AN INTELLIGENT SHIP HANDLING SIMULATOR WITH AUTOMATIC COLLISION AVOIDANCE FUNCTION OF TARGET SHIPS

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ABSTRACT: A new ship handling simulator was developed with function of automatic collision avoidance by target ships for own ship or other target ships. It may drastically change the way of ship handling simulator and its operation for training and education. Normally in the ship handling simulator, target ships are sailing according to the programmed waypoint navigation, or by instructor's manipulation. Therefore trainee's task is normally operating the own ship safely to avoid target ships, even if they are give-way situation. In the actual situation, target ships also avoid the own ship according to rules of the road. Sometimes avoiding action of other ships will require the additional and abnormal own ship's operation. It will be important for trainees to learn these situations and proper decision making against realistic target ships' actions. We can realize these scenarios easily using the proposed intelligent ship handling simulator.

1 NOMENCLATURE

[Symbol]	[Definition] [(Unit)]
ACR	Collision risk for assumed avoiding manoeuvre (-)
C_C	Constant to evaluate $TCPA_C$ taking account of time constant T (-)
CPA	Closest point of approach
CR	Collision risk calculated from TCPA and DCPA (-)
CR_C	CR criteria for changing manoeuvring mode to avoiding mode from waypoint mode (-)
CR_g	CR_C for give-way ship (-)
CR_O	CR criteria for changing manoeuvring mode to returning mode from parallel manoeuvring mode (-)
CR_s	CR_C for stand-on ship (-)
CR_{V1}	CR criteria for changing manoeuvring mode to parallel manoeuvring mode from avoiding mode (-)
CR_{V2}	CR criteria for changing manoeuvring mode to returning mode from parallel manoeuvring mode (-)
C_V	Constant to evaluate $TCPA_V$ taking account of time constant T (-)
DCPA	Distance to closest point of approach (m)
DCPA'	Non-dimensionalised DCPA (-)
L, L_O, L_T	Ship length in general, that of own ship and that of target ship(m)
NMRI	National Maritime Research Institute, Japan
OCR	Collision risk for assumed returning manoeuvre (-)
T	Time constant of a ship (sec)
TCPA	Time to closest point of approach (sec)
$TCPA_C$	TCPA for CR evaluation (sec)
$TCPA_V$	TCPA for VCR evaluation (sec)
VCR	Collision risk for assumed parallel shift manoeuvre (-)
ψ_A	Course changing angle in avoiding mode (deg.)
ψ_{TA}	Relative angle to target ship measured from own ship stern (deg.)
ψ_{TE}	Encounter angle of target ship measured from own ship bow (deg.)

2 INTRODUCTION

Ship handling simulator is now widely used for education, training and research in maritime community. As it is operated by human beings, real-time, real-size and realistic bridge mock-up including navigational aids, wide range of visual display with realistic scenery and own ship's behaviour are regarded as important functions. Nowadays these functions are quite satisfactorily provided as the basic functions. However, there is another important factor, which is not regarded as a standard function. It is automatic collision avoidance by target ships. It was not yet realised, because it is one of the most heuristic operations. If we realize this function into a ship handling simulator, various scenarios can be introduced into training courses, or we may use ship handling simulator to reproduce and

analyse ship casualties.
Hasegawa has developed automatic collision avoidance algorithm for many years and implemented it to marine traffic simulation system (hereafter the system) for various applications [1-11]. The concept of intelligent ship handling simulator was first appeared in [5] and the system was first implemented into a ship handling simulator [12, 13] and the scenarios for the training was discussed [14]. In this paper this simulator is briefly introduced.

3 AUTOMATIC COLLISION AVOIDANCE

3.1 COLLISION RISK

There are many collision risk indices proposed by several researchers. Ship domain concept is probably the first concept treating it [15, 16]. In this study *CR* is used. *CR* is the collision risk defined by *DCPA* and *TCPA* using fuzzy reasoning [1]. Later the definition of *CR* is somewhat modified and now the following definition is used.
For assessing collision risk in normal (WP mode in Fig. 7) condition, *CR* defined by *TCPA* and *DCPA*' (eq. (3)) is used .
For determining avoiding action, *ACR* is used to check the collision risk of the assumed avoiding action. In this case, following modified *TCPA* is used for calculating *ACR* considering individual ship manoeuvrability, especially for large ships.

