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Trajectory planning for Service Ship during emergency STS transfer operation

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Abstract. In this paper trajectory for approaching during emergency STS transfer operation with oil spill is considered as a sequence of navigation manoeuvres in specific navigational environment. The designed way points - ship positions and speed are determined as reference values to support navigator in decision making during steering and to mitigate the risk of collision which mostly results from exceeding the speed limit of approaching. To prevent this, the values of position and speed in each way points are determined with respect to specific manoeuvring procedure during STS approaching and by taking into account constraints resulting from ship's manoeuvre of stopping and speed deceleration performance included in manoeuvring booklet. Additional constraints result from STS transfer operation guide and navigation practise. The task of trajectory planning is defined as optimization process to minimize trajectory length, course alteration and maximize safety.

Keywords: Ship to Ship transfer operation, stopping and speed control characteristics, safe trajectory planning, evolutionary algorithm

1 Introduction

To control ship motion at sea trajectory planning in a dynamic environment is used. The issue consists in determining ship trajectory between start and final points, which enables to avoid collision with static and dynamic obstacles and taking into account ship manoeuvrin performance. Several solutions have been introduced to solve this problem. One of them contains Game Theory, where a problem of non-collision control strategies in the steering at sea is analyzed [7]. Other methods like Genetic or Evolutionary Algorithm, Particle Swarm Algorithm consider collision avoidance as a multi-criteria, nonlinear optimization problem with navigational time, safety and economy criteria [4]. In the above studies, the focuses were trajectory searching represented by the set of way points consists of desired positions and speed or heading. The transformation of the way points to a feasible trajectory was modelled as straight-lines and inscribed circles [5], polynomials or splines [3]. The above methods assume constant ship's speed on a straight line and decreasing in speed during course alteration, alternatively time of manoeuvre as a function of course, speed and load condition. Dynamic

properties of ship have been implemented from turning circle test. However, in low speed manoeuvring operations at sea like Lightering underway, emergency Ship to Ship transfer (STS), docking the stopping and deceleration characteristics are important and should also be taken into consideration. So the above results cannot be used directly in reality.
STS transfer operation generally involve transhipment 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]. Before mooring and cargo transfer start, the Service Ship has to approach the Ship to be Lightered, which moves on a constant heading with slow speed or drifts about zero. For this purpose basically a collision avoidance manoeuvre has to be carried out in order to obtain the required safety distance between two ships and to take side by side position. The most common incident that occurs during STS operations is a collision between the two ships while manoeuvring alongside each other or sailing [14]. Collision between two ships typically occurs because of 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 are 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 speed v_i to take a proper steering decision by ship operator at each stage of ship manoeuvring.
Considered in the paper emergency STS transfer operation means that 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. Small tanker (SS) was designated to emergency STS operation. During this incident can appear additional important aspects like ship and cargo condition (transhipment from undamaged side), wind direction (transhipment from leeward), speed reduction, time limits (optionally to ensure fast transhipment) as well as water area constraints (close to port area), avoidance moving oil spill or other rescue units [16].
Our objective is to determine a desired trajectory for approaching during emergency STS transfer operation taking into account stopping and control manoeuvering characteristics of the vessels involved in manoeuvring booklet. Estimated on available information trajectory allows to take proper manoeuvring decision by ship operator using rudders and propellers and to mitigate oil spill to the environment. The resulting optimal trajectory will have to make an assumption of economic (minimum distance for approaching and course alteration) and safety of manoeuvring (non-collision).

2 Stopping and speed deceleration characteristics

To control the movement of Service Ship during STS Approach Manoeuvre a few general control modes are possible, in order to achieve the final distance from

SBL, parallel course and equal speed. They are recommended based on good navigation practice and STS transfer operation guides [8, 9, 13, 2]. The control modes consist of:

I.Trajectory Tracking (moderate or high-speed manoeuvring)

II.Stopping Manoeuvre (stop ship)

III. Berthing (side manoeuvre)

After Approach Manoeuvre by using I, II control modes ships should manoeuvre alongside at the required safety distance DCPA (Distance at Closest Point of Approach). That means both SS and SBL keep their constant heading $\psi_{\mathrm{SS}} \approx \psi_{\mathrm{SBL}}$ at minimum controllable constant speed $v_{\mathrm{SS}} \approx v_{\mathrm{SBL}}$ or drifting about zero (during emergency). In this condition the Berthing operation by using the tunnel thruster and mooring procedure by using lines can start.

