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LOS guidance for towing an iceberg along a straight-line path

Andreas Orsten[1], Petter Norgren[1,2], and Roger Skjetne[1,2]
[1] *Dept. Marine Technology, Norwegian Univ. of Science and Technology (NTNU).*
[2] *SFI Sustainable Arctic Marine and Coastal Technology (SAMCoT), NTNU.*
andreasorsten@gmail.com, Petter.Norgren@ntnu.no, Roger.Skjetne@ntnu.no

Motivated by the need to develop a reliable and safe way of towing icebergs, this paper investigates the use of a feedback-based guidance algorithm for steering the iceberg along a pre-defined safe track.

A simplified, linear iceberg model is developed in 2 degrees of freedom (DOF) to capture the horizontal motion, including the effect of constant and irrotational ocean currents.

Previously, a Line-of-Sight (LOS) algorithm has been implemented for steering a ship along a pre-defined path. The algorithm has been modified to include the effect of an ocean current, using integral action. In this paper, the current-modified LOS algorithm is augmented in order to apply it to the 2-DOF horizontal iceberg model. The output of the iceberg LOS algorithm is the desired towline angle α_{LOS}. Guidance of the model is achieved through a tow force T with direction α that should conform to α_{LOS}.

Simulation studies, showing the performance of the LOS algorithm, are performed in the presence of both a constant, and a slowly-varying ocean current. A towing vessel reference model is proposed in order to obtain a better resemblance between the change of the towline angle and the movements of the towing vessel.

The simulation studies all show that the iceberg trajectories converge to and move along the desired path, and that the vessel reference model provides feasible trajectories for the towing vessel.

1. Introduction

As oil and gas exploration moves further north, the problem of icebergs threatening stationary installations must be taken into account. This becomes relevant when considering installations, for example in the Barents Sea. Dealing with the risk of icebergs in offshore operations is called *Iceberg Management*.

Much experience on iceberg management is obtained in the Grand Banks area, out of Newfoundland, Canada, where there have been offshore installations in the area since 1997 (McClintock et al., 2007). Further research including model tests, numerical simulations and field experiments in the Barents sea has been performed (Eik, 2010; Marchenko and Eik, 2011). Iceberg management is roughly divided into:

1. Iceberg detection and tracking: Detecting and tracking icebergs that may instigate a threat.
2. Threat assessment: Forecasting iceberg drift pattern and deciding whether the iceberg is a threat to the installation.
3. Iceberg handling: If an iceberg is assessed as a threat, then alleviate the threat by performing some physical action on it.

There is also *iceberg risk management* (McClintock et al., 2007), but this is not within the scope of this paper.

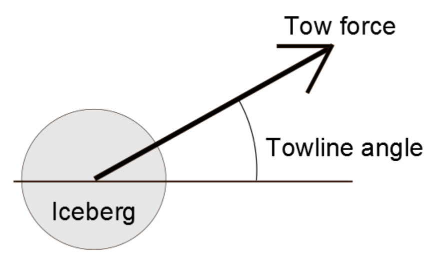


Figure 1. A model of the simplified iceberg-towline system.

Iceberg handling in the Grand Banks area has been performed in many ways, but the most frequently used is *single vessel rope tow* (Rudkin et al., 2005). When towing an iceberg, the main target is changing its trajectory away from the installation, and ensuring it does not threaten the installation after the tow. In the Grand Banks, this has been performed manually, where according to McClintock et al. (2007, p.18), smaller icebergs are usually town away. For larger icebergs, on the other hand, the objective of towing is mainly to deflect the iceberg heading a few degrees from its naturally preferred route.

As with other towing operations, one must avoid towline rupture. In addition, icebergs may be unstable, smooth-surfaced and slippery. Due to this, iceberg overturning and towline slippage are important limitations to iceberg towing (McClintock et al., 2002).

Instead of manually maneuvering the vessel performing the tow, automatic maneuvering could be used. Normally, when maneuvering a ship, the target is to make the ship follow a certain path. In this paper, however, we consider the problem of making the iceberg follow a certain path. With an iceberg steering algorithm in place, one could eventually implement ways to reduce the risk of towline rupture, towline slippage, and iceberg overturning by more intelligent control of the towing force. Better performance with respect to these challenges would make the towing operation safer and more reliable.

The objective of this paper is to steer an iceberg along a straight-line path, using a Line-of-Sight (LOS) algorithm. This is done in a simplified system, only considering the iceberg actuated by the towline (Figure 1). The towline has a force and a direction. By setting the tow force as constant and only controlling the towline angle, this paper investigates the feasibility of using the LOS method to steer the iceberg to and along a specified path.