$$TCPA_C = TCPA - C_C T \quad (1)$$

For determining the timing to take returning to the original path, *VCR* and *OCR* are used to check the collision risk of assumed returning action. In this case following modified *TCPA* is used for calculating *VCR* and *OCR* considering rapid turn of small ships.

$$TCPA_V = TCPA - C_V / T \quad (2)$$

Where C_C and C_V are constants and T is the time constant (of Nomoto's equation) of the subject ship. In the simulation, C_C=2 and C_V=1000 are used based on some simulation results. These modifications are reflecting the difference of course changing ability roughly estimated from the time constant T.
DCPA is non-dimensionalised using longer ship's length of two ships encountered.

$$DCPA' = DCPA / \max(L_O, L_T) \quad (3)$$

Both $TCPA_C$, $TCPA_V$ and *DCPA*' are defined by 8 and 5 linguistic variables using membership functions as shown in Figs. 1 and 2 respectively, which are determined by authors' previous researches on experts knowledge and experience and both maximum values (360 and 7.2 for open sea respectively) can be modified based on the gaming area, or users can tune them as they like. Collision risk *CR* is defined by 8 linguistic variables and membership functions as shown in Fig. 3. The reasoning fuzzy table to determine *CR* is provided using $TCPA_C$ and *DCPA*' as shown in Table 1. *CR* is thus defined between -1and 1 and it is positive before passing CPA and negative after passing CPA. The absolute value is proportional to the collision risk.

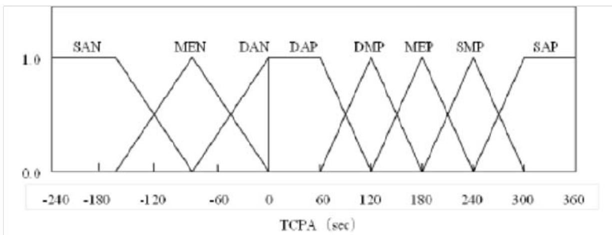


Fig. 1 Membership function for $TCPA_C$ or $TCPA_V$

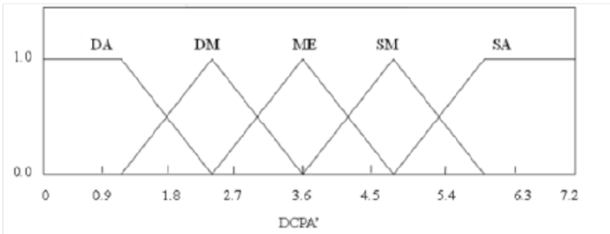


Fig. 2 Membership function for *DCPA*'

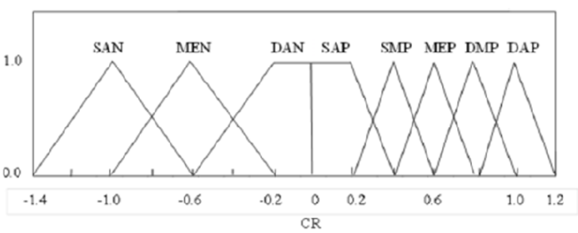


Fig. 3 Membership function for *CR*

Table 1 Fuzzy reasoning table for *CR*

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

3.2 ENCOUNTER SITUATIONS

Encounter situation can be identified using two angles between own ship and target ship as shown in Fig. 4. They will be described and named as shown in Fig. 5 and are categorised into 6 patterns as shown in Fig. 6 as well as their avoiding actions. In Fig. 6, normal is same with WP mode in Fig. 7.

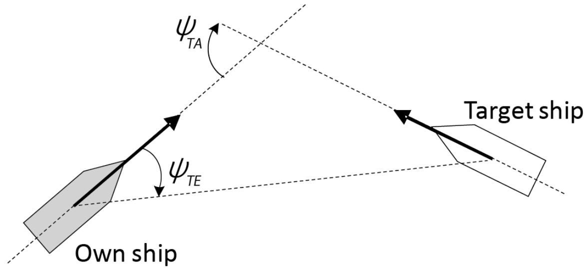


Fig. 4 Relative angle (ψ_{TA}) and encounter angle (ψ_{TE})

