Reducing Fuel Consumption for Trailing Suction Hopper Dredgers using Automatic Steering

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MSc Report

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Preface

Trailing Suction Hopper Dredgers (TSHD), are self-propelled vessels which contain large tanks for transferring sand or slurry. Dredging installations are used on board of these vessels to load and unload the sand. TSHDs work in consecutive cycles with four phases: 1. sailing empty to the loading area, 2. filling the hopper, 3. sailing full to the discharge area, 4. unloading the material.

The aim of this study was to develop a method to reduce propeller thrust and consequently fuel consumption during the two sailing phases of TSHDs.

The task was done by developing a novel control method for automatic steering of TSHDs subject to various disturbances and limitations. The solution involved trajectory planning, speed assignment and steering control which is applicable for underactuated ships. The results of simulation experiments manifested accurate trajectory tracking and reduced thrust. The reduced thrust implies reduced fuel consumption; this benefit is mostly due to the fact that the novel control method allows for a better distribution of required speeds.

This M.Sc. assignment was defined as a collaborative project between IMOTEC B. V. and University of Twente.

The thesis is reported as two papers which are written in IEEE format. The first paper entitled “Towards Automatic Steering of Underactuated Ships” has richer scientific and technical content and is ready for publication. “Reducing Fuel Consumption for Trailing Suction Hopper Dredgers” is an application paper where the automatic steering control developed in first paper is employed to answer the research question of this M.Sc. assignment.
Towards Automatic Steering of Underactuated Ships

Hengameh Noshahri

Abstract—Simple control solutions for steering underactuated ships have been seldom studied in literature. This paper provides a control method for automatic steering of underactuated ships in presence of disturbances and in uncertain environmental conditions. A mathematical model of ship dynamics is developed and validated. Our control method involves introduction of a preparation phase consisting of three algorithms. Waypoints leading to every desired set-point are defined and a continuous Dubins path is generated between these waypoints. A second-order motion profile is assigned to the path to suggest the speed with the best timing for the voyage. The control objective is reformulated from a tracking problem to a regulating problem by changing coordinates of the reference signal. PD-controllers are employed in closed loop to reduce position and heading error. The controller parameters are set in the design phase and do not need additional tuning for different trajectories and ship parameters. Weather information together with the planned motion profile are used in a feedforward controller design to achieve better disturbance rejection and higher accuracy. Performance and robustness of the design are evaluated in simulation by Course-keeping and Course-changing experiments in extreme and uncertain environmental conditions. While the developed control method is simple compared to the methods in literature, it can still achieve quite satisfactory steering performance.

Keywords—Automatic steering, Control design, Mathematical model, Trajectory planning

I. INTRODUCTION

Commanding the rudder, propulsion system, and any other device on board of the ship to reach a specified position, is known as ship steering control. Automatic steering systems have been developed over the course of time to satisfy various purposes. A comprehensive overview of marine vessel’s control systems is provided in [1]. The concept of automatic ship control dates back to the 19th century and it was first realized by fully mechanical autopilot designs. Later, by development of control theory and electronics, closed-loop control systems such as PID-controllers were introduced to correct the rudder angle. Problems associated with tuning of these controllers have led to using methods like pole placement, Linear Quadratic (LQ), Fuzzy, and Genetic Algorithms [2].

In a model-based ship-control approach, it is customary to consider a simplified version of ship dynamics. Single-Input-Single-Output (SISO) transfer function models, such as the Nomoto model [3], facilitate the use of linear control methods. These techniques can only command one variable, which is usually the rudder angle, to control the ship heading. Increased functionality of ship maneuvering however, requires more sophisticated control.

Non-linear Multi-Input-Multi-Output (MIMO) control methods provide high performance features, but they need full measurements or observer systems to operate. State feedback linearization, sliding mode, backstepping, and Lyapunovs direct control are among these methods. A survey on non-linear ship control can be found in [4]. These methods can generally be characterized as complex; the underlying mathematics require a significant amount of skills and expertise.

A system is called fully actuated if it has one or more control inputs for each Degree of Freedom (DOF). A fully actuated ship with three-dimensional configuration space comprised of forward, sideways, and heading would require actuators capable of exerting forces and moments independently to steer the vessel to any point with any desired heading [5].

In most cases, ships are equipped with single or twin propellers and rudders, which provide longitudinal force and moment, respectively. This implies that there is no direct control action available in lateral direction and the moment can not be generated without having speed in longitudinal direction. According to this explanation, most ships are underactuated mechanisms.

As pointed out above, remarkable solutions for steering control have been suggested in literature, but these solutions are usually developed for fully-actuated ships. The control problem of underactuated ships is still an open research area. Reference [6] indicates that the application of classical motion control systems on underactuated ships cannot satisfy performance requirements. However, this work asserts that steering control of the ship is still possible provided that the control objective is well defined.

This paper will provide a method for steering control of underactuated ships exposed to environmental disturbances using trajectory planning, speed assignment and linear control techniques.

The next section will be dedicated to modelling ship kinematics and dynamics for simulation and testing purposes. The procedure will be based on the work of Fossen as presented in [5]. The developed model will be validated by running simulation experiments. Section III will introduce three new algorithms which remedy the control action by defining feasible control objectives for underactuated ships. The control solution will consist of simple feedback and feedforward controllers that are tuned based on a simplified version of the developed model. Efficiency of the presented control method will be tested by running two common sea trials in marine technology. Results will be presented and discussed in Section IV.

II. MODELLING

A. Kinematics

A marine craft can be considered as a rigid body in a three-dimensional space with translational and rotational motion in six DOF. We position the origin of a Body Fixed Frame (BFF) at the Central Point (CP) of the ship. The axes of this coordinate system are denoted by \( x_b \), \( y_b \), and \( z_b \). \( x_b \) axis is
velocities in surge and sway directions respectively, and \( r \) and \( \psi \) are depicted in Fig. 1. 东-南-下坐标系可以使用。这两个坐标系统可以被看作是在低速船舶在局部区域操作时。因此，一个静止观察者的视角。在本研究中，我们关注操纵。三种轴分别称为姿态、俯仰和偏航。并且围绕三个轴的旋转运动在三个方向是相同的。}

In addition to the body fixed coordinates, an Inertial Frame (IF) is used to describe the kinematics of the ship from a stationary observer’s point of view. In this study, we focus on low speed ships which operate in local areas; therefore an earth-fixed-earth-centered reference frame with NED (North-East-Down) coordinates can be used. Both coordinate systems are depicted in Fig. 1.

Two vectors are defined to explain the motion of ship:

\[
\begin{align*}
\eta &= [x, y, \psi]^T \\
\nu &= [u, v, r]^T
\end{align*}
\]

where \((x, y)\) represents Cartesian position of CP defined in IF, and \( \psi \) is heading of the ship. \( u \) and \( v \) are body-fixed linear velocities in surge and sway directions respectively, and \( r \) is rate of turn. \( \eta \) is described relative to the IF, whereas \( \nu \) is expressed in the BFF.

