FIVE STEPS TO ASSURE NAVIGATIONAL SAFETY

Anatoliy S. Maltsev

Prof., Dr., Capt.
Odessa National Maritime Academy (ONMA)
8, Didrikhson Street, 65029, Odessa, Ukraine
E-Mail: maltsev-as@MAAB.COM.UA
Website: www.ma.odessa.ua
Tel: +380 48 731 10 59
Fax: +380 48 731 10 63

1 Formulation of the problem

The passage of objects through air or water is usually planned in advance. This is done graphically on a chart or analytically. The travel of the object is to be watched by the track. This is done at two Control Stations, one located on board the moving object, the other one located on Earth.

Air trips are monitored on Earth at Airport Control Stations, equipped with radars and communications suite.

In an airplane it is the cockpit with resources available to monitor the travel.

Sea trips are monitored on Earth at Traffic Control Stations, equipped with radars and communications suite.

In a ship it is the chart room with resources available to monitor the travel.

The principal difference of the navigating bridge from the cockpit is that when in congested waters bearings are taken mainly by sight. In a plane bearings are found by instruments.

A dispute arises between the two Control Stations due to different opinions as to the assessment of the situation, the priority of the teams and division of responsibility.

Analysis of the problem. Operators of moving objects, when at close quarters, have little time to assess the situation and make the decision. Having insufficient information they have to give orders, using personal experience and knowledge of laws which 'close quarters' comply with.

Airport Control Station operators have difficulties due to heavy air traffic, so they have to solve several problems simultaneously.

Shore Control Station operators have difficulties to evaluate close quarters approach, when immediate actions are required. This is due to employment of navigational instruments which are not precise enough, lack of techniques to assess the risk of collision as well as juridical responsibility for recommendations. The master makes decisions and bears sole responsibility, leaving the shore Control Station functions of coordinator and source of information.

Confirmation of the problem developed were two accidents: one occurred in the sky above Switzerland, the other one at the Black Sea near Novorossiysk. Both accidents were caused by the similar error-uncertain actions of crews at close quarters.

Notwithstanding that decades have passed since the collision of the motor vessels “Admiral Nakhimov” and “Pyotr Vasev” and several years have passed since the collision of the planes, the international community hasn’t taken proper measures for preventing such accidents. Responsibility is placed on aircraft pilots and sea craft captains.

Responsibility of airport control service hasn’t been defined to say nothing about responsibility of shore-based sea traffic control. It was established that just before the collision the Russian plane’s system had warned the commander of it, but the information was either ignored or too late.

2 Statement of research results

The following will concern sea-going vessels, though the results can be used for planes and submarines.

Satellite systems enable more precise position fixing, up to 3-5 meters on sea-going vessels. In consequence thereof, the navigator no more uses other techniques, having lost skills of determining position by (DR) Dead-reckoning, celestial position fixing and radar lines of position using an overlay of fixes plotted for solving the problem to pass well clear, and a number of other knowledge.

Lack of skills prevents the navigator from perceiving physical processes when moving and passing clear, and from monitoring the ship’s position when failure of satellite systems occurs.

The process of approaching and passing clear takes short. Due to this, there is practically no time to analyze the situation, to estimate and to make the decision. In this situation it is required to estimate maneuvering in advance and give the operator recommendations in such form which would enable to perceive the situation and in ample time give orders to the helmsman to prevent close quarters situation.

If parameters of the ship’s movement are described without regard to the forces causing its movement, such equations are called kinematical. If the movement is described with regard to the forces, causing it, such equations are called dynamic (See Fig. 1).

The above equations are of three types:

- dynamic equations of a ship’s movement, derived from laws of motion;
- dynamic equations of a ship’s movement to the pole of the turn, derived from laws of motion:
- kinematics equations of connection of ship’s angular and line speed with space coordinates, derived from kinematical relation between various systems of axes.

The structure and form of equations of ship’s movement depend essentially on the system of axes adopted [2-5]. Three systems of axes are used:

(1) immobile geocentric, connected with the Earth, rectangular $O\xi\eta\zeta$, the ship's movement being considered as regards flat and immobile Earth;

(2) mobile, connected with a ship, originating in its CG, with which it travels in space $GXYZ$, and axis GX points towards the bow, axis GY points towards the starboard side, axis GZ points upwards.