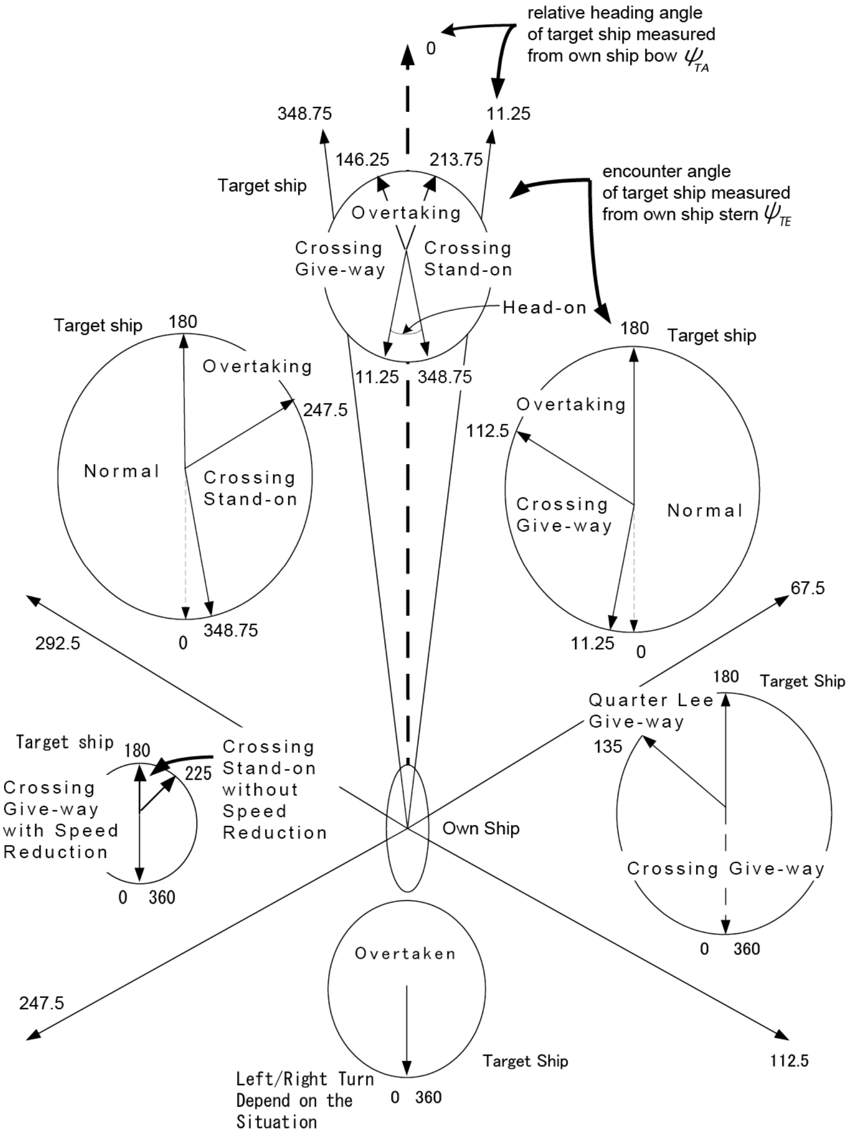


Fig. 5 Categorised encounter situations

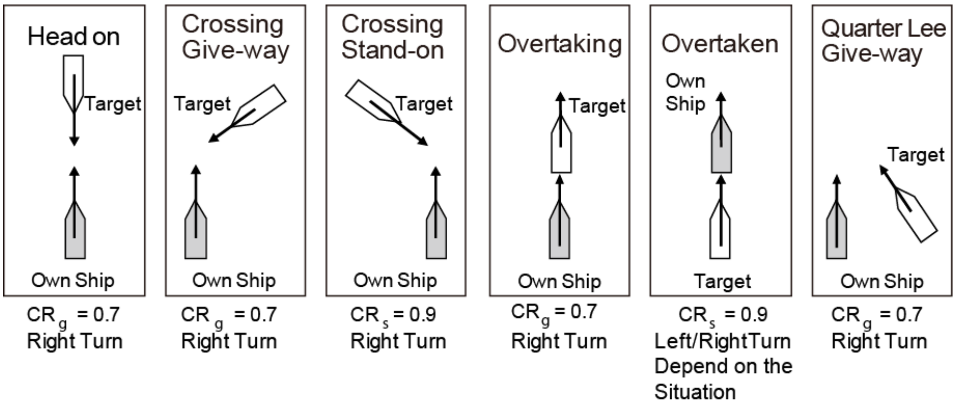


Fig. 6 Categorised encounter situations and own ship's avoidance actions

3.3 AVOIDING ACTION STRAGETY

The own ship will start avoiding when *CR* is equal or greater than CR_C. CR_C is CR_g (0.7 in the system) for the give-way situation and CR_s (0.9 in the system) for the stand-on situation. After detecting the collision risk reaches to the criteria, each ship will take a collision avoidance action as described in Fig. 6. Once avoiding mode started, the ship will take avoiding action normally by turning right. The angle of course change will be determined by *ACR*. *ACR* is *CR* assuming the present heading angle as this angle plus the course changing angle ψ_A. ψ_A is chosen 30 deg. first, but if *ACR* is bigger than CR_C, it will be increased every $\Delta\psi_A$ (= 5 deg. in the system) and repeated until *ACR* becomes lower than CR_C but it stops at 45 deg. in the maximum. After ψ_A is fixed, the own ship will change course to ψ_A. Once getting in the avoiding mode, the system is checking *VCR* continuously until it falls below CR_{V1} (0.7 in the system). The other process is summarised in Table 2.