The inertial-fixed velocity vector is mapped to the body-fixed velocity vector using Rotation Matrix \((R(\psi))\), which complies with the properties of Special Orthonormal Group (SO(3)).

\[
\dot{\eta} = R(\psi)\nu
\]

\[
R(\psi) = \begin{bmatrix} \cos \psi & -\sin \psi & 0 \\ \sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix}
\]

The motion of ship can be explained by Maneuvering theory, which assumes zero-frequency wave excitation [5]. This assumption is valid for a three DOF model comprised of surge, sway, and yaw modes, in which restoring hydrostatic forces are absent. Natural frequencies in these modes can be considered zero when compared to the high frequency motion in roll, pitch, and heave directions. The horizontal plane model can be perceived as a nonlinear mass-damper-spring system, where hydrodynamic forces can be linearly superimposed.

Six differential equations are needed for the three selected modes, which should be solved for six state variables. The states are composed of positions and velocities in three directions.

\[
\begin{align*}
x &= [\eta, \nu] = [x, y, \psi, u, v, r]^T \\
\dot{x} &= g(x, \tau, t)
\end{align*}
\]

\[
\tau = [\tau_X, \tau_Y, \tau_N]^T
\]

\[
\text{is defined as control input vector, which consists of forces in } x, y, \text{ directions and moment around } z_b \text{ axis, respectively; } t \text{ is time, and } g(\cdot) \text{ represents the state equations.}
\]

A Newton-Euler formulation for rigid-body kinetics suggests:

\[
m R_B \ddot{\nu} + C_R \nu = \tau
\]

where \( M_{RB} \) is rigid-body inertia matrix, \( C_{RB} \) is matrix of rigid-body Coriolis and centripetal forces, and \( \tau_{RB} = [X, Y, N]^T \) is vector of generalized external forces in BFF. A symmetric ship with respect to the traversal axis is assumed. This implies that the center of gravity is located at the distance \( x_g \) along the longitudinal axis. \( m \) denotes mass of the ship and \( I_z \) is moment of inertia about the \( z_b \) axis. Equation (6) can be expanded as:

\[
M_{RB} = \begin{bmatrix} m & 0 & 0 \\ 0 & m & m x_g \\ 0 & m x_g & I_z \end{bmatrix}
\]

\[
C_{RB}(\nu) = \begin{bmatrix} 0 & 0 & -m(x_g r + v) \\ 0 & 0 & m u \\ m(x_g r + v) & -m u & 0 \end{bmatrix}
\]

\[
\tau_{RB} = \tau_{\text{hyd}} + \tau_{\text{wave}} + \tau_{\text{wind}} + \tau
\]

The effect of waves and wind is captured as external disturbances in our model and hence are taken to be 0 in the model hereafter. Hydrodynamic forces, which depend on the relative velocity between ship and water current, have dominant influence on the ship dynamics. Non-vortex constant-speed water current \( V_c \) is assumed with angle \( \beta_c \) in the IF. Water current velocity vector \( v_c \) can be represented by:

\[
v_c = \begin{bmatrix} V_c \cos \beta_c \\ V_c \sin \beta_c \\ 0 \end{bmatrix}
\]
Equation (10) can be expressed in the BFF to derive the relative velocity vector.

\[ \nu_c = R(\psi)^T \nu_c \]  
\[ \nu_r = \nu - \nu_c = [u_r, v_r, r]^T \]  

Hydrodynamic forces can be defined as follows:

\[ \tau_{hyd} = -M_A \nu_r - C_A(\nu_r)\nu_r - D\nu_r - d(\nu_r) \]  

where \( M_A \) is the added mass matrix, \( C_A(\nu_r) \) accounts for added Coriolis and centripetal terms, and \( D \) and \( d(\nu_r) \) express linear and non-linear damping effects, respectively.

\[
M_A = \begin{pmatrix}
-X_\delta & 0 & 0 \\
0 & -Y_\delta & -Y_r \\
0 & -N_\delta & -N_r
\end{pmatrix}
\]

\[
C_A(\nu_r) = \begin{pmatrix}
0 & 0 & Y_\delta \dot{u} + Y_r \dot{r} \\
0 & 0 & -X_\delta \dot{u} \\
-Y_\delta \dot{u} - Y_r \dot{r} & X_\delta \dot{u} & 0
\end{pmatrix}
\]

\[
D = \begin{pmatrix}
-X_u & 0 & 0 \\
0 & -Y_u & -Y_r \\
0 & -N_u & -N_r
\end{pmatrix}
\]

\[ d(\nu_r) = \begin{pmatrix}
D_X \\
D_Y \\
D_N
\end{pmatrix} = \begin{pmatrix}
\frac{1}{2} \rho C_X A_{fc} |u_r| |u_r| \\
\frac{1}{2} \rho C_Y A_{lc} |v_r| |v_r| \\
\frac{1}{2} \rho C_N |r| |r|
\end{pmatrix}
\]

The terms used in (14) - (16) are constants called hydrodynamic derivatives, which are the partial derivatives of the forces in \( \tau_{RB} \) with respect to the velocity or acceleration in different directions, i.e.

\[ X_u = \frac{\partial X}{\partial u}, N_v = \frac{\partial N}{\partial v} \]

The nonlinear component of damping force has been modelled as cross flow drag forces, with drag coefficients \( (C_X, C_Y, \text{ and } C_N) \) as unknowns. These parameters can be obtained using experimental data. \( A_{fc} \) and \( A_{lc} \) are the area of wet surface of ship hull in the front and side, respectively. The equations of motion can be rewritten as:

\[ (M_{RB} + M_A) \ddot{\nu} + C_{RB}(\nu)\nu + (C_A(\nu_r) + D)\nu_r + d(\nu_r) = \tau \]  

Equation (18) contains of many parameters to be identified. Except for the mass and dimension related parameters, which can be calculated with rule of thumb relations, the rest should be estimated by doing experiments in towing tanks and employing on-line estimation methods. Running these experiments is very costly and usually not practical for commercial ships. Thus, the number of parameters are reduced by assuming low speeds and turning rates. Based on this assumption, the terms consisting of multiplication of \( \dot{u} \) and \( r \) with small gain are neglected. The simplified expressions for motion of the ship are obtained as follows:

\[ \begin{aligned}
\dot{\delta} &= \frac{1}{m + X_u} \left[ m(x_g r + v) r - D_X + \tau_X \right] \\
\dot{r} &= \frac{1}{m + Y_v} \left[ -m u + D_Y + \tau_Y - (m x_g + Y_r) r \right] \\
\dot{r} &= \frac{1}{m + Y_v} \left[ \frac{m x_g + Y_r}{m + Y_v} + I_\delta + N_r \right] \\
\end{aligned} \]

Equation (19) represents the relation between ship control inputs as forces and the accelerations. There is no direct command for lateral forces in an underactuated ship; therefore \( \tau_Y \) is set to 0. Longitudinal thrust \( \tau_X \) is generated by the ship propellers. In order to produce the desired moment \( \tau_N \), merely commanding the required rudder angle \( \delta_r \), will not change the heading of a stationary ship. In other words, the ship has to be in motion to be able to turn. The moment of ship can be modelled by multiplication of the rudder angle \( \delta_r \) and forward speed with a gain. This gain can be identified during sea trials. The rudder has limited speed and cannot respond to the commands immediately. The relation between rudder angle, ship speed, and resulting moment can be considered to be included in characteristics of the steering machine as represented in Fig. 2 [7].

