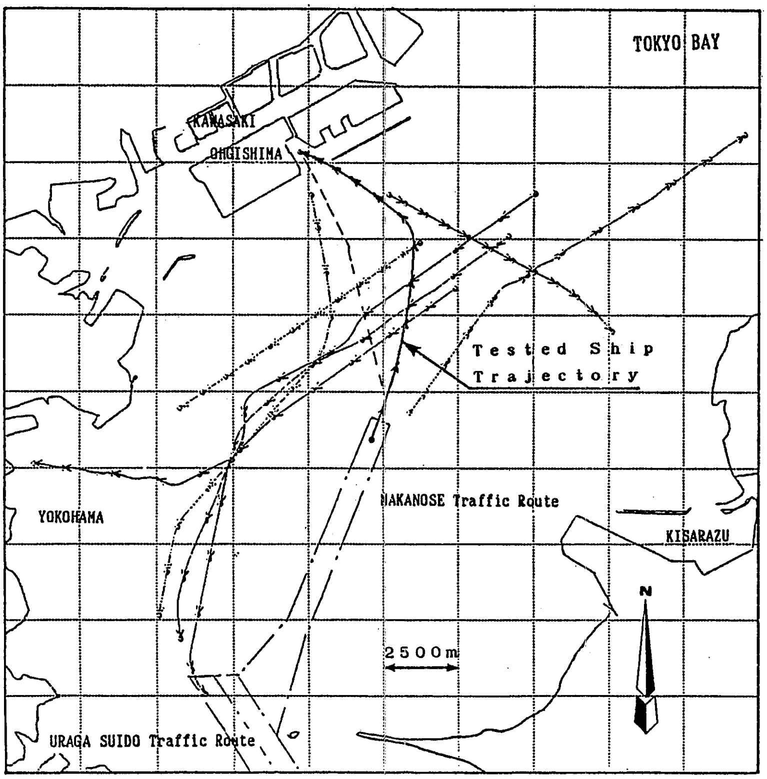



**Fig. 12** Ship Trajectories for Navigation near Ohgishima

ship. Fig. 15 indicates the flow of the judgment by the knowledge based system. Fig. 16 shows relations of rules and facts in the knowledge base at sampled time.

This is a scenario for entering to Tokyo Bay and an accident happens onboard the ship. The following sequence is seen in Fig. 15.

When the ship is running in Uraga Suido Traffic Route, a fire breaks out at time 1. A trouble or accident is noticed by the alarm, and a necessary check is requested by the judgment process. The accident is confirmed to be a fact and reported to the top level judgment process. The top level judgment recognizes that there is a fire onboard. Then the top level gives necessary orders to the lower level judgment processes as the supervision. A command of speed reduction to the three quarters is sent to the navigation system. When results of the checks and other related informations are brought to the top level by the management function of judgment for the trouble and emergency, the top level understands the scale and location of the fire, works for fire etc., and ship navigation conditions. The judgment decides to go out side of the traffic route for the safety of other ships and continue the work for fire. Various commands are ordered one by one, and the top level alters the level