If ψ_A reaches 45 deg. and *ACR* is still larger than CR_C, void course changing and reduce speed to half of the present speed. Speed reduction will be also applied for some cases as shown in Fig. 5.

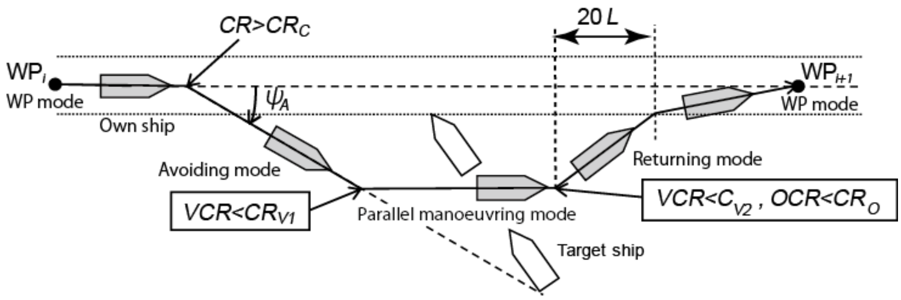


Fig. 7 Procedure of collision avoidance manoeuvre

Table 2 Determination of avoiding angle and switching modes in avoiding action

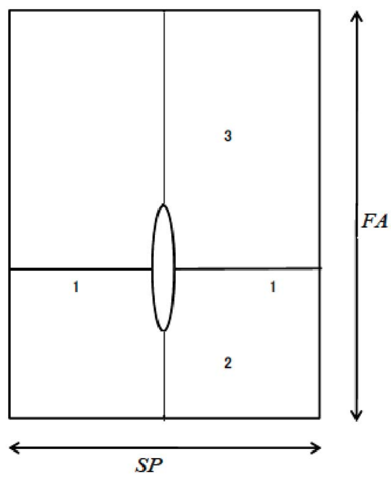
Manoeuvring Mode	Mode change criteria			Keep/change mode or take action
WP	CR	$\prec$	CR_C (CR_g (0.7 in the system) for give-way and CR_s (0.9 in the system) for stand-on)	WP mode
		$\geq$		Avoiding mode
Avoiding	ACR	$\geq$	CR_C	Increase ψ_A until $ACR < CR_C$
		$\prec$		Change course to ψ_A
	VCR	$\prec$	CR_{V1} (0.7 in the system)	Avoiding mode
		$\geq$		Parallel manoeuvring mode
Parallel	VCR	$\geq$	CR_{V2} (0.4 in the system)	Parallel manoeuvring mode
	or			
	OCR	$\geq$	CR_O (0.6 in the system)	
	VCR	$\prec$	CR_{V2}	Returning mode
	and			
	OCR	$\prec$	CR_O	
Returning	Distance to next WP	$\prec$	$20L$	Return to $20L$ ahead on original path within $\pm$ 0.1 mile width error
		$\prec$		Return to next WP

3.4 STEERING/PROPELLER ACTION

After the heading angle or/and speed is instructed, the system will order rudder angle or/and propeller revolution. Hasegawa[1] have proposed the algorithm of fuzzy autopilot with course changing strategy, and the algorithm is still powerful especially for course changing in WP mode.