The traditional LOS method for ships calculates the ship's desired yaw angle (Fossen et al., 2003), and uses this to converge to and move along a path. When towing icebergs, you must instead change the angle of the tow force by properly locating the towing vessel.

In addition, the iceberg may be affected by environmental loads, which for a traditional ship is implemented into the LOS method (Børhaug et al., 2008). In this paper we augment the implementation to include current in the iceberg towline model to robustly compensate the current forces.

2. Iceberg model

Consider the class of marine surface vessels described by the 3-DOF model (Fossen, 2011):

$$\dot{\eta} = R(\psi)\nu \tag{1}$$

$$M_{RB}\dot{\nu} + C_{RB}(\nu)\nu = -M_A\dot{\nu}_r - C_A(\nu_r)\nu_r - D\nu_r + \tau \tag{2}$$

Assumption 1 *In order to develop an iceberg model of sufficient fidelity for a model-based guidance (or control) design, some simplifying assumptions are made as follows:*

1. *The iceberg is approximately cylinder-shaped.*
2. *The symmetric, cylinder-shaped iceberg has no correlated damping or added mass between yaw and surge/sway. This is a fair assumption for a cylindrical shape.*
3. *The symmetric, cylinder-shaped iceberg can be towed in every direction, regardless of the iceberg yaw angle. This is also a fair assumption for a cylindrical iceberg.*
4. *The tow force is assumed to act directly through the centres of gravity (CoG) and buoyancy (CoB) of the iceberg. This is fair for a stable iceberg with small roll/pitch motions. In reality roll and pitch motion would move CoG or CoB away from the tow force, causing yaw rotation. However, due to Assumption 1.3, this is ignored.*
5. *The Coriolis effect and nonlinear damping terms are disregarded, due to low velocities.*
6. *The ocean current ν_c is assumed constant and irrotational, meaning that $\dot{\nu}_c = 0$.*

Thus, the simplified iceberg model is a linear, 2-DOF model, disregarding the rotational matrix:

$$\dot{\eta} = \nu \tag{3}$$

$$\nu_r = \nu - \nu_c \tag{4}$$

$$(M_{RB} + M_A)\dot{\nu} - M_A\dot{\nu}_c + D\nu_r = \tau, \tag{5}$$

where $\eta = [x, y]^\top$ and $\nu = [u, v]^\top$ describe the iceberg position and velocity in Cartesian coordinates, M_{RB}, M_A and D are the rigid body mass-, added mass-, and linear damping matrices, respectively, and ν_r is the relative velocity between iceberg velocity (ν) and current velocity $\nu_c = [u_c, v_c]^\top$.

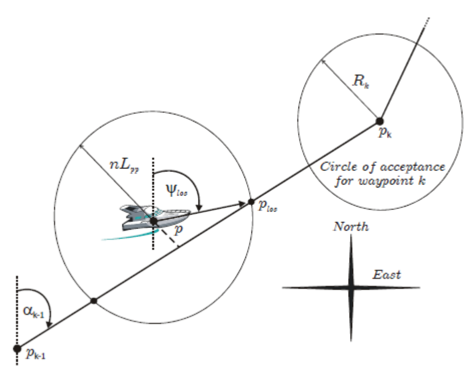


Figure 2. An interpretation of the desired path in a Cartesian coordinate system, courtesy of Fossen et al. (2003).

3. Line-of-Sight guidance

3.1. Traditional LOS guidance

LOS guidance has been used to solve the geometric task of the maneuvering problem (Skjetne et al., 2011). Fossen et al. (2003) has described the LOS angle in Cartesian coordinates, as seen in Figure 2. Børhaug et al. (2008), on the other hand, described the LOS angle in a waypoint-path fixed coordinate system. As the iceberg model described in Equation (5) is in Cartesian coordinates, this paper will continue with Cartesian coordinates. The LOS angle for a ship is then described as:

$$\psi_{LOS} = atan2(y_{LOS} - y, x_{LOS} - x) \tag{6}$$

The use of *atan2*, as opposed to $arctan$, ensures that the LOS angle is placed in the correct quadrant and within the set $(-\pi, \pi]$.

The procedure for waypoint path-following, and the equations to obtain the LOS angle ψ_{LOS} are found in Fossen et al. (2003). Breivik (2003, pp.33-35) presented a way to solve these equations and obtain the projected point $p_{LOS} = [x_{LOS}, y_{LOS}]^\top$.