### C. Model validation

The parameters required by (19) were set as given in Table I. We used the dimensions and parameters of a scale model with length of 1.255[m], which are presented in [8]. The drag coefficients have been calculated based on the ITTC 1957 method [9].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>2.3800</td>
<td>kg</td>
<td>I_\delta</td>
<td>1.7600</td>
<td>[kgm²]</td>
</tr>
<tr>
<td>X_u</td>
<td>2.0000</td>
<td>kg</td>
<td>Y_r</td>
<td>0.0000</td>
<td>[kgm]</td>
</tr>
<tr>
<td>Y_v</td>
<td>10.0000</td>
<td>kg</td>
<td>N_r</td>
<td>1.0000</td>
<td>[kgm²]</td>
</tr>
<tr>
<td>C_X</td>
<td>0.1000</td>
<td>[-]</td>
<td>C_Y</td>
<td>0.5560</td>
<td>[-]</td>
</tr>
<tr>
<td>C_N</td>
<td>0.0200</td>
<td>[-]</td>
<td>A_{fc}</td>
<td>0.0725</td>
<td>[m²]</td>
</tr>
<tr>
<td>A_{lc}</td>
<td>0.3137</td>
<td>[-]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A number of experiments can be conducted to check the validity of the developed model. Here, we present the results for the Turning circle experiment as part of the maneuvering
tests for ships in sea trials [9]. The experiment was done for the rudder angles of \( \delta = 2, 6, 10, 15, \) and 20 degrees. The test started with propelling the ship in a straight track in the calm water situation. As soon as the ship reached a constant speed (at \( t = 100[s] \)), the rudder was turned to the angle \( \delta \) and was kept at that position. The rudder command caused the ship to change heading and to start moving in a circle. Fig. 3 illustrates the position of the ship in IF. It can be observed in Fig. 4 that the forward speed drops when the ship starts to turn. Larger rudder angles imply a higher rate of turn, more speed loss, and smaller turning circles.

Therewith, it can be concluded that the developed model manifests results similar to the ones obtained by the Nomoto Model and the experimental data which are presented in [7].

### III. Control

In order to facilitate the control action and steering of the ship, three algorithms have been developed, namely, Waypoint generation, Arcs and lines segmented path generation, and Second-order motion profile planning. These algorithms define the control objective and together with feedback and feedforward controllers, they ensure that any maneuvering task can be fulfilled by the ship. In this new approach, the underactuation of the vessel will not hinder the steering performance anymore.

#### A. Waypoint generation

In practice, ships cannot reach any arbitrary position in workspace with a direct command. For instance, if the desired position is located within a long distance at the back or at the side of the ship, the solution is to take a turn and then head to the target. Achieving this performance only by inputting the final destination would demand complex control methods. We mediate the use of simple PD-controllers by generating waypoints from the starting position of the vessel towards the desired point. This decision will simplify the control action significantly.

In the developed algorithm, the workspace of the ship has been classified into three regions according to Fig. 5. Region 1 is close vicinity of the ship where it can be accurately positioned with low speed by use of bow and stern thrusters. This region can also be called full actuation area. Region 2 is within maximum turning angle of the ship and the vessel can reach any point in this region with no extra maneuvering. Region 3 is the directly inaccessible area, where the ship should perform extra maneuvers to arrive at a point. Note that in reality, the demarcation lines between Region 2 and Region 3 are curves based on the turning circle of ships; but here a simplified version is employed.

The algorithm starts with receiving information including location and heading of the ship, position of final point, and maximum turning angle. The final point is translated to the body fixed coordinate system and it is decided upon which region it belongs. If the final point is in Region 3, maximum turning will be recommended and the next waypoint will be set such that the target would gradually be placed in region one or two. In case the final point is in Region 2, ship heading will be corrected on demand. The distance between waypoints is set to two times the length of ship according to a convention in marine technology [5]. Generation of waypoints will be continued until the final point is reached.

The result of algorithm is illustrated in Fig. 6, where ship starts from \((x_s, y_s) = (10, 20)\) with heading of \(60[deg]\). The ship is supposed to arrive at point \((10, 10)\), which is initially in Region 3. Waypoints are generated to turn the ship and place the target in Region 2. Once the heading is corrected, the waypoints are continued until the commanded destination.
Fig. 5. Classification of workspace in BFF into regions; Region 1: full actuation, Region 2: Directly accessible, Region 3: Directly inaccessible

B. Arcs and lines segmented path generation

Direct introduction of the waypoints in discrete form to a controller will cause discontinuities and sudden changes in the heading, which are undesired. To avoid this problem, the reference signal should be smooth and continuous. We construct line and arc segments between the generated waypoints as Dubins path, which is the shortest path that connects between two points [10]. Fig. 7 presents the smooth path for generated waypoints extended from \((0, 0)\) to \((-10, 10)\). The dashed circles are used to generate the arcs.

C. Second-order motion profile planning

Steering a ship towards a desired path or position is done in an over-damped manner; because it is costly and sometimes unacceptable to have any overshoots in position. Adjustment of speed with correct timing is usually done manually and by relying on the experience of ship crew. One way to attain the same performance in an automatic steering system is to attribute this over-damped behaviour to the controller. However, this requires a complete knowledge of the system equations and parameters which is not possible in practice.

In order to keep the controller simple and to achieve the desired performance, the position reference is planned as a second-order motion profile. This method leads the ship to a target point with any desired speed. In addition, time is optimized to avoid the disadvantage of slow over-damped systems. The aforementioned features are added to the algorithm presented in [11], where motion planing for point-to-point and standstill to standstill profile has been done.

The motion profile consists of three phases of acceleration, constant velocity, and deceleration. The optimization problem can be formulated for three unknowns which are the duration of each phase. These timings should satisfy two requirements for the desired distance and the velocity subject to the constraint of total time of the task. The defined nonlinear multi-variable optimization problem is solved using “fmincon” function from MATLAB Optimization Toolbox.