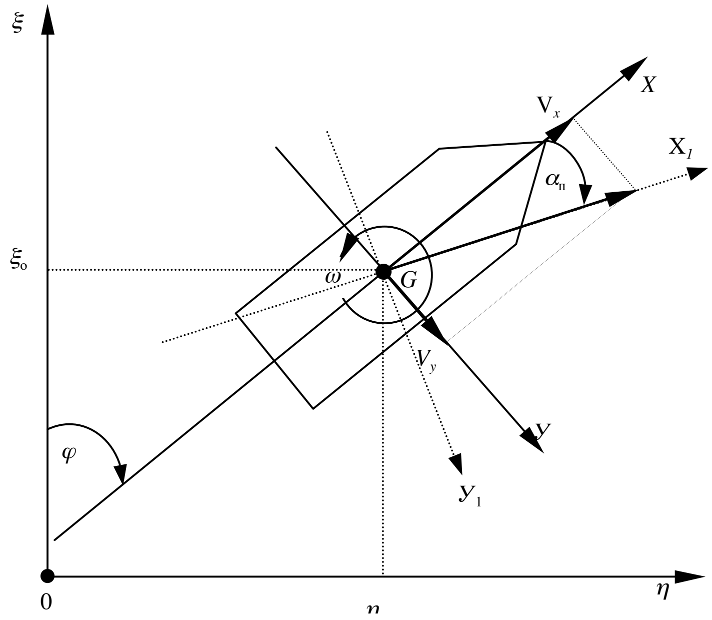


Fig. 1 System of axes and position fixes of a ship

(3) semi connected, mobile $GX_1Y_1Z_1$ (wind axis), originating in GZ, connected with line speed vector.

Axes GX_1 go along speed vector V, and axis GY_1 points towards the starboard side.

Kinematical equations of connection of rotation in matrix can be written in the form[1].

$$\begin{bmatrix}\omega_x\\ \omega_y\\ \omega_z\end{bmatrix}=\begin{bmatrix}1 & \sin\Psi & 0\\ 0 & -\cos\varphi\cdot\sin\Theta & \cos\Psi\\ 0 & \cos\varphi\cdot\cos\Theta & \sin\Psi\end{bmatrix}\begin{bmatrix}\Theta\\ \Psi\\ \varphi\end{bmatrix} \quad (1)$$

Where φ is angle of yaw; ψ is angle of trim; θ s angle of list; $\omega_x\ \omega_y\ \omega_z$ are projections of angular speed of rotation on the axes.

At Ailer minor angles and similar level of derivatives, kinematical matrices become single, and the projections of angular speed on connected axes coincide with the derivatives of corresponding Ailer angles.

$$\omega_x = \dot{\Theta}\,;\quad \omega_y = \dot{\Psi}\,;\quad \omega_z = \dot{\varphi}\,.$$

Planes $O\xi\eta$ and GXY coincide with water plane, kinematical parameters of movement being line speed V, angular speed of rotation $\grave{u}$ and drift angle αt due to turn.

To describe movement of objects we'll use kinematical differential equations, as parameters of ships' travel are described without regard to the forces causing the movement.

Let own vessel *A* be at the origin of geocentric system of axes, and vessel *B* is at a distance of D_{bg} and bearing B_{bg}, as shown in Fig. 2.

Analytical method to estimate the parameters of close approach is based on the fact that the vector of speed of relative travel $\overrightarrow{V_{\tilde{n}}}$ equals vector difference in speed of vessels *A* and *B*:

$$\overrightarrow{V_{\tilde{n}}} = \overrightarrow{V_{\text{B}}} - \overrightarrow{V_{\text{A}}} \qquad (2)$$