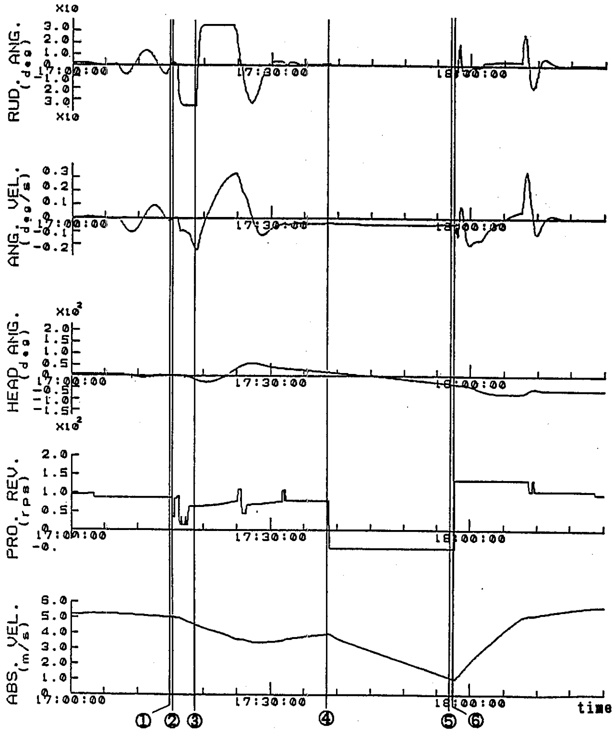



**Fig. 13** Simulation for Emergency (Time Histories)

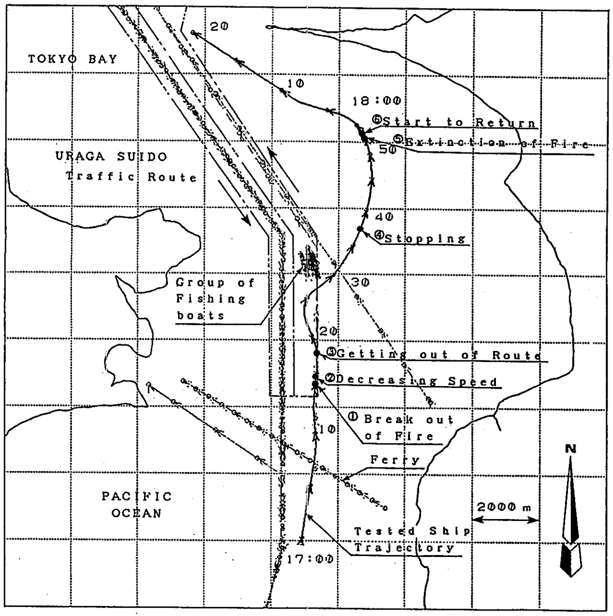
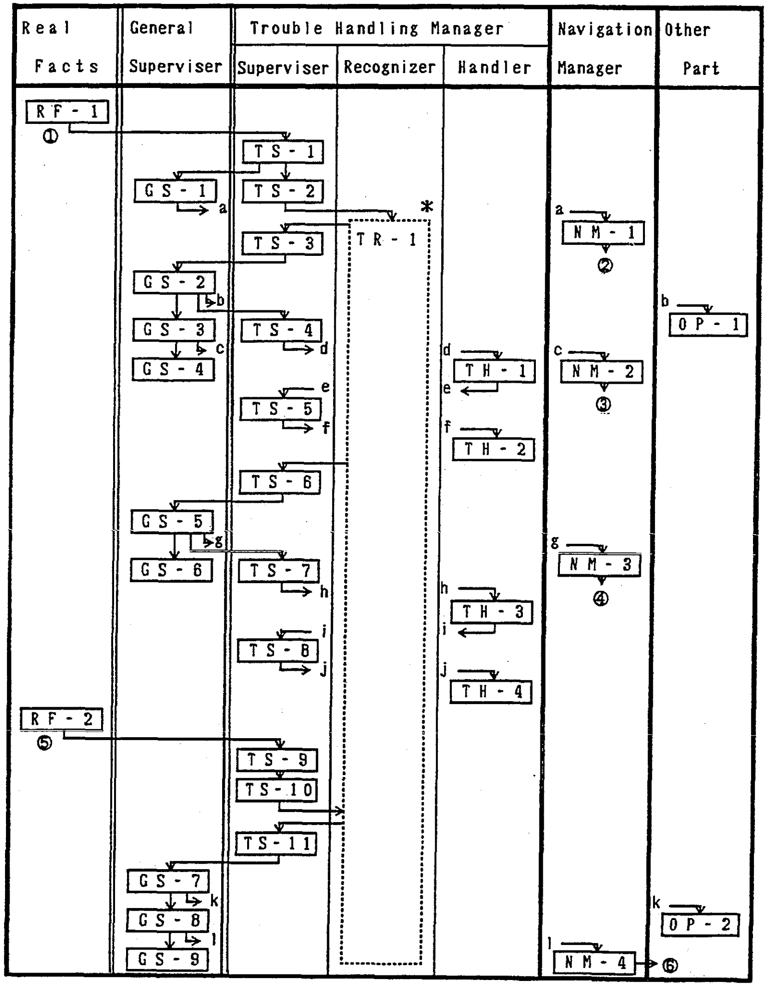