3.5 SOME ADDITIONSL RULES

In case of narrow and confined waterways, some parameters like linguistic maximum value for *TCPA* and *DCPA* in Figs. 1 and 2 are changed, just like human's conception may change.
Rules for restricted waterways are described in Hasegawa [3] using virtual ship concept and rules for overtaking are described in Hasegawa [7], although the exclusive area in overtaking is replaced with a rectangular of *FA* height and *SP* width around the own ship as shown in Fig. 8, where *FA* and *SP* are defined by Inoue [18] as



$$FA = (0.015 L_T + 2.076) L_O \quad (4)$$

$$SP = (0.008 L_T + 0.666) L_o \quad (5)$$

Fig. 8 Exclusive area for overtaking ship [18]

3.6 COLLISION AVOIDANCE STRATEGY FOR MULTIPLE-SHIP ENCOUNTERS

In the real situation, there are multiple ships. It is very important how to apply the above-mentioned algorithm into multiple-ship encounters. There are few proposals published clearly before for such conflicted situations.
In the system it checks *CR* for all ships in the simulation area, although the search area from one own ship is restricted (7 mile square in the system). For each own ship, a ship whose *CR* is maximum is selected as the target

ship. Once target ship is selected, each own ship will take action described in 3.3.
During the avoiding actions to a certain target ship, the system also check *CR* for other ships simultaneously, and if the *CR* for any other ship exceeds the *CR* for the present target ship, the system will change the target ship to this ship as new target ship and the same procedure will be done for this new target ship.
This process is executed for all ships in the simulation area, and actions (steering rudder or/and propeller revolution) to be taken are fixed for all ships, then the command will be executed for each ship and each ship motion will be calculated for one step time interval (1 sec. in the system). The process continues for each time step until the end of simulation. If no conflicted target ships exist, it is just successive one-to-one encounter problem, but the system is tolerant for conflict situations.
Imazu problems [19] as shown in Fig. 9 is a kind of a set of benchmark scenarios for difficult encounter situations, and left-hand side cases are sometimes used to check collision avoidance capability of human beings in ship handling simulator or of automatic system. Fig. 10 shows a result of one of Imazu problems done by the system, where each ship is like a dot in black circle with velocity vector. Velocity vectors are also added manually with black circles for easy looking. In four scenes from six except first and last, ships are avoiding other ships and in the third scene, two ships reduce their speed. Including other cases, the system can instruct each ship appropriately and safely.

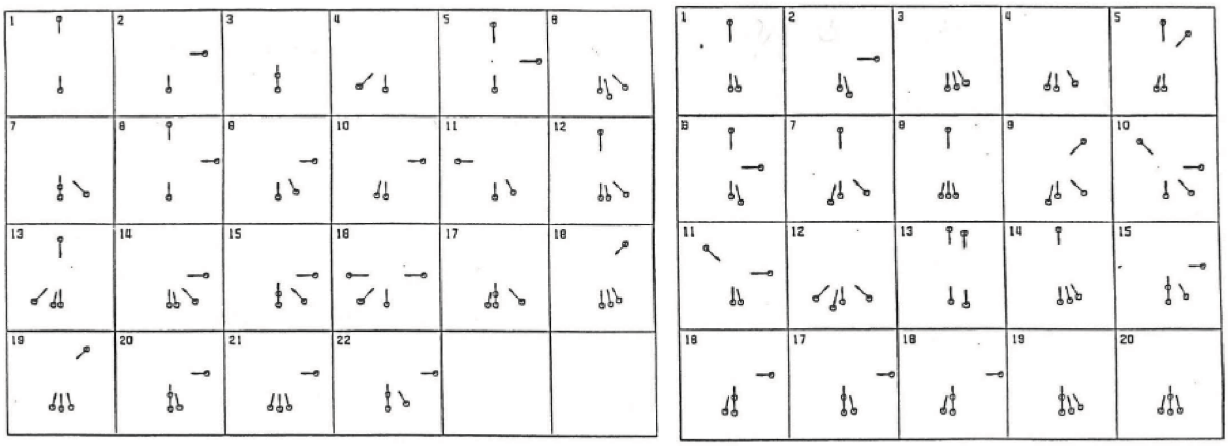


Fig. 9 Imazu problems [19]
Left: simple (1,2) and relatively difficult encounters (3-22)
Right: rather difficult encounters (1-20)