Comprehensive details of the ship stopping and speed deceleration characteristics are included in the manoeuvring booklet. This booklet is required to be on board and it has to be available for navigators. Most of the manoeuvring information in the booklet can be estimated but some should be obtained from trials. They contain (among other relevant data) characteristics of main engine, stopping test results (emergency and normal) and speed deceleration performance.

The characteristics of main engine contain possible engine order (Full Sea Ahead, Full Ahead, Half Ahead, Slow Ahead, Dead Slow Ahead, Dead Slow Astern, Slow Astern, Half Astern, Full Astern), propeller revolution, speed, power, pitch ratio. Stopping ability [15] of SS is measured by the track, head, side reach, time required to speed reduction and final course. It covers the following modes of emergency stopping manoeuvres: from Full Sea Ahead to Full Astern; from Full Ahead to Full Astern; from Half Ahead to Full Astern; from Slow Ahead to Full Astern; from Full Sea Ahead to stop engine and following modes of normal stopping manoeuvres: from Full Ahead to stop engine; from Half Ahead to stop engine; from Slow Ahead to stop engine. Deceleration performance concern track reach, head reach and time required. It covers the following modes: from Full Sea Ahead to Full Ahead; from Full Ahead to Half Ahead; from Half Ahead to Slow Ahead; from Slow Ahead to Dead Slow Ahead. When vessel travels along a straight line with the original course (autopilot is on) the track reach and time reach values are taken as the longest travelling distance and the maximum time to decelerate ship speed.

3 Trajectory Planning for approaching

The Service Ship trajectory for approaching is defined as a set of turning points $\mathrm{P} = \{p_0,\ p_1, ...,\ p_k\}$ on ship route from current position (initial point) p_0 to the destination (final point) p_k and a set $\mathrm{S} = \{s_1, s_2, \ldots, s_k\}$ of trajectory segments between them with a segment lengths $\mathrm{D} = \{d_1, d_2, \ldots, d_k\}$. The way points $p_i\,(x_i,\ y_i,\ v_i, t_i)\,,\quad i \in \{0, 1, \ldots, k\}$ of desired trajectory are interpreted as geometrical position $x_i,\ y_i$ with respect to a maximum ship speed

$v_i,\ i \in \{0, 1, \ldots, k\}$and time t_i of approaching i-th position. Trajectory segments s_i compose of the path position sequences between way points on straight line as a function in time $s_i\,(t)$. It can satisfy speed deceleration performance. Deceleration performance means that for a given starting reference speed v_{i-1} at p_{i-1} it is possible to approach by ship the ending one $v_i {\leq} v_{i-1}$ at p_i with segment length d_i. When the vessel travels on a straight line along the original course this segment length value can't be less than track reach needed for speed deceleration or stop ship.

3.1 Modelling of the way points

Additional modelling require the way points in close proximity of SBL $p_k,\ p_{k-1}$ and $p_{k-2},\ k \geq 2$ .They depend directly on STS transfer operation guide and navigation practise during STS Approach Manoeuvre [1, 10]. The example of modelling way points is shown in a Fig.1, where starboard side manoeuvre and NE'ly wind direction is considered. In the open waters the last phase of standard Approach Manoeuvre begins at distance R about 0.5 Nm from the destination point and finish at DCPA approximately 50-100 meters off. The initial way point p_0 consist of a current position (x_0, y_0), speed v_0 of Service Ship at t_0, when it start Approach Manoeuvre. The destination point $p_k\,(x_k,\ y_k,\ v_k, t_k\})$ has parallel position $(l_{\mathrm{SS}} \|\ l_{\mathrm{SBL}})$ in a safety distance (DCPA) from SBL and the same speed $v_k \approx v$, to allow starting manoeuvring alongside. When emergency STS trajectory is being planned the SBL maintain its current position (x, y) constant and speed drifting about zero $v \approx 0$. In this case the initial p_0 and destination p_k points have approximately constant positions chosen by the operator or calculated by the simple geometric relationship:

$$\begin{aligned} p_{k\ |(x_k,y_k)} &\in l_{\mathrm{SS}},\quad l_{\mathrm{SS}} \parallel l_{\mathrm{SBL}}, \\ \mathrm{DCPA} &= \left\| p_{|(x,y)}\ p_{k\ |(x_k,y_k)} \right\|_2, \\ v_k &\approx\ \ v, \end{aligned} \tag{1}$$

where
$p_{|(x,y)} = (x, y)\,,\ p_{k\ |(x_k,y_k)} = (x_k, y_k)$,
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}:

$$p_{k-1|(x_{k-1},\ y_{k-1})} \in l_{\mathrm{SS}},\ l_{\mathrm{SS}} \parallel l_{\mathrm{SBL}}. \tag{2}$$

The reference speed v_{k-1} at p_{k-1} is modelled as minimum controllable speed v_{DSA} (Dead Slow Ahead) for safety manoeuvring in close proximity $v_{k-1} = v_{\mathrm{DSA}}$, with satisfying deceleration performance on trajectory segment s_k :

$$d_k = \left\| p_{k-1|(x_{k-1},\ y_{k-1})}\ p_{k\ |(x_k,y_k)} \right\|_2 \geq track\ reach_k, \tag{3}$$

where $track\ reach_k$ is the travelling distance need to decelerate ship's speed from v_{DSA} to stop.

