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Navigational decision support system during approach manoeuvre in emergency STS transfer operation

Keywords

lightering, trajectory planning , approach manoeuver

Abstract

The paper is concerned with the problem of safe trajectory planning for approaching during emergency STS (Ship to Ship) transfer operation with oil spill. The safe trajectory means that the way points does not cross in the area of the environment with the static and dynamic obstacles and at the same time satisfies ship's stopping and speed deceleration performance. The evolutionary path planning algorithm is used to determine trajectory designed as way points and straight line segments between them. The way points - ship positions and velocity can be treated as reference value to support navigator in decision making during Approach Manoeuvre and to mitigate the risk of collision which mostly results from exceed velocity of approaching. The task of trajectory planning is defined as constant optimization process to minimize trajectory length, course alteration and maximize safety in a navigational environment. This paper examines exemplary navigational scenario based on emergency STS accident.

1. Introduction

The Ship to Ship transfer operation (STS) are expected to increase significantly in frequency, and expand into new geographical areas in the coming years. STS transfer operation generally involve transshipment between two ships, the large called SBL (Ship to be Lightered) and small one called SS (Service Ship) positioned alongside each other, either while stationary or underway in order to commence cargo transfer [8,9]. Usually this operation is carried out for huge oil tankers in open sea, when ship does not berth in port or jetty, especially due to draught restrictions or the port berthing charges. The motivation for performing these operations is a lack of deep water ports and economic aspects. Other reason to carry out the cargo transfer between damaged ship and another one is to safe cargo (crude oil, petroleum products, liquefied gas) as a result of tankers incidents and to mitigate emission to the environment. Nowadays more than 90% of trade is estimated to be transported by sea [2]. This statistics portrays also that the world oil tanker account for about

30% of global seaborne trade. Through the use of new technology of shipbuilding, modern navigation and control systems, shipping in the world's become more secure. Despite this, the total number of ships involved in accidents is still large. The accidents often result from collision, loss control, grounding and structural damage, fires or explosion. Only from 2011 to 2014 about 4620 cargo ships involved in accidents, of which oil tankers represent about 9% (415 units). In the last decade the total volume of oil lost to the environment was approximately 33 000 tonnes.

The STS transfer operation requires proper coordination, equipment in according to STS operation plan and administration approval. The purpose of the STS transfer operation plan is to provide a step by step description of STS procedure according to guidelines or recommendations from Iranian Classification Society (ICS), Oil Companies International Marine Forum (OCIMF) and the International Maritime Organization (IMO). This plan should deal with the following stages of operation:

- Pre-Approach Planning;

- Approach Manoeuvre;
- Mooring;
- Cargo Transfer;
- Unmooring;
- Departure Manoeuvre.

Each stage consists of different procedures to follow and check-lists to complete. A standard way to carry out an STS transfer operation is when the SBL maintain a constant heading at minimum controllable speed (5 knots or less) or drift with wind and currents but SS approach the first one and berths normally with its port side to the starboard side of the constant heading ship (Figure 1). The standard Approach Manoeuvre is divided into two phases. The initial phase is basically a collision avoidance manoeuvre from current position p_0 to final position p_k in order to obtain the required safety distance between Service Ship and Ship to be Lightered. The safety distance is called the Distance at Closest Point of Approach (DCPA) and it is appropriate to the conditions. During this phase SS must approach the first one on a parallel course and adjust its velocity to equal SBL. The second phase which is operation of a ships alongside takes place after the required safety distance has been verified. On closer approach, the manoeuvring ship should then position itself relative to the constant heading ship. Contact is made by the manoeuvring ship, reducing the distance until the fenders touch. Subsequently both ships are on parallel courses with similar velocity and their manifold in line to minimize force of berthing simultaneously on all fenders.

In the open waters the standard Approach Manoeuvre begins at distance of 0.5 Nm from the destination point and finish at DCPA approximately 50-100 m off. The mooring lines start about 20-30 m away from each ship. Normally the manoeuvre will be made with the wind and sea ahead, however local conditions and knowledge may indicate an alternative side. Usually transshipment is completed after 10-24 h depending on cargo quality and weather condition.