3.2. LOS algorithm with constant ocean current

The traditional LOS algorithm does not take into account environmental forces, such as ocean currents. Børhaug et al. (2008) suggested a guidance law, in the waypoint-path fixed coordinate system, using integral action, and obtained the current-modified LOS angle. To avoid confusion with yaw motion, this paper will replace ψ^m_{LOS} with an iceberg towline angle, α_{LOS}:

$$\alpha_{LOS} \triangleq -\arctan(\frac{y' + \sigma y'_{int}}{\Delta}), \Delta > 0 \tag{7}$$

$$\dot{y}'_{int} = \frac{\Delta y'}{(y' + \sigma y'_{int})^2 + \Delta^2} \tag{8}$$

In order to apply it to the iceberg model, it must be transformed into Cartesian coordinates. Using the notation from Figure 3, the following relationships hold:

$$a = \sqrt{(x(t) - x_{k-1})^2 + (y(t) - y_{k-1})^2} \tag{9}$$

$$b = \sqrt{(x_{LOS} - x(t))^2 + (y_{LOS} - y(t))^2} \tag{10}$$

$$c = \sqrt{(x_{LOS} - x_{k-1})^2 + (y_{LOS} - y_{k-1})^2} \tag{11}$$

$$x' = \frac{a^2 + c^2 - b^2}{2c} \tag{12}$$

$$y' = \pm\sqrt{a^2 - (x')^2} \tag{13}$$

$$\Delta = c - x' \tag{14}$$

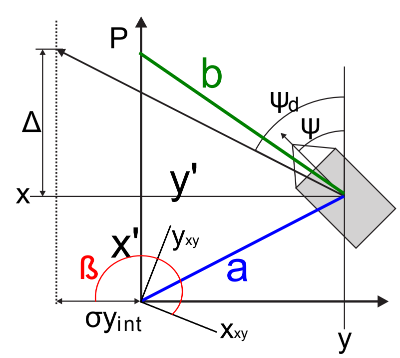


Figure 3. Notation for transforming between Path-fixed and Cartesian coordinates. Original illustration is found in Børhaug et al. (2008).

If the path lies on the iceberg's port side, y' is positive. Otherwise, y' is negative. When having obtained all these values, $\dot{y}_{int}$ is obtained and can be integrated. The integrated value y_{int} must then be transformed into Cartesian coordinates:

$$\beta = atan2(y_k - y_{k-1}, x_k - x_{k-1}) + \frac{\pi}{2} \tag{15}$$

$$y_{int,x} = y_{int} \cos(\beta) \tag{16}$$

$$y_{int,y} = y_{int} \sin(\beta) \tag{17}$$

The index k denotes the selected waypoint. β is perpendicular to the angle between the Cartesian and the waypoint-path fixed coordinate system. Then, finally the Cartesian LOS angle can be calculated:

$$\Delta y_{LOS} = y_{LOS} - y \quad [18]$$

$$\Delta x_{LOS} = x_{LOS} - x \quad [19]$$

$$\alpha^{xy}_{LOS} = atan2(\Delta y_{LOS} + \sigma y_{int,y}, \Delta x_{LOS} + \sigma y_{int,x}) \quad [20]$$

4. Iceberg guidance law

The main objective of this paper is to demonstrate the LOS method. For the purpose of testing the LOS method, a direct feed of the desired towline angle is used.

The model (Figure 1) consists of a tow force (T) which is held constant, and a towline angle (α), which is set equal to the calculated towline angle from the LOS algorithm:

$$T = T_0 \quad [21]$$

$$\alpha = \alpha^{xy}_{LOS} \quad [22]$$

Simple trigonometry then suggests the following desired towing force:

$$\tau = \begin{bmatrix} \tau_x \\ \tau_y \end{bmatrix} = \begin{bmatrix} T_0 \cos(\alpha^{xy}_{LOS}) \\ T_0 \sin(\alpha^{xy}_{LOS}) \end{bmatrix} \quad [23]$$

It is imperative that the towing force amplitude T_0 overcomes the environmental loads on the iceberg, such that a positive forward speed over ground is attained.