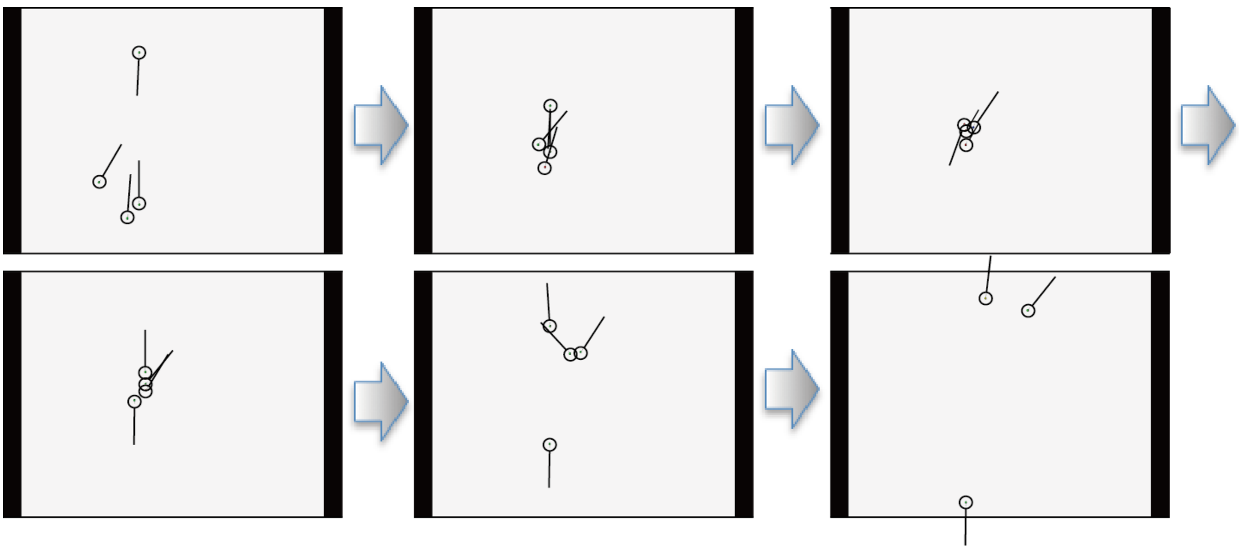


Fig. 10 System result for one of Imazu problems

4 INTELLIGENT SHIP HANDLING SIMULATOR

4.1 IMPLEMENTATION OF AUTOMATIC COLLISION AVOIDANCE FOR TARGET SHIPS

In 2011 Fukoto, Hasegawa et al.[13] have succeeded to implement this function into a ship handling simulator of NMRI, Japan.
Fig. 10 is "Bridge Simulator for Navigational Risk Analysis Research", which is the full mission ship handling simulator of NMRI, Tokyo, Japan.
The brief structure of intelligent ship handling simulator is shown in Fig. 11. The main point is add-on function of automatic collision avoidance for target ships, which is done by an external PC.

Fig. 10 Bridge Simulator of NMRI

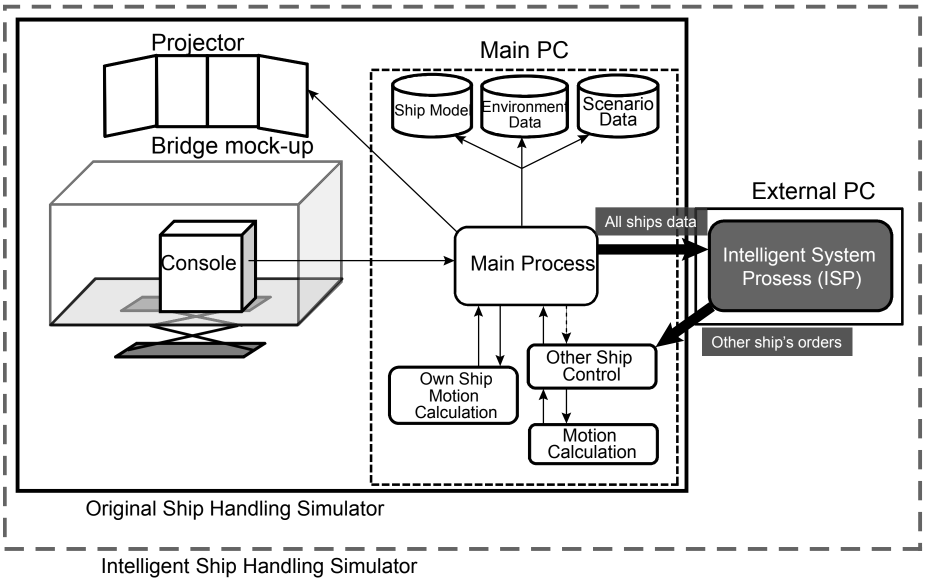


Fig. 11 Structure of intelligent ship handling simulator

4.2 SCENARIO EXAPLES USING INTELLIGENT SHIP HANDLING SIMULATOR

Using the NMRI Bridge Simulator for Navigational Risk Analysis Research implemented automatic collision avoidance system for target ships, hereafter intelligent ship handling simulator in general, two scenarios were tested. Fig. 12 shows the result of Akashi Strait double collision accident in 2008 [12]