Throughout any berthing operation the visibility should be good enough for safe manoeuvring, taking into account safe navigation and collision avoidance requirements. This standard Approach Manoeuvre (Figure 1) is of assistance when ships are under power, considering normal STS transfer operation. The procedures may vary from this guidance according to circumstances (emergency with oil spill, inshore operation, limited geographical scope of operation), dynamical and kinematical ship properties, weather condition and traffic density. In each unique situation Approach Manoeuvre almost base on knowledge, experience and assessment of navigational situation from navigators.

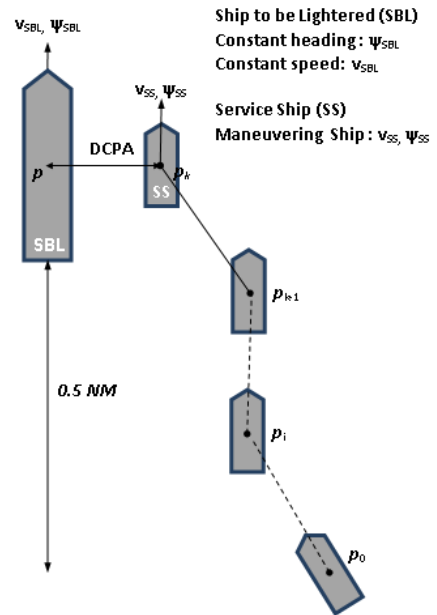


Figure 1. The principle of a standard Approach Manoeuvre in STS lightering operations (OCIMF/ICS 2005, OCIMF 2009)

The most common incident to occur during STS operations is a collision between the two ships while manoeuvring alongside each other or sailing [4,5,10,11]. Collision between two ships typically occur for reasons which include: incorrect approach angle between the manoeuvring ships; approaching at excessive speed; failure of one or both ships to appreciate meteorological conditions. To mitigate the risk of incidents, guidelines will be needed for the navigator of Service Ship, which include information about reference trajectory for approaching in meaning of reference way points p_i : position (x_i, y_i) /or (heading ψ_i) and velocity v_i to take a proper steering decision by ship operator at each stage of ship manoeuvring. Our objective is to define Approach Manoeuvre during emergency STS transfer operation as a problem of safe trajectory planning for approaching taking into account weather condition (wind direction), traffic density and stop and speed control performance of the vessels involved. Trajectory of approaching determined on available information allows to take proper manoeuvring decision by ship operator using rudders and propellers and to mitigate oil spill to the environment.

2. Trajectory Planning for approaching

The Service Ship trajectory planning for approaching bases the first on STS transfer operation guide [12], and the second on good navigation practice and data information. Data information comes from ARPA, AIS, Electronic Chart and takes into account IMO regulations. It include

- stationary obstacles (land, islands, shallow water, restricted area)
- dynamical obstacles (SBL ship, other ships, oil spill area)
- modelling of ships and obstacles by domains
- ships and obstacles domains position, course, and speed.
- Service Ship stopping and speed control characteristics (from manoeuvring booklet).

Modelling reference trajectory depend additionally on different circumstances like :

- wind direction (manoeuvring from leeward),
- oil spill area (manoeuvring from starboard or port side),
- ship actuator equipment (manoeuvring performance).

The example trajectory for approaching in navigational environment shown in *Figure 2*. The static obstacles X_{stat} such as land, islands, shallow water are modelled by domains, represented geometrically by convex polygons. The dynamic obstacles X_{dyn} such as other ships are modelled by domains, evaluating in time and represented by hexagon with known current and predicted position, constant course and speed (containing Colregs rule) (Śmierzchalski, Michalewicz). Among them can set oil spill domain X_{oil} , SBL domain X_{sbl} and unavailable (forbidden) region X_{uava} apart which can be treated as static or dynamic (*Figure 3*). The shape and size of X_{sbl} depend on ship velocity, wind direction, DCPA and side of approach. Oil spill domain X_{oil} can also evaluate in time and depend on emergency and weather conditions. It is also possibly to modelling prediction of oil spill area [7]. In the paper an oil spill and SBL domain are represented respectively by static hexagon and triangle domain because of SBL drifting and oil barrier. Unavailable domain X_{uava} contain forbidden sectors which results from ship maneuvering and operation constraints by using rudders at low speed [3].