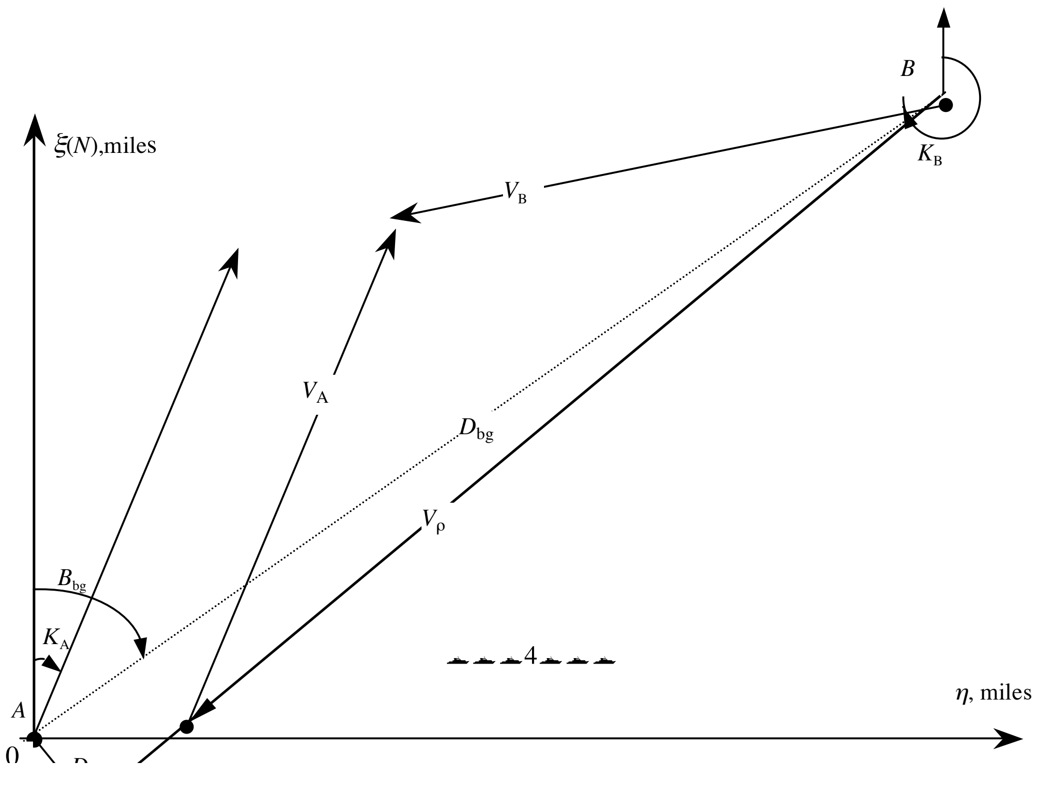
Let/s determine the projections of relative speed on axes ζ and η:

$$V_{\text{oç}} = V_{\text{Bç}} - V_{\text{Aç}} = V_{\text{B}} \cdot \sin K_{\text{B}} - V_{\text{A}} \cdot \sin K_{\text{A}} \qquad (3)$$

$$V_{\text{oî}} = V_{\text{Bî}} - V_{\text{Aî}} = V_{\text{B}} \cdot \cos K_{\text{B}} - V_{\text{A}} \cdot \cos K_{\text{A}} \qquad (4)$$

The module of relative speed $V_{\tilde{n}}$ is:

$$V_{\rho} = \sqrt{V_{\rho\eta}^2 + V_{\rho\xi}^2} \qquad (5)$$



With invariable courses and speeds of the objects' movement the track of the objects' movement the track of movement of vessel *B* relative to *A* is a straight line, the equation of which can be written in the form

$$\xi - \xi_B = \lambda \cdot (\eta - \eta_B) \tag{6}$$

Where $\lambda = \tan\alpha = V_{\tilde{n}\hat{i}} / V_{\tilde{n}ç}$ is the tangent of angle to the axes η, and η_{B} and ζB are the ship's fixes. They can be estimated through polar coordinates:

$$\eta_{\mathrm{B}} = D_{\mathrm{bg}} \sin B_{\mathrm{bg}}, \ \xi_B = D_{\mathrm{bg}} \cos B_{\mathrm{bg}} \tag{7}$$

The distance of the closest approach D_{cpa} is determined by a perpendicular drawn from the origin of the axes on RML_{B} and it can be estimated from:

$$D_{\mathrm{CPA}} = \frac{\left| \xi_B - \lambda \cdot \eta_{\mathrm{B}} \right|}{\sqrt{1 + \lambda^2}} \tag{8}$$

The distance to the point of the closest approach can be determined from (Fig. 2):

$$\hat{A}\tilde{N} = \sqrt{D_{bg}^2 - D_{cpa}^2} \quad (9)$$

To draw diagrams of dependence of the distance between the vessels on time it is necessary to estimate regular ships' movements on the axes η and ξ :

$$\eta_A = V_A \cdot \sin K_A \cdot t\, ; \;\; \xi_A = V_A \cdot \cos K_A \cdot t \quad (10)$$

$$\eta_B = D_{bg} \cdot \sin B_{bg} + V_B \cdot \sin K_B \cdot t$$

$$\xi_B = D_{bg} \cdot \cos B_{bg} + V_B \cdot \cos K_B \cdot t \quad (11)$$

With regard to dependence (10) and (11) the distance between the ship will be determined from:

$$D(t) = \sqrt{(\eta_B - \eta_A)^2 + (\xi_B - \xi_A)^2} \quad (12)$$

The dependence shown enables to draw a diagram of relative distance variation and to determine the risk of 'close quarters'.