Fig. 8 illustrates the planned motion profile for a 50\([m]\) voyage under 30\([s]\). Initial speed of the ship is 0.1\([m/s]\) and it is expected to arrive at final point with speed of 0.5\([m/s]\). The values for acceleration and deceleration are considered 0.6\([m/s^2]\) and \(-0.3[m/s^2]\), respectively. The vessel can reach to the maximum speed of 2\([m/s]\). The solution provides the best timing and satisfies all the requirements.

When combining this algorithm with two prior steps for reference signal generation, it is assumed that the speed at each waypoint has been determined manually and it is given as a requirement. The decision on speed of the ship is not planned automatically since it depends on many elements, e.g., sea traffic and ship stability.

Fig. 6. Waypoint generation algorithm results for scaled model. Starting state: \((x_s, y_s, \psi_s) = (10, 20, \pi/3)\), desired position: \((x_d, y_d) = (10, 10)\)

Fig. 7. Arcs and lines segmented path generation, starting state: \((x_s, y_s, \psi_s) = (0, 0, 0)\), desired position: \((x_d, y_d) = (-10, 10)\). The dashed circles are used to generate the arcs.
D. Feedback control

In the developed control method, we introduce the path to be tracked by the vessel in BFF. This choice transforms the tracking problem to a regulation control problem, where the aim is to reduce the distance to reference and the turning to zero. The transformation is done by two-dimensional orthonormal change of coordinates as follows:

\[ P^I = H_B^I P^B \rightarrow P^B = H_B^B P^I \]  

(20)

where \( I \) and \( B \) stand for IF and BFF, respectively, and \( P \) represents the general motion. \( H_B^I \) is a homogeneous matrix, which is defined as:

\[ H_B^I = \begin{pmatrix} R_B^I & O_B^I \end{pmatrix} \]  

(21)

\[ R_B^I = \begin{pmatrix} \cos \psi & -\sin \psi \\ \sin \psi & \cos \psi \end{pmatrix}, \quad O_B^I = \begin{pmatrix} x \\ y \end{pmatrix} \]  

(22)

The homogeneous matrix should be inverted to obtain the position of any arbitrary point in the BFF:

\[ H_B^B = (H_B^I)^{-1} = \begin{pmatrix} (R_B^I)^T & -(R_B^I)^T O_B^I \end{pmatrix} \]  

(23)

The control action is done by closing the feedback loop using three PD-controllers with low-pass filters for regulating three signals, namely, longitudinal error, lateral error, and error in the heading. The output of controller in the longitudinal case commands the main propeller’s thrust. The next two control signals are added to suggest the required rudder angle and the corresponding moment. For all controllers, the P and D parameters are tuned based on decoupled simplified models as single-masses so that the open-loop system would have crossover frequency about \( 1 [rad/s] \). The gains are set according to mechanical specifications to avoid saturation in controllers. Note that there is little need for increasing the type of the system by adding an I-element to this control design, since the constant errors are largely eliminated with a feedforward controller.

E. Feedforward control

The thrust generated by the main propulsion system can be divided into three forces; the force needed to achieve the desired acceleration, the force which overcomes the drag force acting on the ship hull, and the force required to compensate for the errors. The latter is generated by the feedback controller. We use the planned acceleration and speed together with weather information and ship parameters to generate an estimate for the first two forces in form of a feedforward controller. This decision provides higher positioning accuracy and better error handling. The following relations are used to calculate feedforward forces:

\[ FF_{acc} = (m + X_a)\ddot{a}^* \]  

(24)

\[ FF_{vel} = \frac{1}{2} \rho A_{fc} C_X |v_r^*|^2 v_r^* \]  

(25)

where the asterisks represent the planned variables. It can be seen that only four parameters from the ship specifications are used in the controllers, namely mass \( m \), virtual mass \( X_a \), front ship area \( A_{fc} \), and drag coefficient \( C_X \). The low number of model variables helps the robustness of the method. If there is uncertainty involved in the parameters, the feedback control should compensate for the differences in forces.

Fig. 9 shows block diagram presentation of the designed control structure. The reference position and heading signals in IF are obtained using the three introduced algorithms. The desired reference position signals in BFF \( x_{db} \) and \( y_{db} \) and heading error \( \psi_{error} \) are generated using feedback from system states. Acceleration and velocity signals are used in feedforward controller. The output of both feedback and feedforward controllers are added to form the command signals for ship’s thrust and moment. The Ship block in the figure contains the model presented in (19) and Fig. 2.

IV. Results

The performance of the developed control method was tested by conducting Course-keeping and Course-changing simulation experiments. Effects of large waves and wind were simulated as multiple frequency sine signals to resemble the forces slamming the ship hull as depicted in Fig. 10. In order to evaluate the robustness of design against uncertainties, 10% error was introduced for water current speed and heading data. The error induced by the mismatch between real weather data and the one used in calculations had to be compensated by feedback control signals. The speed adjustments were planned by the second-order motion profile algorithm in both cases.
A. Course-keeping

A straight trajectory was planned to be followed which consisted of the final point at 100[m] as the only waypoint. The ship was continuously exposed to extreme water current perpendicular to the planned voyage with a constant speed of 0.3[m/s] towards east. The ship started from stand-still position and it was planned to reach a forward speed of 1[m/s] at the end of path within 55[sec].

Fig. 11a shows reference path, voyage made by the ship and ship heading. It was observed that the heading (indicated by green arrows) was inclined towards the west. This helped the ship to overcome the lateral force while propelling the body forward. The result was maximum error of 0.5[m] in ye direction. As shown in Fig. 11b, the ship follows the planned motion profile to satisfy the forward speed requirements. Side speed and turning rate were influenced by water current and lateral waves and wind. Water current gave a bias to the side speed while the slamming waves sequence could be identified in the measured speed. The turning rate was higher at the beginning of the motion because of starting in stationery state. This observation implies the necessity of staying above minimum maneuverability speed to ensure full control over ship heading.

B. Course-changing

The aim of the second experiment was to test the ship heading in curved paths with presence of disturbances. The trajectory was planned using one middle waypoint at (50, 10) and the Arcs and lines segmented path generation algorithm. The second-order motion profile algorithm was used to ensure full speed at the given waypoint, best timing, and complete halting at the end of the path. The ship was exposed to head and side waves and water current with speed of 0.1[m/s] running towards south-east.
limited to the model used in the simulations could apply thrust and moment to the ship in both experiments. It was assumed that the scaled model could also handle side forces.