2.1. Modeling of the way points

The trajectory is defined as a set of turning points $\mathbf{P} = \{p_0, p_1, \dots, p_k\}$ on ship route from current position p_0 to the destination p_k . The way points $p_i(x_i, y_i, v_i), i \in \{0, 1, \dots, k\}$ of desired trajectory have position x_i, y_i determined to avoid obstacles on considered area with respect to a top ship speed $v_i, i \in \{0, 1, \dots, k\}$ on each way points. The way points divide trajectory into a set $S = \{s_1, s_2, \dots, s_k\}$ of trajectory segments with a lengths $D = \{d_1, d_2, \dots, d_k\}$. The s_i compose of the path position sequences between way points on straight

line. The way points components are respectively reference ship position and speed on each turning point. Planning of the safe trajectory during STS assumed that each of trajectory segment $s_i, i = \{1, \dots, k\}$, between way $p_i, i = \{0, \dots, k\}$ points does not cross in the area of the environment with the static and dynamic obstacles. The choice of top speed elements $v_i, i \in \{0, 1, \dots, k\}$ at each way points of desired trajectory depend on set $v_i \in V, V = \{0, v_{FA}, v_{HA}, v_{SA}, v_{DSA}\}$, where the following engine orders are considered: Full Ahead (v_{FA}), Half Ahead (v_{HA}), Slow Ahead (v_{SA}), Dead Slow Ahead (v_{DSA}).

The designed trajectory satisfies deceleration condition if the ship is able on each trajectory segment s_{i+1} to decelerate ship velocity. It means that for a given starting reference speed v_i at p_i it is possible to approach by ship the ending one $v_{i+1} < v_i$ at p_{i+1} with segment length d_{i+1} . The feasibility of trajectory is checked based on stop and speed control constraints collected in manoeuvring booklet. When the vessel travels in a straight line along the original course the segment length value can't be less than track reach needed for speed deceleration or stop ship:

$$d_{i+1} \geq \text{track reach}_{i+1} \quad (1)$$

where track reach_{i+1} is the travelling distance need to decelerate ship velocity from v_i to v_{i+1} .

The initial way point p_0 consist of a current position (x_0, y_0) and velocity v_0 of Service Ship when it start Approach Manoeuvre (*Figure 2*). The destination point $p_k(x_k, y_k, v_k)$ has a parallel position ($l_{SS} \parallel l_{SBL}$) in a safety distance (DCPA) from position of Ship to be Lightered and the some velocity $v_k = v$, to allow starting manoeuvring alongside. When emergency STS trajectory is planning the SBL maintain its current position (x, y) constant and speed about zero, $v \approx 0$. In this case the initial p_0 and destination p_k points are approximately constant and chosen by the operator or calculated by the simple geometric relationship:

$$p_k |_{(x_k, y_k)} \in l_{SS}, \quad l_{SS} \parallel l_{SBL}, \quad (2)$$

$$v_k \approx 0, \quad DCPA = \left\| p |_{(x, y)} p_k |_{(x_k, y_k)} \right\|_2, \quad (3)$$

where

$$p |_{(x, y)} = (x, y), \quad p_k |_{(x_k, y_k)} = (x_k, y_k),$$

l_{SS} –straight line covers SS diametrical line,
 l_{SBL} –straight line covers SBL diametrical line.

The previous way point p_{k-1} has position determined on straight line l_{SS} parallel to l_{SBL} .

$$p_{k-1}|_{(x_{k-1}, y_{k-1})} \in l_{SS}, \quad l_{SS} \parallel l_{SBL}. \quad (4)$$

The reference speed v_{k-1} is modelled as minimum controllable speed v_{DSA} (Dead Slow Ahead) for safety manoeuvring in close proximity.

$$v_{k-1} = v_{DSA}, \quad (5)$$

with satisfying feasibility condition of trajectory segment s_k :

$$d_k = \|p_{k-1}|_{(x_{k-1}, y_{k-1})} p_k|_{(x_k, y_k)}\|_2 \geq \text{track reach}_k \quad (6)$$

where track reach_k is the travelling distance need to decelerate ship velocity from v_{DSA} to about 0.