At close quarters it is practically impossible to solve the problem of safe passage. Such a situation occurs when the target is detected visually or spotted on the radar screen suddenly at close quarters, due to unforeseen maneuver, low reflectance or lack of proper lookout. It is impossible to do any estimates under such situation, and delay of maneuver can result in an accident. Such a maneuver, which should be carried out immediately to prevent collision, in theory and practice of ship/s control is called "maneuver of the last moment" [6-8].

Its peculiarity is in the requirement for strong, maximum operating effects. Moreover, in compliance with Rule 2 of Colregs-72 it is not required to observe any rules, which are in force under ordinary conditions, but one: to choose such a maneuver which would enable to avoid a collision, and if it is impossible, to minimize possible damages.

Variety of situations and a great number of alternatives at the first sight do not make it possible to solve the problem.

In the meanwhile thorough analysis of the close quarters situation with regard to all factors enable both to propose the algorithm of the problem solution and derive analytical formulas to choose the single maneuver possible. To solve the problem it is necessary to introduce two axioms, which are obvious and do not require to be proved.

Axiom 1. If risk of collision exists, these targets are dangerous and the condition $(\mathrm{d}Br/\mathrm{d}t) = 0; (\mathrm{d}D/\mathrm{d}t) < 0$ is fulfilled (See Fig. 3).

Axiom 2. The optimum altering course for preventing collision is parallel or counter course of the hazardous vessel. If our vessel thus alters her course, it will minimize the dependence of hazardous approach on probable maneuver of the vessel on reciprocal course. Increasing or decreasing her speed and altering her course off our vessel improve the close quarters situation and altering course towards our vessel is hardly possible, but it can be foreseen and given regard to by introducing safe distance, of which it will be said more detailed below. By introducing Axiom 2 we bring in certainty into the problem solution and we can estimate the last moment maneuver for the hazardous vessel beforehand. It is convenient to estimate the time for maneuver commencement by the parameter observed, i.e. the distance between the vessels.

To obtain analytical dependencies we'll consider the triangle AMB from

which we'll derive correlations provided that the target's bearing doesn't change:

$$\sin q = \frac{k \sin P}{\sqrt{1 - 2k \cos P + k^2}} \qquad D_{\text{ÒÀÊ}} = V_{\text{A}} \cdot t_{\text{crs}} \sqrt{1 - 2k \cos P + k^2} \tag{13}$$

where P–is relative course, changing from 0 to 180º; t_{crs} – is period of time from the commencement of observations until arrival at the position of crossing courses; k– is relation of speeds $V_{\text{A}} / V_{\text{B}}$; q– is course angle.

The dependences derived (13) show that the situation of hazardous approach is determined by correlation of speeds of movement of our vessel and targets, by value of relative course and, what is particularly important, by our vessel's speed, and the less the speed is the more preferable the situation of close quarters is.

To derive analytical dependences for the calculation of the vessel's maneuvering characteristics while the last moment maneuver with reference to dependences (13), from Fig. 3 we derive [6-8]:

$$D_{\text{br}} = \text{Í}_{\text{br}} \text{Ì} \sqrt{1 - 2k \cos P + k^2} \tag{14}$$

$$D_{\text{stb}} = \text{Í}_{\text{stb}} \text{Ì} \sqrt{1 - 2k \cos P + k^2} \tag{15}$$

$$D_{\text{port}} = \text{Í}_{\text{port}} \text{Ì} \sqrt{1 - 2k \cos P + k^2} \tag{16}$$

The expression under the radical will be $R = \sqrt{1 - 2k \cos P + k^2}$.