5. Simulation studies

The proposed LOS algorithm was tested using *MatLab*™ and *Simulink*™. The simulated iceberg was chosen as a *small berg* (McClintock et al., 2007) with the following dimensions:

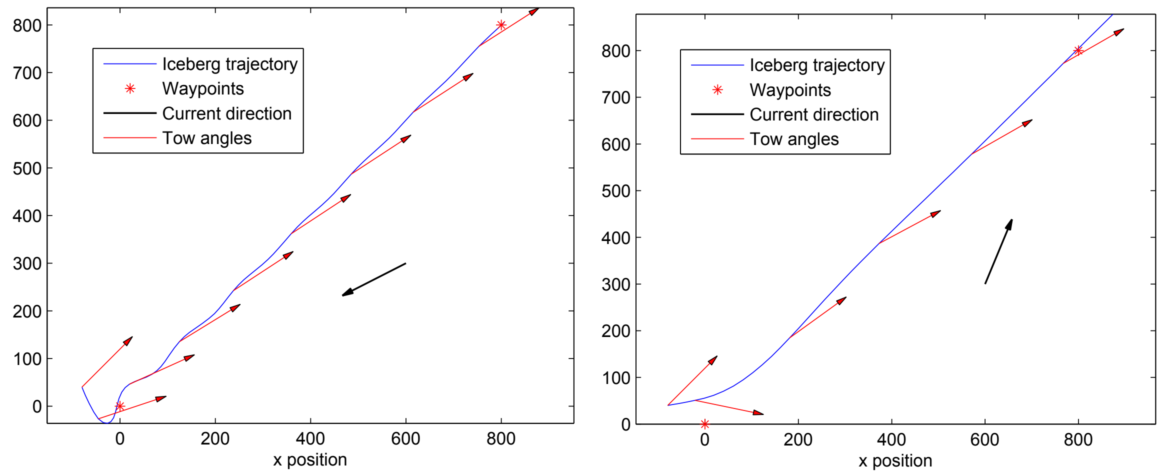
- Diameter/Length/Width: 25 m
- Height above waterline: 5 m
- Draught: 42.7465 m
- Water-iceberg form drag coefficient: $C_{wi} = 0.75$ (Robe, 1980)
- Mass: 2.1487×10^7 kg ($\rho_i = 916.7$ kg/m^3)

The maximum near-surface current in both Newfoundland and the Barents sea is $1.3\frac{m}{s}$. (ISO 19906, 2010, pp.342-408) In order to overcome the current velocity, the constant tow force was chosen to be $T_0 = 5 \times 10^6$. The integral gain used was $\sigma = 0.3$.

5.1. Constant current

The algorithm was simulated with a constant ocean current of $1.3\frac{m}{s}$, in 2 different directions. To create a straight-line path, the following waypoints were used:

$$WP = \begin{bmatrix} i & x & y \\ 1 & 0 & 0 \\ 2 & 800 & 800 \end{bmatrix} \quad [24]$$



(a) $\beta = \frac{9\pi}{10} rad, T = 1900s$ **(b)** $\beta = \frac{\pi}{8} rad, T = 450s$

Figure 4. Plotted Simulink results for a current with a β relative angle to the waypoint path. Simulation ran for T seconds.

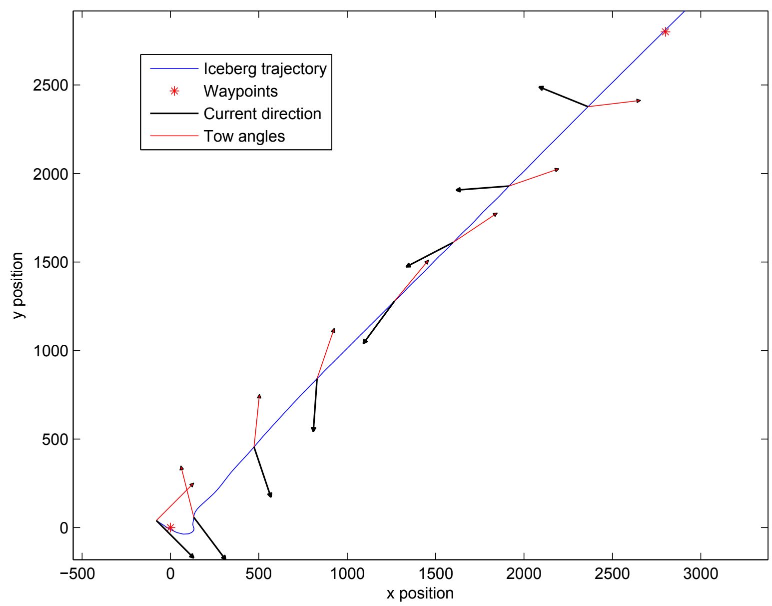


Figure 5. Plotted Simulink results for a current rotating from $-\pi$ to π relative angle to the waypoint path.