Side speed and turning rate were influenced by curvature of the path and also external side forces. Speed fluctuations in forward speed were caused by the heading waves. Speed was measured as shown in Fig. 12b. The fluctuations in forward speed were caused by the heading waves. Side speed and turning rate were influenced by curvature of the path and also external side forces.

Fig. 12a manifests the performance of the ship in this scenario; the path was followed with correct heading, and the environmental disturbances did not deviate the ship. Maximum lateral error was 0.7[m], which occurred during the course changing. Speed was measured as shown in Fig. 12b. The fluctuations in forward speed were caused by the heading waves. Speed was measured as shown in Fig. 12b. The fluctuations in forward speed were caused by the heading waves. Side speed and turning rate were influenced by curvature of the path and also external side forces.

Fig. 13 compares the resulting control signals for steering the ship in both experiments. It was assumed that the scaled model used in the simulations could apply thrust and moment limited to $[-5, 15][N]$ and $[-0.5, 0.5][Nm]$, respectively.

V. Conclusion

In this paper, we addressed the problem of steering underactuated ships subject to various disturbances. A model was developed based on the ship hydrodynamics. Validity of the model was shown by running Turning circle experiment. The contribution to the control problem was made from a novel perspective. First, the control objective was redefined to suit the limitations of an underactuated ship. This remedy involved generating waypoints and developing continuous trajectories to ensure that every point in workspace is accessible by the ship. Speed along the path was planned by a time-optimized second-order motion profile to accommodate the over-damped behaviour of ships. Our method was also able to satisfy the speed requirements upon arrival. We changed the tracking problem to a regulation problem in an innovative approach by defining the reference signals in Body Fixed Frame. This choice allowed the use of linear feedback controllers in the next stage. Simple PD-controllers were employed to compensate for the position and heading errors. Better accuracy and disturbance rejection was achieved by adding feedforward controllers based on weather data and motion profile. Our control method was tested during two simulation experiments by commanding the ship to follow trajectories in extreme environmental conditions. The tasks were done by engaging the introduced algorithms to compute the desired path, timing, and speed. There was no need for task-based fine-tuning of the PD-controllers and the same controller setting was used in both experiments. The robustness of control design was asserted by adding mismatch between the provided weather information and simulation conditions. All in all, the behaviour of the developed automatic steering control is quite satisfactory.

REFERENCES

APPENDIX A
WAYPOINT GENERATION ALGORITHM BLOCK DIAGRAM

Fig. 14, represents the graphical interpretation of the Waypoint generation algorithm, which has been explained in section III.

APPENDIX B
ARC AND LINES SEGMENTED PATH GENERATION
PROCEDURE

The algorithm starts with receiving waypoints and starting position of the vessel. The number of required segments is calculated and the lines between each two consecutive waypoints are found. Circles with defined radius are formed around each waypoint. This radius should be chosen according to the ship’s specifications. A small radius would result in sharper corner which might hinder the ship turning, whereas a bigger circle would generate a smoother path but larger deviation from waypoint. Next, the intersection points of the circles and the connecting lines are found. This results in two intersection points per each waypoint. The lines perpendicular to the connecting lines are found at these intersection points. The points where these perpendicular lines meet, are centers of the circles which form the arc segments. At this point, all the arc and line segments are defined. Next step is to form a continuous path with these arcs and lines. Starting from the given position of the ship, the algorithm moves towards the next waypoint until the final point is reached. Whenever a waypoint is met the algorithm toggles between line and arc segments.

The output of this algorithm is the position of the points on the path in IF, which are close enough to resemble a continuous path.

APPENDIX C
SECOND-ORDER MOTION PROFILE GENERATION

The second-order motion consists of three phases: acceleration, constant velocity and deceleration. The maximum velocity and rate of change of speed while accelerating and decelerating are calculated according to the ship dynamics. The kinematics of voyage can be written as following:

\[ \begin{align*}
\text{Phase 1} : & \quad \begin{cases} 
    x_1 = \frac{1}{2}a_1 t_1^2 + v_{s1} t_1 + x_{s1} \\
    v_1 = a_1 t_1 + v_{s1} \\
    a_1 = a
\end{cases} \\
\text{Phase 2} : & \quad \begin{cases} 
    x_2 = v_{s2} t_2 + x_{s2} \\
    v_2 = a_1 t_2 + v_{s2} \\
    a_2 = 0
\end{cases} \\
\text{Phase 3} : & \quad \begin{cases} 
    x_3 = \frac{1}{2}a_3 t_3^2 + v_{s3} t_3 + x_{s3} \\
    v_3 = a_3 t_3 + v_{s3} \quad a_3 = a
\end{cases}
\end{align*} \]

with three unknowns, two equations and one constraint can be formulated:

\[
\Delta x = \frac{1}{2}a_1 t_1^2 + v_{s1} t_1 + a_1 t_1 t_2 + v_{s1} t_2 + \frac{1}{2}a_3 t_3^2 + a_1 t_1 t_3 + v_{s1} t_3 \\
\Delta v = a_1 t_1 + a_3 t_3 \\
t_1 + t_2 + t_3 < t_l
\]

which \( \Delta x = x_e - x_{s1} \) and \( \Delta v = v_e - v_{s1} \) are defined. After simplifying the expressions the final optimization problem should be solved to obtain the time period for each frame:

\[
\begin{align*}
\Delta x &= \frac{1}{2}a(t_1^2 - t_3^2) + v_{s1}(t_1 + t_2 + t_3) + a t_1(t_2 + t_3) \\
\Delta v &= a(t_1 - t_3) \\
t_1 + t_2 + t_3 &< t_l
\end{align*}
\]

APPENDIX D
PD-CONTROLLER TUNING

The PD-controllers were designed in the frequency domain by using bode plot of the open-loop system. For this purpose, the plant was assumed to be decoupled and it was considered as a single mass in every mode. The relations between the control inputs and the state variables in (19) can be obtained as following:

\[
\begin{align*}
\dot{u} &= \frac{1}{m + X_\dot{u}} X \\
\dot{v} &= -\frac{(m x_y - Y_r)}{m + Y_v} N + \frac{1}{m + Y_v} I_x + N_r \\
\dot{r} &= -\frac{(m x_y - Y_r)^2}{m + Y_v} + I_x + N_r
\end{align*}
\]

We write the Laplace transformation of (29) and substitute parameters from Table I. In the following equations, \( X(s) \), \( Y(s) \), and \( \Psi(s) \) denote Laplace transformation of \( x, y, \) and \( \psi \), respectively; whereas, \( F(s) \) and \( N(s) \) are Laplace transformations of forward thrust, \( X \) and moment, \( N \).

\[
\begin{align*}
X(s) &= \frac{1}{25.8s^2} F(s) \\
Y(s) &= -\frac{1}{84.11535s^2} N(s) \\
\Psi(s) &= \frac{1}{2.7245s^2} N(s)
\end{align*}
\]

Equation (29) is comparable to transfer function:

\[
G(s) = \frac{X(s)}{F(s)} = \frac{1}{ms^2}
\]

Bode plots for the three presented transfer functions are presented in Fig. 15 - 17. Low frequency behaviour of ship model can be observed according to the cross-over frequencies, which are less than \( 1[\text{rad/s}] \) for all modes.