**Fig. 14** Simulation for Emergency (Ship Trajectories)




* : Called Periodically

**Fig. 15** Flow of Judgment and Dicision-Making

RF-1 : Break out of trouble (fire)
RF-2 : Trouble repaired (Extinction of fire)

GS-1 : Order emergency action 1
GS-2 : Declare trouble
GS-3 : Order emergency action 2
GS-4 : Change mode
GS-5 : Order emergency action 3
GS-6 : Change mode
GS-7 : Declare end of trouble
GS-8 : Order recovery action
GS-9 : Change mode

TS-1 : Detect trouble
TS-2 : Order Diagnosis
TS-3 : Recognize trouble
TS-4 : Order making plan-1 of trouble handling
TS-5 : Order trouble handling (1)
TS-6 : Recognize change of level of trouble
TS-7 : Order making plan-2 of trouble handling
TS-8 : Order trouble handling (2)
TS-9 : Detect end of trouble
TS-10 : Order verification of end of trouble
TS-11 : Recognize end of trouble

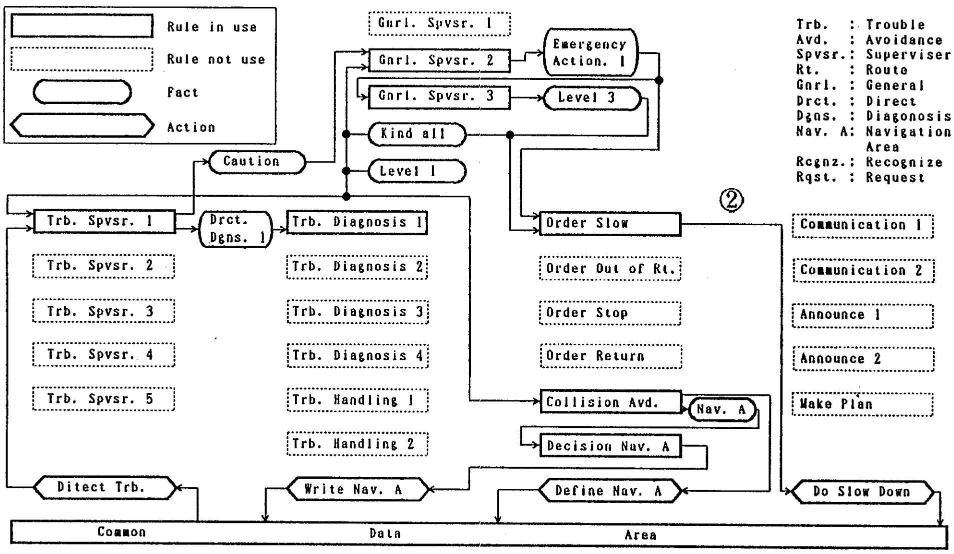
TR-1 : Diagnosis trouble (kind and level) and verification of end of trouble

TH-1 : Making plan-1 of trouble handling
TH-2 : Trouble handling (1)
TH-3 : Making plan-2 of trouble handling
TH-4 : Trouble Handling (2)

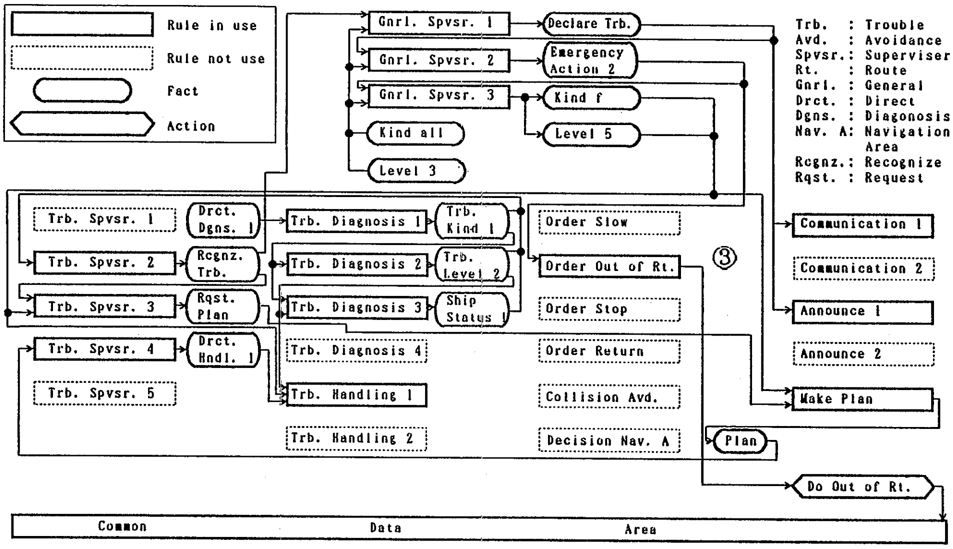
NM-1 : Order decreasing speed
NM-2 : Order getting out of route
NM-3 : Order emergency stop
NM-4 : Order of start to return