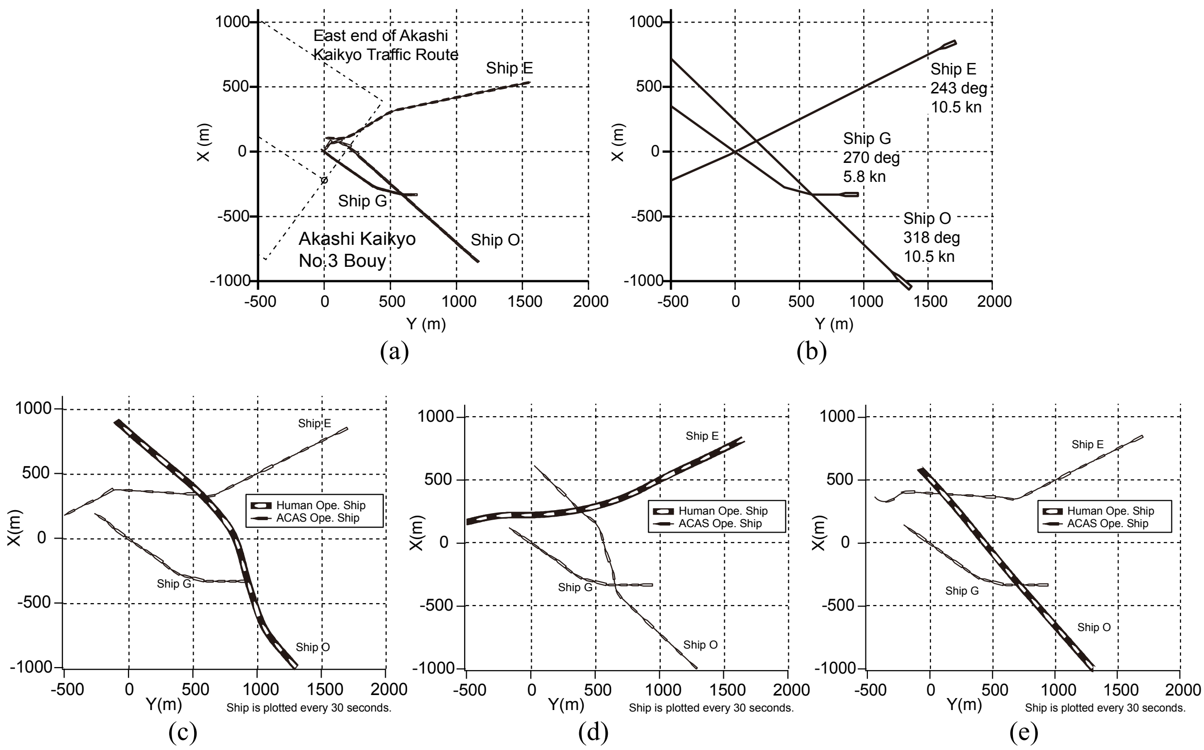
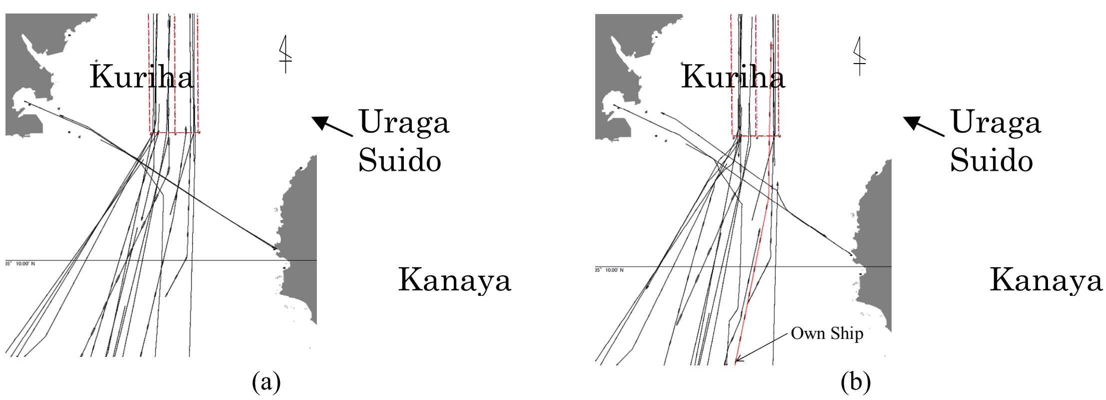