Following transfer function represents the relation for PD-controller with low-pass filter (lead compensator):

\[
G(s) = \frac{X(s)}{F(s)} = \frac{1}{ms^2}
\]
Fig. 14. Waypoint generation algorithm,*n.w.p: next way point

Fig. 15. Bode plot, transfer function $G(s)$ and controller with transfer function $G(s)C(s)$ in $x$ mode

Fig. 16. Bode plot, transfer function $G(s)$ and controller with transfer function $G(s)C(s)$ in $y$ mode

We define:

$$C(s) = P + \frac{Ds}{\frac{N}{N} + 1}$$  \hspace{1cm} (31)
Equation (31) can be written as:

\[ C(s) = K \frac{\alpha Ts + 1}{\tau s + 1} \] (32)

In all three cases the cut-off frequencies were chosen around 1 [rad/s] to resemble the low frequency behaviour of ships. Phase margins were selected big enough to ensure system stability, while keeping the bandwidth small enough to reject any high frequency signal. After calculating the controller parameters in frequency domain, simulations were done using the ship model. In some cases, the gains were reduced to comply with mechanical considerations and to avoid saturation in the actuators. However, by trying different values it was observed that the discrepancy from the selected value did not cause large errors. Bode plots of the open-loop systems consisting of the transfer functions and controllers are illustrated in Fig. 15 - 17.

It is important to note that the same controllers were used for Course-keeping and Course-changing experiments in section IV. It can be concluded that as long as the controller parameters provide low cross-over frequency and low gain, the response is not sensitive to model specifications and external disturbances.

Fig. 18 and 19 present output signals of the designed feedback and feedforward controllers in Course-keeping and Course-changing tests, respectively. In these figures, two situations are compared: 1. there is a mismatch according to Table II between weather data used in feedforward calculations and simulation environment. 2. correct weather data is used. Measured positions in two situations are illustrated in Fig. 20 and 21. It can be observed that there is no considerable difference in the followed path, which implies correct action of PD-controllers.
TABLE II. INFLUENCE OF ERRONEOUS WEATHER DATA

<table>
<thead>
<tr>
<th>Water current</th>
<th>Real values</th>
<th>Values in calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed [m/s]</td>
<td>Heading [deg]</td>
<td>Speed [m/s]</td>
</tr>
<tr>
<td>Course-keeping</td>
<td>0.3</td>
<td>90</td>
</tr>
<tr>
<td>Course-changing</td>
<td>0.1</td>
<td>145</td>
</tr>
</tbody>
</table>

![Image of Fig. 20. Course-keeping experiment, measured position](image)

![Image of Fig. 21. Course-changing experiment, measured position](image)
Reducing Fuel Consumption for Trailing Suction Hopper Dredgers

Hengameh Noshahri

Abstract—This work is motivated by recent restricting regulations on carbon footprint and fuel consumption of marine vessels. Reducing fuel consumption during sailing trips of Trailing Suction Hopper Dredgers (TSHD) is addressed. Utilizing an automatic ship steering control which features speed assignment based on a second-order motion profile is presented as primary solution. This method is applicable for sailing trips in all operating conditions and can contribute in fuel saving by preventing deviations from the planned course. Three cases are defined to study the influence of ship speed, water current, and sailing trajectory and results are compared between customary operation decisions and our suggested method. Comparison is made based on accumulated propelling thrust which represents fuel consumption. Simulation experiments are done using parameters of a scaled ship model. Numerical comparisons reflect achieving notable fuel saving percentages using our method. The results question the fuel efficiency of common practice in sailing, which is characterized by propelling with maximum speed and on a straight line without taking detailed maritime forecasts into account. This study necessitates better distribution of speed along voyages and considering environmental forces in project timing and path planning of dredging trips.

Keywords—Automatic ship steering, Fuel consumption, Trailing suction hopper dredgers

I. INTRODUCTION

Recent alarming environmental concerns have urged the international authorities to define regulations to limit the carbon footprint of marine vessels. Energy efficiency measures have been formulated and updated during recent years. The main objective of standards such as Energy Efficiency Design Index (EEDI), is to determine how much CO₂ is released for conducting a special task of displacing goods over a distance [1].

In order to comply with the defined standards, research has been done to optimize the design of the ships. Solutions involve optimizing hull form, improving the propulsion system, and use of alternative fuels, to name a few [2]. In addition, algorithms have been developed for ships in service; namely, trim adjustment, fuel consumption monitoring, heading correction, speed recommendation, and weather routing [2]–[6]. Optimization studies in literature mainly focus on ocean-going vessels with long voyages, e.g., container ships and oil tankers. Since service ships share some features with transoceanic vessels, some of the developed solutions can be applied to dredging ships as well.

According to the definition of the European Dredging Association (EuDA), dredging is the maritime transportation of natural materials from one part of the water environment to another by specialised dredging vessels [7]. The most widely used dredging ship in civil projects, which is the focus of this study, is called Trailing Suction Hopper Dredger (TSHD).

TSHDs are self-propelled vessels which contain large tanks for transferring sand or slurry. They work in consecutive cycles with four phases: 1. sailing empty to the loading area, 2. filling the hopper, 3. sailing full to the discharge area, 4. unloading the material [8] (See Fig. 1).

To the knowledge of the author, no fuel-reduction methods have been investigated for in-service dredgers in literature. Studies about optimizing dredging operations mainly focus on solutions for newly built ships. The design phase considerations include installing high efficiency dredge pumps and drag heads. In addition, assisting systems have been developed to suggest settings for dredging equipment. The goal of these adjustments is to improve the production rate of projects by increasing the amount of loaded sand in shorter time [9].

The aim of this study is to develop a method to reduce the accumulated propelling thrust and consequently fuel consumption during the two sailing phases of TSHD’s working cycle. An automatic ship steering method will be employed, which consists of a second-order motion profile planning, to ensure accurate trajectory tracking in presence of disturbances and extreme weather conditions [10]. This method can reduce fuel consumption by preventing deviations from the sailing trajectory.