With reference to error of *dimensions*, size of ships and probable unfavorable maneuver by the

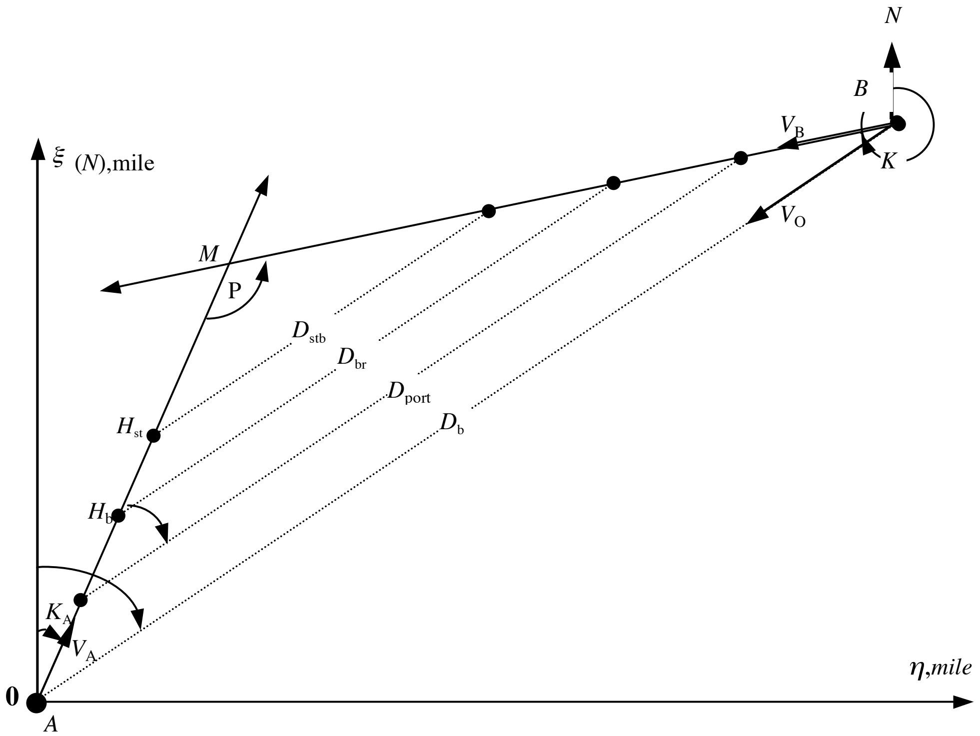


Fig. 3. Diagram of close quarters situation when ships pass clear

on-coming vessel towards ours, it is necessary to introduce safe navigation distance $S_{res} = f(L, M_D, t)$. With reference to dependences (13) the expressions (14)~(16) will look like:

$$D_{br} = \left(S_{br} + S_{res}\right)R \,; \tag{17}$$

$$D_{port} = \left[\left(\grave{a}_{port} + b_{port} \cdot tg\frac{\Delta k_{port}}{2}\right) + S_{res}\right] \cdot R \,; \tag{18}$$

$$D_{stb} = \left[\left(\grave{a}_{stb} + b_{stb} \cdot tg\frac{\Delta k_{stb}}{2}\right) + S_{res}\right] \cdot R \cdot \tag{19}$$

where $a_{port}, b_{port}, a_{stb}, b_{stb}$ - coefficient of turn ability, $S_{br.}$ – is headway for mode astern fool; ΔK - is turn angle, determined by the expressions:

$\Delta k_{port} = D$ while

$$q_{stb} \,; \;\; \Delta k_{stb} = 180 - D \;\text{ while }\; q_{stb} \,; \tag{20}$$

$$\Delta k_{port} = 180 - D \;\text{ while }\; q_{ports} \,; \;\; \Delta k_{stb} = D \;\text{ while }\; q_{ports} \,. \tag{21}$$

Safe navigation distance is determined by the expression:

$$S_{\text{res}} = L_{\text{rs}} + M_{\text{D}} \frac{\sin P}{\sin(P+q)} + \ell_2 \cdot \cot \frac{P}{2}, \tag{22}$$

where L_{rs} is the distance from the position of Radar antenna to the vessel's forepeak; M_{D} is mean square error of distance determination; ℓ_2 is direct target-shifting when putting the rudder hard over; D_{cur} current distance.