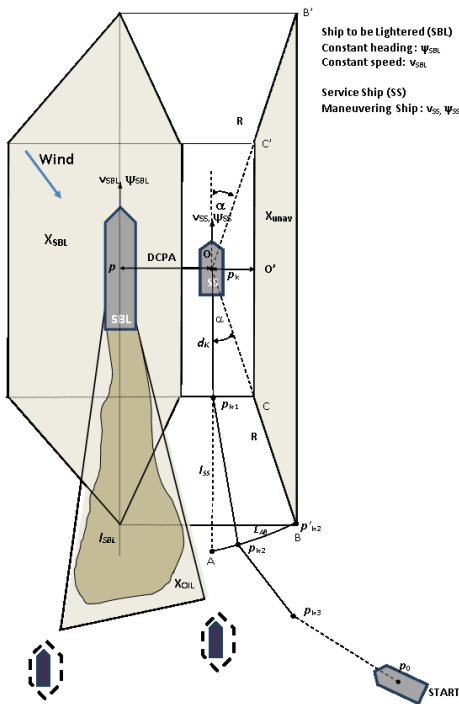


Figure 2. The example trajectory for approaching in STS transfer operations

The way point p_{k-1} is determined on the arc L_{AB} between the end points A and B satisfying $A \in l_{SS}$. The arc is a part of a circle $O(p_k, |AO|, \alpha)$ with a radius $|AO| = 0.5$ nautical miles of cells and central angle $\alpha \in \langle 0, 30^\circ \rangle$. We also assume that reference velocity $v_{k-2} = v_{DSA}$ is predetermine as minimum controllable.

$$p_{k-2}|_{(x_{k-2}, y_{k-2})} \in L_{AB}, \quad A \in l_{SS} \quad (7)$$

$$v_{k-2} = v_{DSA} \quad (8)$$

where

$$L_{AB} \in O(p_k, |AO|, \alpha), \quad \alpha \in \langle 0, 30^\circ \rangle, \quad |AO| = 0.5 \text{ NM}$$

The evolutionary path planning algorithm is proposed based on a natural selection mechanism to determine STS trajectory for approaching as an optimization task. Its most important advantages are build-on adaptation mechanism for a dynamic environment and reaching a multi-criteria task solution in a near-real time. The modification to a classical evolutionary path planning method in collision avoidance problem [6] lie in using additional constraints taking into account engine orders, track and time reach from stopping and speed deceleration characteristics. In actual implementation introduced several modification of earlier version of evolutionary path planning method to adapt algorithm to STS problem. Each node consists of x, y and v coordinates. Velocity v in each way points is generated randomly from set V of engine orders. The feasibility of trajectory means that way points does not cross in the area of the environment with the static and dynamic obstacles and at the same time satisfies ship's stopping and speed deceleration performance (1). The algorithm takes into account the direction of wind (ship SS approaches from leeward. The next difference is related with a reduction of current ship velocity along trajectory segments between way points. Speed of own ship on straight –line segments between way points can be fixed or decelerated in a non-linear manner according to the speed deceleration characteristics. So the collision time is also calculated in a non-linear manner on the basis of data from speed deceleration characteristics. The genetic operators such as mutations, crossover are also specified to STS transfer operation problem.

The way points components calculated from Evolutionary Algorithm (EA) are determined as references position (or heading) and speed values for navigator to support decision making at each stage of ship manoeuvring.

3. Simulation test results

The SS model of Chemical Tanker type with 6000 DWT, of length over all 103,6 m powered by one diesel engine rating 3600kW at 200 rpm was used in the simulation tests. The tank is propeller by 1 fixed pitch propeller. The ship is steered with one rudder which maximum angle 65° . This ship is equipped with one bow tunnel thruster rating 400kW.

3.1 Stopping and speed deceleration characteristics

Stopping ability in deep water can be judged from emergency stop manoeuvre when autopilot is turned on [1]. Table 1 shows a possible engine order in engine

telegraph setting with information about propeller revolution rpm and speed in knots. They contain Full Sea Ahead, Full Ahead, Half Ahead, Slow Ahead, Dead Slow Ahead.

Table 1. Characteristics of main engine

Engine order	Propeller RPM	Speed Knots
Full Sea Ahead	240	12.9
Full Ahead	214	11.6
Half Ahead	175	9.5
Slow Ahead	130	7.0
Dead Slow Ahead	83	4.5

It can be note that in considered approach maneuvering during way point planning only stopping ability from Dead Slow Ahead and deceleration ability from all engine order are needed. Deceleration performance concern track reach, head reach and time reach. It covers the following modes: from Full Sea Ahaed to Full Ahead; from Full Ahead to Half Ahead; from Half Ahead to Slow Ahead; from Slow Ahead to Dead Slow Ahead. *Figure 3* present deceleration ability of SS in detail when autopilot is turned on. The *Table 2* includes estimated value of track reach (TR) (distance travelled), head reach (HR), side reach (SR), speed and time (T) to stop (time till vessel is dead in water) from Dead Slow Ahead.