OP-1 : Inform break out of trouble to VTS etc.
OP-2 : Inform end of trouble to VTS

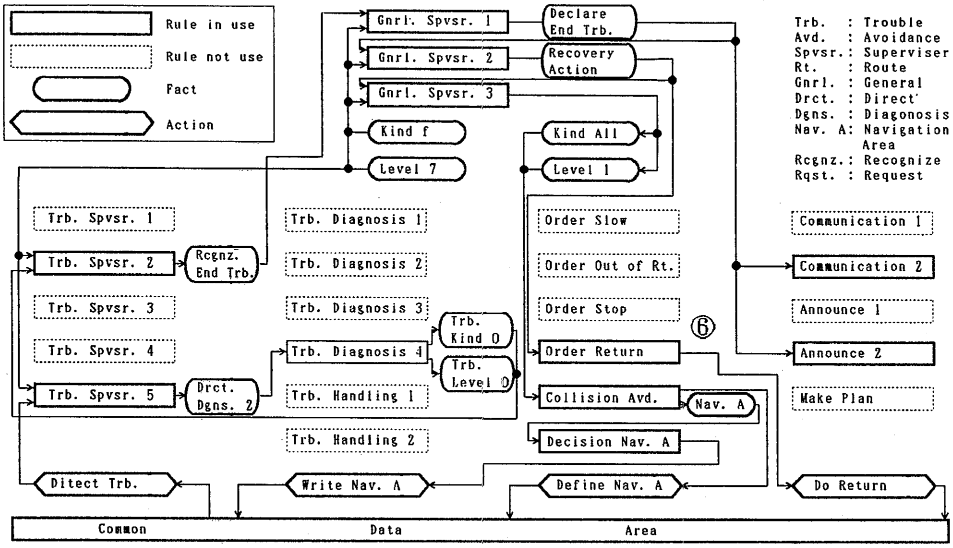
of situation to severe one for the supervision of the lower judgments. At time 4 the top level gets sufficient informations about the accident and fully understands the situation. By the supervision of the top level it is decided to stop the ship. At time 5 the fire is put off by the work and the extinction is reported to the top after confirmation. The top level judgment declares that the fire is over, and the judgment sets the level of the situation to the ordinary level. The various tasks, which




② Inference for Speed Reduction




③ Inference for Getting out of Route




⑥ **Inference for Return to Original Course**

**Fig. 16** Rules and Facts in Knowledge Base for Inference

have been suppressed during the fire, begin to be performed again. The ship starts again and returns to the original reference course by means of a new by-pass route.

It is seen by the results in Figs. 16 that suitable rules in the knowledge based system are matched and used for the inference process. According to the initial facts different chaining of reasoning are performed.

Knowledge for the emergency increased their importance in the knowledge base by the functions of supervising rules in the top level of the judgment when they are expected. Therefore dynamic tuning of the knowledge-based system is performed by the event and design of the process structure.

Though it is a prototype of the system, the simulation results seem promising. Speed of inference, is a key point for real time system and some treatments in the simulation management might be required.

A knowledge base is, as its nature, easy to be built and extends its range of availability by the additional knowledge. And only the application for various kinds of problem improves the system. So it is difficult to judge the completion of the system.

The knowledge based system works asynchronously to the other processes in the simulation system. Command and information exchange is modeled as data exchange by calling functions or writing data in common data area. The top level judgment works with the other part of simulation and affect the inference results indirectly. Performance speed of inference depends on *Facts, Rules* and CPU. Therefore strictly speaking, the repeatability or stability of the simulation results by the system used for this study is not certified.