The way point p_{k-2} is determined on the arc L_{AB} between the end points A and B satisfying $\mathrm{A} \in l_{\mathrm{SS}}$. The arc is a part of a circle $O\left(p_k,\ |\mathrm{AO}|\,,\ \alpha\right)$ with a radius $|\mathrm{AO}| = \mathrm{R}$ of cells and central angle $\alpha \in <0,\ 30^0>$. It is also assumed that reference speed $v_{k-2} = v_{\mathrm{DSA}}$ was predetermined as minimum controllable

$$p_{k-2|(x_{k-2},\ y_{k-2})} \in L_{\mathrm{AB}},\ v_{k-2} = v_{\mathrm{DSA}}, \tag{4}$$

where

$$L_{\mathrm{AB}} \in\ O\left(p_k,\ |\mathrm{AO}|\,,\alpha\right), \quad \alpha \in <0, 30^0>, \quad |\mathrm{AO}| = \mathrm{R}.$$

4 Formal problem definition

The process of Trajectory Planning for approaching is considered as an example of classical avoiding collisions at sea. It is reduced to an optimization task with static and dynamic constraints in the navigational environment with safety and economic criteria [12, 11].

4.1 Configuration Space/ Search Space

The search space of position variables (the set of all possible solutions) is defined in two-dimensional Euclidean space of navigational environment:

$$\mathrm{X}_{\mathrm{env}} = \left\{(x, y) \in \mathrm{E}^2 \colon a \le x \le b,\ c \le y \le d\right\}. \tag{5}$$

The space consists of: safe areas $\mathrm{X}_{\mathrm{safe}}\,(t)$, static obstacles domains $\mathrm{X}_{\mathrm{stat}}$, dynamic obstacles domains $\mathrm{X}_{\mathrm{dyn}}\ (t)$.

$$\mathrm{X}_{\mathrm{env}} = \mathrm{X}_{\mathrm{safe}}(t) \cup \mathrm{X}_{\mathrm{stat}}\ \cup\ \mathrm{X}_{\mathrm{dyn}}\,(t)\,. \tag{6}$$

The choice of maximum speed values $v_i,\ \ i \in \{0,\ 1, \ldots, k{-}1\}$ at each way points of desired trajectory depend on set

$$\mathrm{V} = \{v_{\mathrm{FSS}},\ v_{\mathrm{FA}}, v_{\mathrm{HA}},\ v_{\mathrm{SA}}, v_{\mathrm{DSA}}\} \tag{7}$$

and $v_i \approx 0$ for $i{=}k$.
The following engine orders are considered: Full Sea Ahead (v_{FSA}), Full Ahead (v_{FA}), Half Ahead (v_{HA}), Slow Ahead (v_{SA}), Dead Slow Ahead (v_{DSA}). The static obstacles $\mathrm{X}_{\mathrm{stat}}$ such as land, islands, shallow water are modelled by domains, represented geometrically by convex polygons. The dynamic obstacles $\mathrm{X}_{\mathrm{dyn}}$ 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 rules).

Among them can models oil spill domain $\mathrm{X}_{\mathrm{oil}}$, SBL domain $\mathrm{X}_{\mathrm{sbl}}$ and unavailable sector $\mathrm{X}_{\mathrm{unav}}$ apart which can be treated as static or dynamic, see Fig.1. The shape and size of $\mathrm{X}_{\mathrm{sbl}}$ depend on ship speed, wind direction, DCPA and side of approach. Oil spill domain $\mathrm{X}_{\mathrm{oil}}$ can also evaluate in time and depend on emergency and weather conditions. It is also possible to model prediction of the oil spill area [6]. In the paper an oil spill and SBL domain are represented by static hexagon and triangle domain respectively because of SBL drifting and oil barrier. Unavailable domain $\mathrm{X_{unav}}$ contains forbidden sectors which results from ship manoeuvring and operation constraints by using rudders at low speed.