It is customary for TSHDs to sail with maximum speed and on the shortest path between loading and unloading areas, regardless of water and weather conditions. This strategy is believed to be the most profitable way of operating TSHDs. Since it is not common for dredging trips to be planned based on detailed weather data and maritime forecasts, a trip will start once the sea condition does not threaten the operation.
In order to evaluate the influence of this strategy on fuel consumption, three application cases will be defined where the effect of speed, water current, and path planning will be studied. Fuel consumption is proportional to thrust by means of Thrust Specific Fuel Consumption (TSFC), which is defined for each type of engine [11]. In this work, accumulated thrust represents fuel consumption and is defined as performance indicator. In each application case, the performance indicator will be compared between the conventional operation decision and our suggested method. The results will be reported for simulation experiments based on parameters of a scaled ship model with a length of 1.255[m].

II. METHODOLOGY

TSHDs are mainly equipped with single or twin propellers. The heading of the ship is changed by adjusting the rudder angle. This implies that there are two control commands available to steer the ship in three degrees of freedom; namely, northing, easting, and heading. Therefore, TSHDs can be considered as underactuated systems during sailing phases, where the bow and stern thrusters are not operated.

Reference [10] presents a horizontal-plane three Degrees of Freedom (DOF) mathematical model to describe the kinematics and dynamics of an underactuated ship. The assumptions of low speed and low turning rate, which are made in this modelling, are well applicable for TSHDs. The developed model with given parameters as in [10] is employed for simulation purposes in this study.

The steering method together with the control assisting algorithms which are provided in [10], ensure reliable trajectory tracking by the ship. The ability of accurate course keeping and course changing contributes significantly in fuel savings, especially when the ship faces extreme weather conditions. Any deviation from the planned path would result in additional distance and time, and consequently more fuel consumption. Therefore, our primary solution, which is applicable in every voyage, is to employ automatic steering of TSHDs.

There are items during sailing trips which cannot be controlled; namely, ship design parameters such as engine capacity and maximum speed, and environmental conditions such as water current. Moreover, time limit of dredging task and loading and unloading areas are fixed and defined by project description. Sailing time, sailing path, and speed should be selected by the crew to satisfy the given requirements. Our fuel saving strategy involves selecting the three aforementioned controllable parameters based on enforced conditions in favor of demanded thrust. This strategy requires knowledge about the weather forecast and project planning.

Since fuel consumption can be modelled with a third-power relation between ship speed and power, any reduction in speed will have a large influence on the amount of saved fuel [12]. The speed reduction however, implies more trip duration, which is usually not favorable for projects. The automatic steering control utilized in our method features speed assignment based on a second-order motion profile, which consists of acceleration, constant speed, and deceleration phases [10]. One of the advantages of the employed algorithm is its flexibility; the voyage can be planned before the sailing trip, so that the speed can be adjusted according to the available time and desired fuel savings. In case of stringent time limits, the constant-speed phase of the motion profile will be closer to the full speed. If idle times can be identified in the whole dredging process, more sailing time can be allowed by accurate time planning so that the algorithm will provide a better speed distribution in favor of reducing fuel consumption.

The effect of head and following current in voyages is studied to determine the amount of possible fuel saving. A TSHD trip is desired to start whenever there is a following current along the planned sailing trip. Moreover, in most water ways, such as The North sea, water current changes direction every few hours due to tide. TSHD trips usually consist of going back and forth between loading and unloading areas; therefore, project timing can be planned to sail the TSHD in following sea more often.

It is possible in some dredging projects that the loading and unloading areas are located in extended geographical positions. In this situation, the sailing trajectory can be planned according to the water current to result in the least fuel consumption.

The efficiency of our general solution and these case based methods is evaluated in the next section. Note that in this study the selected speed, sailing duration, and path are not optimal since they are not resulted from solving an optimization problem. Reducing fuel consumption for TSHDs can be considered as an optimisation problem where ship speed, sailing path, and sailing time should be selected such that the cost function which is defined as demanded fuel, is minimised. The optimization problem should be solved subject to the boundaries which are defined as loading and unloading areas, restrictions on water way, project duration, and ship specifications such as maximum speed.

III. RESULTS AND DISCUSSION

A. General solution: Automatic steering of TSHD

The automatic steering method which is utilized in this paper consists of waypoint generation, continuous path planning and second-order motion profile generation [10]. In order to test the performance of the control method, an arbitrary path and environment was defined. The ship was positioned initially at (0, 0) (Northing [m], Easting [m]), heading towards the north. Three waypoints were planned at: (30, 10), (70, -15), and (110, 10) to test ship’s ability in course keeping and course changing.

A smooth and continuous path was planned between these points. The TSHD was expected to arrive and stop at the final point in 70 seconds. No speed requirement was considered for the waypoints and the speed was assigned to the path by the second-order motion profile generation algorithm to satisfy the time, distance, and speed requirements. The environmental conditions consisted of a water current with speed of 0.3[m/s] and with an angle of 60[deg] flowing towards North-West. The side and front of the ship hull were continuously exposed to sinusoidal waves with different frequencies and magnitudes.

Fig. 2 illustrates the waypoints, reference trajectory, ship position, and ship heading. Maximum error in Northing and Easting directions were observed to be 1.17[m] and 1.32[m]
respectively. Moreover, the speed requirement, which was complete halting at the end of the trajectory, was satisfied. These observations prove efficient disturbance rejection and accurate trajectory following.

Results and advantages of the employed automatic steering method are discussed in more details in [10].

B. Case 1: Influence of speed in straight path

Two experiments were conducted for sailing on a straight path with length of 100 [m] in the same environmental conditions where no water current and waves were present. Complete halting of TSHD was demanded at the final point. Automatic steering control was used to assign sailing speed and to steer the TSHD in both experiments. Accumulated thrust was recorded for comparison.

The conventional full speed sailing was employed in the first experiment. In order to realize this behaviour, a strict time limit of 57 [sec] was given to the second-order motion profile generation algorithm. This was the shortest time duration that could be possible with full speed of 2 [m/s] in the constant-speed phase. More sailing time was given for the second experiment. Speed was assigned by the algorithm with time limit of 67 [sec] which led to lower speed values throughout the voyage.

Fig. 3 compares the covered distance over time for both methods. According to Fig. 4 and Fig. 5 where measured speed and thrust are illustrated, respectively, the TSHD was sailing with full speed in the first experiment by using maximum capacity of thrust which was set to 15 [N]. In the last few seconds the ship decelerated and stopped as it reached to the final point. In the time-flexible voyage however, thrust was lowered once TSHD reached to the planned constant-phase speed of 1.63 [m/s]. Although in the second experiment the ship was sailing for longer time, lower accumulated thrust was demanded compared to the full-speed experiment.

Table I compares the values for the average and accumulated thrust. The results show 15.77% lower accumulated thrust in time-flexible experiment. This number can be converted to a fuel saving percentage based on the engine specifications of the TSHD.