5.2. Slowly-varying current

The algorithm was tested in a scenario where the ocean current with an intensity of $1.3\frac{m}{s}$ changes direction from $-\pi$ to π relative to the straight-line path during $T = 5000s$, as seen in Figure 5.

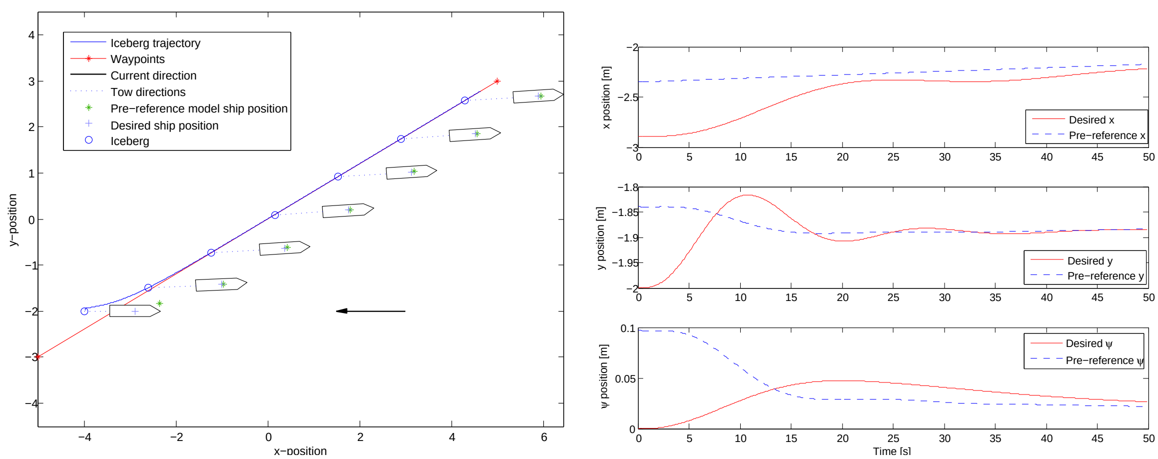
5.3. Towline with towing vessel dynamics

The main practical issue with the LOS algorithm is that the towline angle can not be changed without restriction. It must follow the dynamics of a towing vessel. The simulation setup has followed these few steps:

1. The current-modified LOS angle is calculated.

2. The desired towing vessel position is calculated. This position is placed in the direction of the LOS angle, α^{xy}_{LOS}, and distance of the towline away from the iceberg.
3. The desired LOS-based position is then entered into a reference model for the towing vessel. The output of the reference model is a more realistic and feasible desired vessel position. The reference model is created to simulate the towing vessel's dynamics and provides smooth changes of the desired position.
4. The angle between the new, more realistic desired vessel position and the iceberg is then used as the desired towline angle, and fed into the controller as in the previous simulations.

In order to make a reference model work, data from the model vessel C/S Enterprise 1 at the Norwegian University of Science and Technology was used (Tran, 2014). The simulated iceberg is thus a model scaled, cylindrical iceberg with a diameter of $20cm$ and draught of $79.18cm$.



(a) $T = 2500s$ **(b)** $T = 50s$

Figure 6. (6a) Iceberg path following in a constant current, with towing vessel positions following vessel dynamics. (6b) Plots showing LOS ship position (pre-referenced) versus position obtained after the reference model (desired), during the initiation phase of the path following.

6. Conclusion

In this paper we have shown how we can tow an iceberg along a straight-line path by applying a Line-of-Sight-based algorithm to determine the towline direction, robustly in the presence of ocean currents.

The results seen in Figure 4 show that the algorithm makes the iceberg converge to the desired path when exposed to a constant ocean current, and the towline direction changed slowly enough to be feasible to determine the position of the towing vessel. Figure 5 shows that the iceberg also converges when exposed to a slowly varying ocean current. Similar scenarios in other waypoint directions were also tested, and worked satisfactorily.

As seen from Figure 6 it is possible to make the iceberg converge to the desired path, even when the tow angle is influenced by towing vessel dynamics. As seen in Figure 6b the initiation phase is important in order to obtain a stable tow angle. To avoid large oscillations during initiation, the LOS integral action σ value must be set sufficiently low.

In order to apply the LOS algorithm in real cases, it must be extended to include a towing vessel controller and towing vessel model, following the ideas of Section 5.3. Furthermore, with the algorithm working in a real case scenario, measures could be included in controlling the iceberg to avoid towline slippage, towline rupture and iceberg overturning. This would ensure safer and more reliable iceberg towing operations.

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