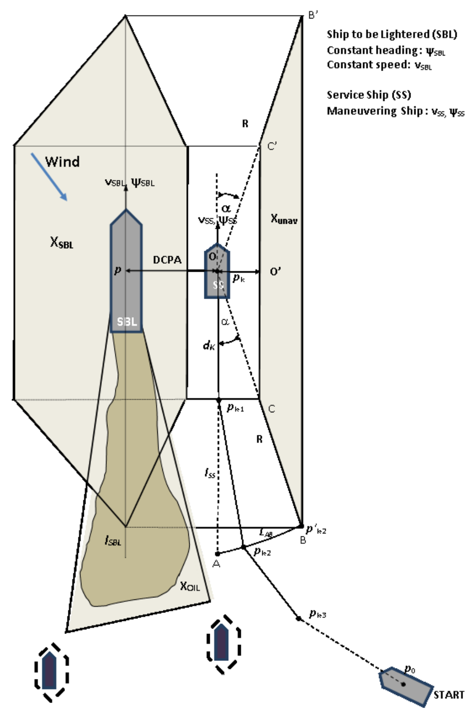

Fig. 1. Modeling of the way points in navigational environment

4.2 Constraints

Desired trajectory satisfies safety and deceleration condition. The reference trajectory during STS assume to be safe if each of way point p_i, $i = \{0, \ldots, k\}$ and segment s_i, $i = \{1, \ldots, k\}$, between way points does not cross in the area of the environment with the static and dynamic obstacles:

$$\mathrm{S} \subset \mathrm{X_{safe}}(\mathrm{t}) \text{ and } \mathrm{P} \subset \mathrm{X_{safe}}(\mathrm{t}). \tag{8}$$

Deceleration condition means satisfying ship's stopping and speed deceleration performance.

$$v_i \leq v_{i-1}, \quad i = \{1, \ldots, k\}, \; v_k \approx 0, \tag{9}$$

$$d_i \geq track\ reach_i,\quad i\ = \{1,\ \ldots,\ k\}. \tag{10}$$

Additional constraints can result from weather condition, STS transfer operation guide and navigation practise (see Chap. 3.1).

4.3 Optimization criteria

The problem of determining STS trajectory for approaching is defined as multi-criteria optimization task due to the presence of a function to opposing criteria. Therefore, it is proposed to use an approach based on replacing the multi-objective function by the function single-criterion $f(\mathrm{P}, \mathrm{S})$ with weighting factors w_1,w_2,w_3.

$$f(\mathrm{P},\ \mathrm{S}) = f_{\mathrm{econ}}(\mathrm{P},\ \mathrm{S}) + f_{\mathrm{safe}}(\mathrm{P},\ \mathrm{S}), \tag{11}$$

where
$f_{\mathrm{econ}}(\mathrm{P},\ \mathrm{S}) = w_1 f_{\mathrm{dist}}(\mathrm{P},\ \mathrm{S}) + w_2 f_{\mathrm{smooth}}(\mathrm{P},\ \mathrm{S})$,
$f_{\mathrm{safe}}(\mathrm{P},\ \mathrm{S})\ = w_3\ f_{\mathrm{clear}}(\mathrm{P},\ \mathrm{S})$.

The function f consists of costs related to the economics of shipping f_{econ} and safety costs f_{safe}. The economic cost f_{econ} are related to the length of the trajectory f_{dist} as well as the degree of smoothness f_{smooth} associated with course alteration.

Safety costs f_{safe} are associated with avoiding navigation constraints of both static and dynamic f_{clear}. Component f_{clear} defines a safe distance of passing navigation constraints.

5 Simulation tests results

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. In actual implementation introduced several modification of earliest version of evolutionary path planning method [11] to adapt an algorithm to STS. Each node consists of x, y and v coordinates. Velocity v is generated randomly from the set V (7) and satisfies (9).The feasibility of trajectory means that the trajectory is safe (8) and at the same time satisfies ship's stopping and speed deceleration performance (10). The algorithm takes into account the direction of wind (SS approaches from leeward (Fig.1)). Speed of own ship on straight-line segments can be fixed or variable in a non-linear manner according to speed deceleration performance (Fig.2). So the collision time is also calculated in a non-linear manner on the basis of data from speed deceleration characteristics. The repair mechanism of speed is introduces to satisfies (9) after genetic operators are used. 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.