<table>
<thead>
<tr>
<th></th>
<th>Time [s]</th>
<th>Average thrust [N]</th>
<th>Accumulated thrust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full-speed</td>
<td>57</td>
<td>13.0687</td>
<td>745.049</td>
</tr>
<tr>
<td>Time-flexible</td>
<td>67</td>
<td>9.3653</td>
<td>627.5682</td>
</tr>
</tbody>
</table>

Fig. 3. Case 1: Influence of speed, Full speed vs. Time-flexible sailing, Position

Fig. 4. Case 1: Influence of speed, Full speed vs. Time-flexible sailing, Speed
C. Case 2: Influence of water current in straight path

The influence of water current on fuel consumption in a straight path was examined. Three situations were put into test, where: 1. No current, 2. 0.1 [m/s] following current, 3. 0.1 [m/s] head current was present. The speeds were assigned according to a second-order motion profile. In order to have a better evaluation over thrust, voyage time was equal to 59 [s] for all three tests. As seen in Fig. 6, the distance covered by TSHD in each test was almost the same. This also implies rather same constant speed during the voyage, which is shown in Fig. 7. The propelling thrust for all three tests is depicted in Fig. 8. Progressing with the assigned speed when head current was present required more forward thrust; it can be observed that in order to overcome the induced resistance, the TSHD was running with maximum capacity of thrust. The thrust was reduced in the following sea, to prevent exceeding the planned speed.

Table II represents numerical comparison of the average and overall thrusts. The comparison implies achieving a remarkable fuel saving percentage when sailing in following sea condition. The results of this experiment indicate the importance of considering maritime forecasts in project planning.

D. Case 3: Influence of path in presence of water current

It is customary to steer TSHDs on the shortest path between loading and unloading areas. In this experiment we study the effect of path planning on fuel consumption in the case of loading or discharging materials in extended areas. The destination area was considered at 100 [m] north of the ship’s starting position (See Fig. 9). Extreme sea conditions were simulated where the water current was flowing with a speed of 0.3 [m/s] towards the east. Three paths were compared with respect to thrust; namely: 1. Straight path, 2. Inclined path with heading of 10 [deg], 3. Inclined path with heading of 20 [deg]. The time limits of all cases were set equal to 70 [s] and speed along the paths was assigned based on a second-order motion profile.

It was predicted that an inclined path would demand less forward thrust since part of the required propelling force could be supplied by water flow in the inclined case. However, a more inclined path implies a longer voyage and since the sailing time is fixed, a longer distance demands a higher speed and thrust. Therefore, the amount of deviation from the straight path should be chosen according to this trade-off. This argument can be clarified in our experiment.

Fig. 9 shows the position and heading of the TSHD in each case. The start and end position of the paths were selected different for better visualisation of the results. It can be observed that when the straight path was followed, ship heading was inclined towards west to provide a counteracting force against the flowing water current which leads to fuel
TABLE II.  CASE 2: NO CURRENT VS. HEAD CURRENT VS. FOLLOWING CURRENT, NUMERICAL COMPARISON

<table>
<thead>
<tr>
<th></th>
<th>Average thrust [N]</th>
<th>Accumulated thrust [N]</th>
<th>Thrust reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>No current</td>
<td>12.2959</td>
<td>724.599</td>
<td>7.78%</td>
</tr>
<tr>
<td>Following current</td>
<td>11.1477</td>
<td>656.9332</td>
<td>16.38%</td>
</tr>
<tr>
<td>Head current</td>
<td>13.3314</td>
<td>785.6189</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 8. Case 2: No current vs. Following current vs. Head current, Thrust

TABLE III. CASE 3: STRAIGHT VS. INCLINED PATH, NUMERICAL COMPARISON

<table>
<thead>
<tr>
<th></th>
<th>Average thrust [N]</th>
<th>Accumulated thrust [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight path</td>
<td>8.7266</td>
<td>610.9526</td>
</tr>
<tr>
<td>Inclined path 10[deg]</td>
<td>8.4337</td>
<td>590.4427</td>
</tr>
<tr>
<td>Inclined path 20[deg]</td>
<td>8.6531</td>
<td>605.8022</td>
</tr>
</tbody>
</table>

Fig. 9. Case 3: Straight vs. Inclined path, Ship position and heading

Fig. 10. Case 3: Straight vs. Inclined path, Speed

dissipation. When following the second path, the TSHD had almost straight heading. This heading was favorable for fuel consumption since the generated thrust was mainly used for propelling the ship north; in addition, the water current dragged the TSHD to east and roughly no extra fuel was consumed to move the ship in this direction. The ship heading in the more inclined path was tilted towards east. Once again, this indicated fuel dissipation for supplying motion in lateral direction which was not desired.

Corresponding velocities are illustrated in Fig. 10 where the ship speed is higher in the more inclined path to compensate for the longer voyage. According to Fig. 11, this higher speed does not demand noticeable higher thrust than the straight path since the TSHD is partly accelerated by the water flow. Numerical results are presented in Table III. The inclined path with 10[deg] heading results in about 3% less accumulated thrust compared to the straight path.

While the paths were selected manually in this experiment, an optimization algorithm can be used to suggest the best heading in different sailing distances and environmental conditions.

IV. CONCLUSION

Methods of reducing fuel consumption during sailing trips of Trailing Suction Hopper Dredgers were studied in response to the recent regulations on carbon footprint of marine vessels. Since any deviation from the planned course results in more fuel consumption and project duration, an automatic steering control method was presented as our principal solution for all voyages. The results manifested accurate trajectory tracking and disturbance rejection. Accumulated propelling thrust was
considered as performance indicator since it is proportional to fuel consumption. Three application scenarios were defined to study the effect of sailing speed, water current, and sailing path on thrust. The conventional sailing strategy, which is sailing with full speed and on a straight path regardless of water current information, was challenged in these application cases. Simulation experiments were conducted based on a scaled ship model with a length of 1.255[m]. First, thrust was compared between a full speed voyage and a sailing trip with more time duration; 15.77% reduced thrust in the latter case suggests that in order to save fuel, the TSHD speed should be reduced whenever time requirements of project allows. Next, it was shown that presence of merely 0.1[m/s] following current demands 9.34% and 16.38% less thrust compared to heading current and no current situations, respectively. Finally, the importance of path planning was highlighted by comparing the thrust between a straight path and inclined paths when water current perpendicular to the voyage was present.

All in all, this study reveals the significance of employing accurate steering control of TSHDs and reconsidering full speed sailing trips in favor of fuel consumption. Moreover, results indicate the importance of time and path planning based on maritime forecasts which consist of water current information.

The future work may consist of developing an optimization algorithm to select the sailing speed, sailing path, and project timing based on ship characteristics, environmental conditions, and project requirements to reduce fuel consumption. The model parameters used for optimization can be replaced with measured values of Trailing Suction Hopper Dredgers and engine model can be added to the design in order to suggest accurate amount of fuel consumption.

REFERENCES