Fig. 12 Intelligent ship handling simulator experiment for Akashi Kaikyo (Strait) double collision accident in 2008 [12]
(a) Ship trajectories of the accident measured by AIS
(b) Scenario for intelligent ship handling simulator experiment
(c) Result of intelligent ship handling simulator experiment (Ship O: own ship)
(d) Result of intelligent ship handling simulator experiment (Ship E: own ship)
(e) Result of intelligent ship handling simulator experiment (Ship O: own ship kept course)

For each case, even for case (e), target ships take an appropriate action cooperated with own ship's behaviour and can avoid collision as happened. Intelligent ship handling simulator is expected to be utilised for analysing accidents and education/training.

Another example is for congested waterways. Fig. 13 shows a case. The test area is south entrance to Tokyo Bay. There is Uraga Suido (Channel) navigational lane and all big ships concentrate to this area and there is a ferry crossing service. In this scenario totally 22 ships are sailing during 15:10-15:50, Nov. 11, 2010.

In this experiment, the collision avoidance algorithm is tested through the comparison with the real trajectory (a) and operator's perception, and actually some modification of the system is done successfully like (d) to (e). Intelligent ship handling simulator is also a powerful tool to check collision avoidance algorithm through operator's perception.



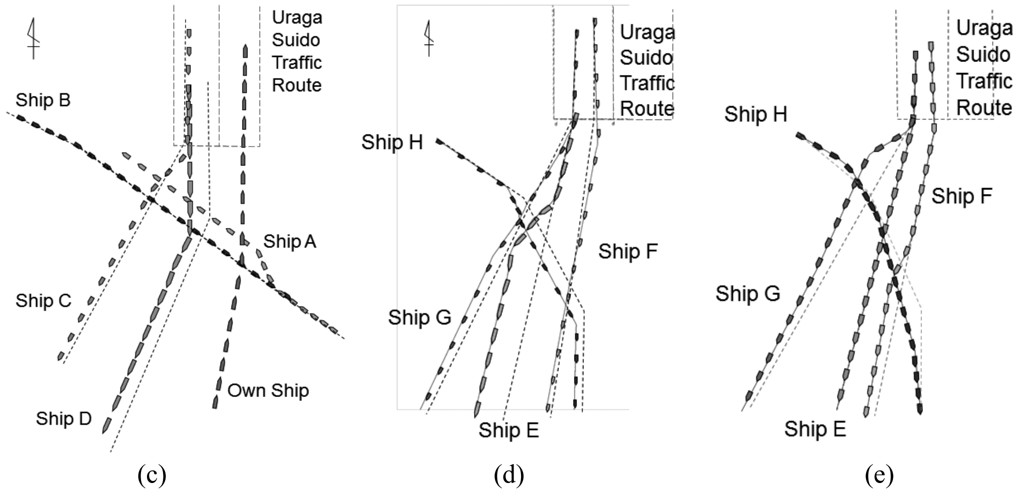


Fig. 13 Intelligent ship handling simulator experiment for Uraga Suido (Channel) south entrance [13]
(a) Ship trajectories measured by AIS
(b) Result of intelligent ship handling simulator experiment
(c) Picked-up trajectory (Own ship and Ship A, B, C and D)
(d) Picked-up trajectory (Ship E, F, G and H)
(e) Picked-up trajectory (Ship E, F, G and H with modified algorithm)

5 CONCLUSIONS

The brief introduction of intelligent ship handling simulator is done. Main conclusions drawn are as follows.

1) Automatic collision avoidance algorithm for two-ship encounter including strategy for multiple-ship encounter is described.
2) Intelligent ship handling simulator is introduced with results of two cases.
3) Intelligent ship handling simulator is a powerful tool to analyse ship collision accident.
4) Intelligent ship handling simulator is a powerful tool to test and improve automatic collision avoidance algorithm through operator's perception.

For future works,

5) Intelligent ship handling simulator will give a new scenario for training and education of ship operators or bridge management system.
6) Intelligent ship handling simulator will be useful to test new navigational aids or supporting system from the viewpoint of man-machine system.

6 ACKNOWLEDGEMENTS

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