## 7. CONCLUSION

The following conclusions are obtained as the results of simulation study performed for the automatic navigation system with the new structure and model of judgment and decision-making process.

(1) A hierarchical model for the judgment and decision-making is proposed and a prototype is programmed in the multi-process type of simulation system for the automatic ship navigation. The top and higher level of the judgment process are realized as a knowledge based system, and the lower level programs in FORTRAN.

(2) Owing to the supervision and system management by means of the knowledge based system, each algorithm possesses more validity and wider range of application. In the case of collision avoidance maneuver, rather simple algorithm available for the typical encounter patterns including few ships, can work well in much more complex encounter condition. Flexibility and easiness for the improvement of the judgment process brought by the knowledge based system, seem to be useful for the practical system and effective for their development.

(3) The top level judgment process, which plays a role of supervision and managements of the lower level judgment, is also expressed as in the form of *IF* ____ *THEN* ____*RULE*s in the knowledge base by the introduction of *FACT*s for *RULE* control. The hierarchical structure in the knowledge based system is useful and seems to be plenty of applications in practice.

(4) It is shown that the real time simulation is possible with the knowledge based system. Results obtained by means of a realistic simulation for ship navigation in Tokyo Bay and in emergency, are quite reasonable and promising. Advantages of knowledge-based system is confirmed by means of computer simulation.

## ACKNOWLEDGMENT

The simulation system used in the present study is constructed under the cooperation of the Japan Ship Research Association and the Ship Research Institute. Authors are grateful to the Japan Ship Research Association for its cooperation and to the Japan Maritime Safety Agency for its useful informations and valuable suggestions. Authors are deeply indebted to Professor T. Koyama, University of Tokyo, who gave them a guidance and valuable advice. Authors would like to acknowledge the continuing encouragement by Mr. K. Ohnaga, their colleagues in the Ship Research Institute and many partners in the cooperated research program.

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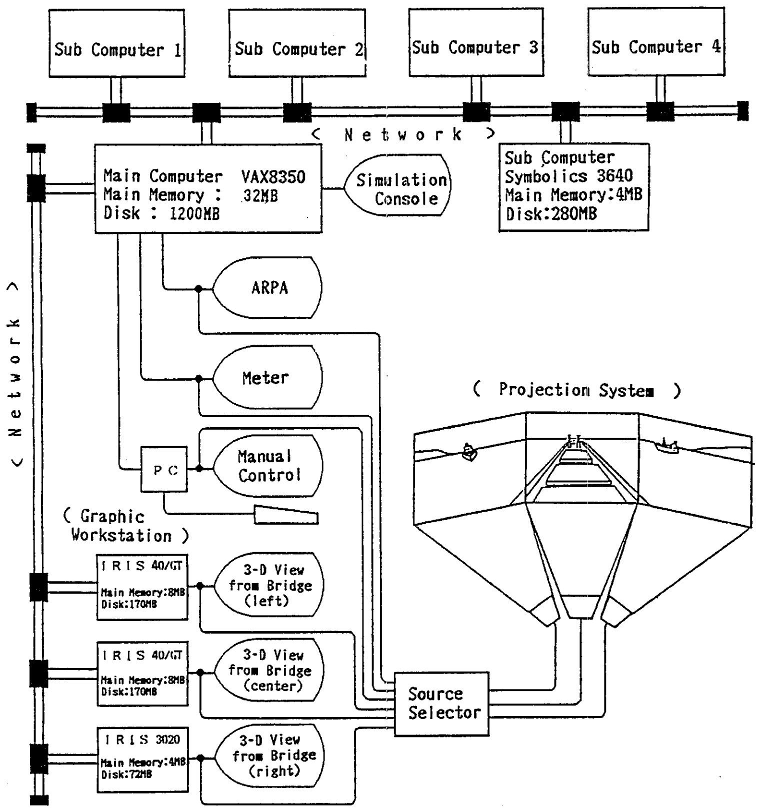


**Fig. 17** Composition of Simulation System

## APPENDIX Extension of SISANAM

After the 1st report the simulation system SISANAM is modified and extended. (See Fig. 17) Here major changes are shown.