Table 2. Emergency stopping ability (to Full Astern from Dead Slow Ahead)

	TR [Nm]	HR [Nm]	SR [Nm]	T [min-s]	FC [°]
DSA	0.075	0.075	0.00185	1-27	9

Figure 4 presents continuous approximation of speed deceleration and track reach data in time.

Track reach [Nm]	4-50		6-44		7.2		9-31		4.7	
0.9										
0.8			4-50	9.7		5-55	7.3	8-39		4.8
0.7			3-59	9.8		5-06	7.4	7-24		4.9
0.6	3-09	11.8								
			3-23	10.0	4-18	7.6	6-11			5.0
0.5	2-26	11.9	2-47	10.1	3-31	7.8	5-01			5.2
0.4	1-56	12.0	2-12	10.3	2-45	8.0	3-54			5.5
0.3	1-26	12.2	1-37	10.6	2-01	8.3	2-50			5.8
0.2	0-57	12.4	1-04	10.9	1-19	8.7	1-50			6.1
0.1	0-28	12.7	0-31	11.3	0-39	9.1	0-53			6.6
0	0-00	12.9	0-00	11.6	0-00	9.5	0-00			7.0
	min-s	knots	min-s	knots	min-s	knots	min-s	knots	min-s	knots
	FSA to FA		FA to HA		HA to SA		SA to DSA			

Figure 3. Deceleration performance (from trial test)

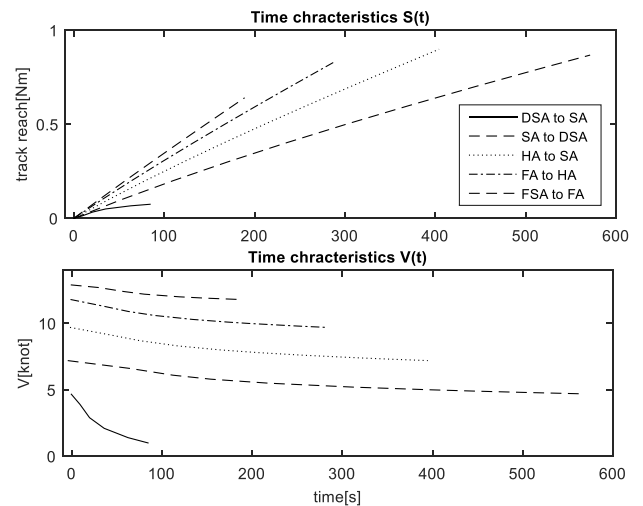


Figure 4. Approximation of speed and track reach data

3.2 Emergency STS scenario

Product tanker (SBL) after collision with general cargo ship lost its ability to manoeuvre and start drifting due to wind. Immediate actions were carried out to reduce oil spill overboard, arranged transfer cargo from damaged tank to other compatible tanks and increased heel to port using ballast tanks to keep all cracks on bulkhead above the sea water level. Prepare floating cotton barrier to reduce oil spot in the vicinity of ship, started oil spill pump and collected oily water to slops tanks. At the same time all parties (administration, owner, charterer, insurer) were informed accordingly. Small Chemical Tanker (SS) with very good manoeuvring characteristic was designated to emergency STS operation.

Exemplary test of navigational situation was considered and graphically illustrated in *Figures 5-6*. The navigational scenario assumes 3 dynamic obstacles and 3 static obstacles in the area of SBL ship (X_{oil} , X_{SBL} , X_{unav}).