In the simulation test, the approach trajectory was determine for the SS type Chemical Tanker 6000 DWT, of length overall 103,6 m powered by one diesel engine rating 3600kW at 200 rpm. The tanker is propeller by 1 fixed pitch propeller. The ship is steered with one rudder which maximum angle 65^0. This ship is equipped with one bow tunnel thruster rating 400kW. Stopping ability in deep water can be judged from emergency stop manoeuvre when autopilot is turned on. Figure 2 present deceleration ability of SS in detail when autopilot is turned on. Table 1 includes estimated value of track reach (distance travelled), head reach, side reach, speed and time to stop (time till vessel is dead in water) from Dead Slow Ahead to Stop. The example trajectory of approaching is shown in a Figure 3. It is composed of four way points p_0, p_1, p_2 and p_3. On the resulting trajectory are determined additional points to support the navigator in decision making. The detailed data as positions, velocities, lengths and times on each trajectory segment are shown in Table 2. 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}, $p_{\mathrm{II}}, p_{\mathrm{III}}$) by own ship to avoidance collision was calculated depending on the way from time (Fig. 2).

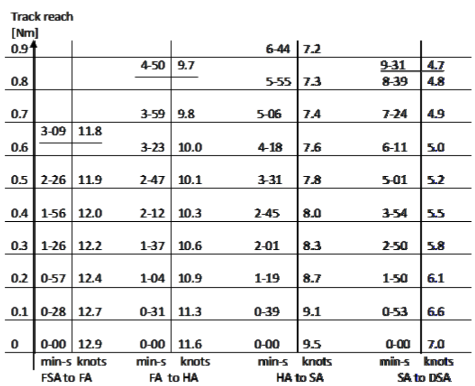

Fig. 2. Deceleration performance (from trial test)

Table 1. Emergency stopping ability

To Stop from:	Track R. Nm	Head R. Nm	Side R. Nm	Time R. min-s	Final course ^{0}
Dead Slow Ahead	0.075	0.075	0.00185	1-27	9

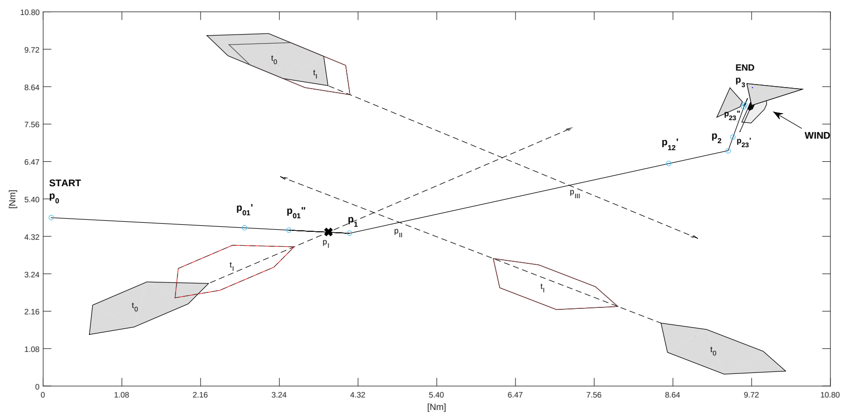

Fig. 3. Example of desired trajectory

6 Conclusion

The paper describe the problem of trajectory planning for approaching during emergency STS transfer operation with oil spill. The problem is considered as a collision avoidance task with respect to additional constraints resulting from transfer operation guide and control possibility. The guide gives us only a possible final Approach Manoeuvre without any 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 manoeuvring and type of steering operation using rudder and propeller and estimated time duration to complete operation.

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Table 2. Trajectory way points data

	(P, S)	Additional points	x_k[Nm]	y_k[Nm]	v_k[kn]	d_k[Nm]	t_k[min-s]	Track R. [Nm]
1	(p_0)		0.1080	4.8596	12.8996	0	0	-
2		($p_{01'}$,$s_{01'}$)	2.7591	4.5665	12.8996	2.6674	12-24	-
3		($p_{01"}$,$s_{01"}$)	3.3695	4.4988	11.6000	0.614	3-9	0.614
4	(p_1,s_1)		4.2004	4.4069	9.4978	0.8360	4-50	0.8360
5		($p_{12'}$,$s_{12'}$)	8.5802	6.4189	9.4978	4.8201	30-26	-
6	(p_2,s_2)		9.3971	6.7942	7.0000	0.8990	6-44	0.8990
7		($p_{23'}$,$s_{23'}$)	9.4649	7.1900	7.0000	0.4016	3-26	-
8		($p_{23"}$,$s_{23"}$)	9.6115	8.0456	4.5000	0.8680	9-31	0.8680
9	(p_3,s_3)		9.6241	8.1195	0	0.0750	1-27	0.075

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