(1) Grade up of the main computer : A super mini computer VAX 8200 model used as the main computer of SISANAM, is replaced to a VAX 8350 model. The new main computer has a co-processors and is almost twice in CPU ability as before.

(2) AI tool in the main computer : AI tool 'ART' has been installed in the LISP Machine, 'ART' for VAX system is installed in the main computer.

(3) Graphic Workstations : Beside IRIS 3020 Graphic Workstation, two IRIS 4D/GT workstations are connected in the network.

Photo. 1 shows an example of the graphic views with the new simulation system.

(4) Projection System : 3-Dimensional views from the bridge of a navigating ship by means of CGI technique on the graphic workstations are sent to projection system. The system is composed on three pojectors and large screen. Size of the screen is 3 panels of 100 inch flat screen connected in the horizen.

Photo 2 shows the projection system.

(5) Program package for analysis : Program package for analysis and data processing of simulation results is prepared. A color-hard copy machine is installed. The machine draws ship's trajectories, time history of ship behavier and several index values such as TCPA, DCPA. Program package can clip any kind of time historical data from the output records of a simulation, which are used for various evaluations.

(6) Manual ship control : Manual ship control system on PC-9801 is attached to the network. The system enables to control any 4 ships' rudder angles and engine revolutions/course angle and ship speed from the keyboard.

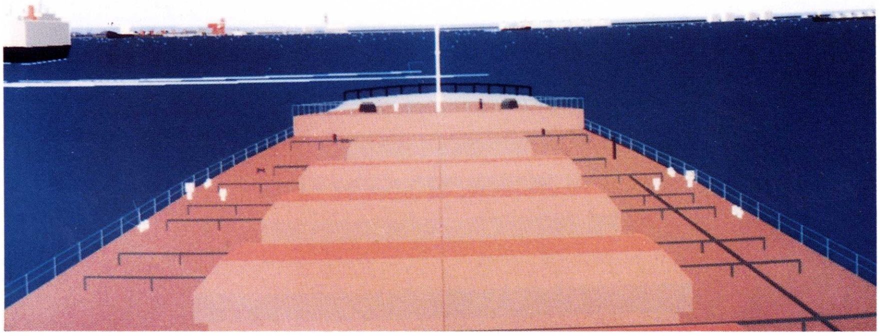

**Photo. 1** 3-Dimensional View from Bridge (Example of C. G. I. Moniter-ing for Computer Simulation)

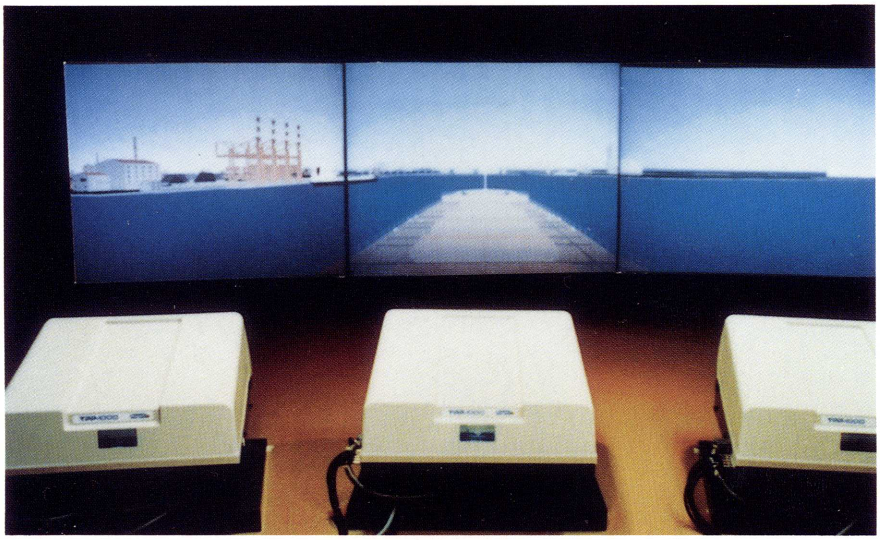

**Photo. 2** Projection System