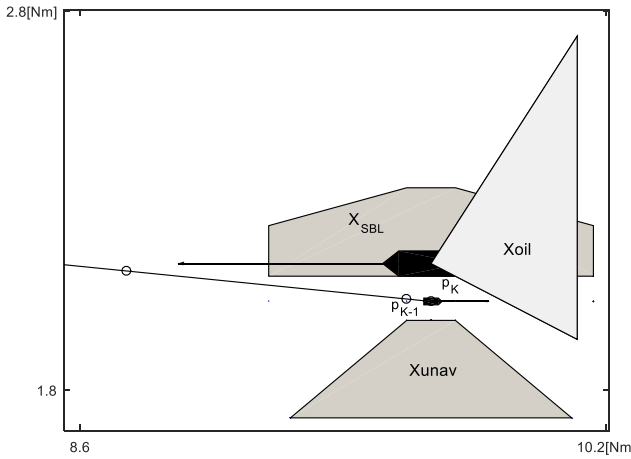


Figure 5. An exemplary navigational situation in the area of SBL ship.

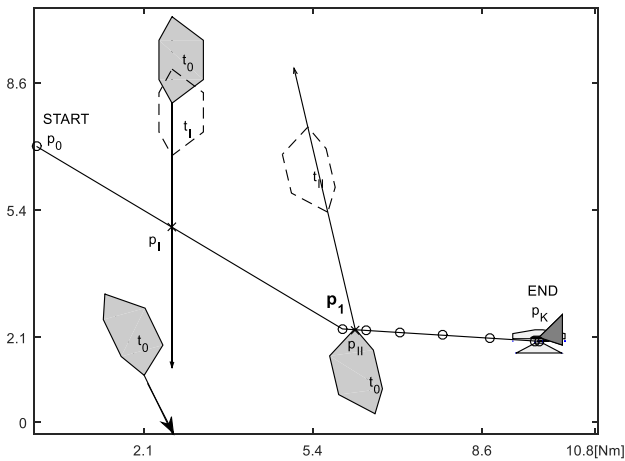


Figure 6. Graphical solution of an exemplary navigational situation using evolutionary path planning algorithm

Data information describing actual navigational situation include initial position, course and speed of SBL ship and targets shown in Table 3.

Table 3. Data of an exemplary navigational situation

	Course ^[0]	Speed[kn]	Start Position[Nm]
SBL	270	0	
target1	350	8.7	(6.47, 8.09)
target2	160	1.8	(1.61, 2.69)
target3	180	5.2	(2.69, 9.71)

Data information about start position of SS, wind direction and DCPA collected in Table 4.

Table 4. Data of an exemplary navigational situation-cont.

	Start point [Nm]	Wind direction ^[0]	DCPA [m]
Test	(0.11,7.02)	60	180

Reference trajectory is composed of seven way points $\{p_0, \dots, p_7\}$. On the resulting trajectory are determined additional points to support decision making during manoeuvring. The detailed information as positions, velocities, lengths and times on each trajectory segment are shown in Table 5. The resulting trajectory is safe and satisfies speed deceleration performance in meaning of satisfying velocity, time and track reach constraints. Time to reach intersection points (p_i, p_{ii}) by own ship to avoidance collision was calculated depending on manoeuvring characteristics and deceleration performance.

Table 5. Reference trajectory way points

p_k	x_k [Nm]	y_k [Nm]	v_k [kn]	d_k [Nm]	t_k [min-s]
p_0	0.108	7.019	12.96	0	0
p_1	5.961	2.375	12.96	7.471	34-45
p_2	6.411	2.338	12.96	0.452	2-6
p_3	7.050	2.285	11.6	0.641	3-09
p_4	7.883	2.215	9.50	0.8360	6-44
p_5	8.779	2.140	7.00	0.8990	4-50
p_6	9.644	2.068	4.50	0.8680	9-31
p_7	9.719	2.062	0.10	0.0750	1-27

5. Conclusion

The presented navigational decision support system can be applied on a Service Ship vessel during STS transfer operation. The developed path planning and collision avoidance algorithm is based on Evolutionary Algorithm. The problem is considered as a collision avoidance task with respect to additional constraints resulting from transfer operation guide and control possibility. The algorithm gives us step by step instruction about desirable position and speed of reference trajectory which mostly depend on ship speed manoeuvring properties. The information about desired speed at each way points can reduce possible factors that cause collision during STS like incorrect approach angle between the SS and SBL ships, the manoeuvring ship approaching at excessive speed, some form of human error. Taking into account ship manoeuvring characteristics during STS trajectory planning process can support Navigator in decision making to determine desired speed in each phase of the manoeuvre and type of steering operation using rudder and propeller and estimated time duration to complete operation.

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