With reference to dependences (17)~(22), the period of time required to make the last moment maneuver by braking will be determined from the expression:

$$\grave{O}_{\text{br}} = \left(D_{\text{CUR}} - D_{\text{br}}\right)/V_{\tilde{n}}R \tag{23}$$

The time of approach of the last moment maneuver by turning to port is:

$$\grave{O}_{\text{port}} = \left(D_{\text{CUR}} - D_{\text{port}}\right)/V_{\tilde{n}}R \tag{24}$$

The time of approach of the last moment maneuver by turning to starboard is:

$$\grave{O}_{\text{stb}} = \left(D_{\text{CUR}} - D_{\text{stb}}\right)/V_{\tilde{n}} \cdot R \tag{25}$$

The dependences derived (17)-(25) allow to elaborate recommendations necessary for the last moment maneuver, and to automate selection of the maneuver type with reference to the parameters of target movement, to the close quarters situation and to the vessel's maneuvering characteristics.

The dependences derived are true for an ideal model of danger pass-by, when the vessel's bearing doesn't change. If the vessel's bearing changes within dangerous limits (which are set by a navigator through bringing in value $\pm dq_{\text{set}}$), the problem should be solved in compliance with the axiom taken regarding the position of crossing courses.

Solution technique will be the former one, but the dependences will vary.

The algorythm of selection of the maneuver type is in determining the distance between the vessels and the time of approach of the last moment with regard to the close-quarters situation, the parameters of movement of the targets and the vessel, maneuvering characteristics of own ship and targets to carry out for all possible alternatives, including the last one. If the time of the last moment maneuver is lost, it is necessary to maneuver by stopping FAS and make the last turning maneuver.

Conclusion. The subjects in question relate to the preliminary preparation of the vessel for navigation in special conditions. This enables to develop the manoeuvring algorythm and automate certain navigation processes.

One of the ways to improve is to reduce the navigator's workload on the bridge through the use of automatic tools, and to establish expert systems.

Navigational control procedure of the vessel's position involves the information of two types - procedural and declarative.

Procedural information is in the algorythms of actions involved with maintaining navigational control and giving orders. Declarative information is in the data involved with the navigator's work.

The combination of these two types comprises the information base. This information may be described through vectors, matrices or hierarchic structures.

There is a lot of information about vessels and effects on them in the same base, and it's required to establish a special system to control the information base. It enables to exploit the information and, if necessary, to extract it from the base, modify and enter again in the form required.

With improvement of the information base of maneuvering process information is presented in the form of knowledge, this form having combined the features of procedural and declarative types.

With lack of knowledge maneuvering process is controlled through test and error which results in increasing probability of error and navigational incident.

The dependencies derived have enabled to establish regularities of the navigator's actions in close quarters, called "the law of the last maneuver moment".

It is true for all types of moving objects–above water, marine and submarine.

However, it is necessary to make calculations in horizontal plane for above water and submarine objects. If there is no close quarters situation in horizontal plane, collision will not occur in vertical plane either.

The main point of the law is that the operator's actions depend on 'close quarters' geometry, defined by relative course p and course angle q.

If the starboard side course angle and $p > 90^\circ$ first comes the moment of turn to port and then turn to starboard.

The moment of commencement of full astern depends on the present speed of the vessel and either comes first or follows turn to port or turn to starboard.

If the starboard side course angle and $p < 90^\circ$ first comes the moment of turn to starboard and then turn to port.

The moment of commencement of full astern depends on the present speed of the vessel and either comes first or follows turn to port or turn to starboard.

In case of aircraft it is necessary to consider brake action handsomely.

To calculate the moment of commencement of 'close quarters' it is required to know manoeuverability of the object to select the type of maneuver.

The 'close quarters' situation may be controlled by sole parameter–relative distance.

3 Suggestions

With lack of knowledge maneuvering process is controlled through test and error which results in increasing probability of error and navigational incident.

Due to the lack of systematized concept when providing maneuver characteristics, only 20% of data about providing certain reserve of speed control to prevent ship control loss, providing maneuvering characteristics, rules of the road, predicting collision danger, proper quantity of is available.

In order to solve the problem, we offer 5 basic steps.

(1) To develop positioning system and systematize data presentation as to ship's maneuvering characteristics.

(2) Develop ships navigation guide, that will contain all necessary information on maneuvering in congested waters, in poor weather conditions, in shallow waters, choosing optimal speed and how to control it.

(3) Systematize collision avoidance systems, including relative motion patterns.

(4) Develop and implement "segregation of duties" schemes for masters and pilots, including legal models of sharing liabilities and duties.

(5) Develop computer-based Safety Assurance System.

All these will help to find proper solution in providing navigational safety onboard and will help to minimize accidents risk.

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