Towing with sailboat robots

Luc Jaulin and Fabrice Le Bars

Abstract Moving huge objects floating at the surface of the ocean (such as containers or icebergs) with boats requires many human operators and a lot of energy. This is mainly due to the fact that when humans operate such equipment, time is costly. Now, when we have time (as when robots operate, for instance), it is possible to move arbitrarily large objects, for over long distances, with a limited quantity of energy. This is a consequence of the fact that in the water, the friction forces are proportional to the square of the speed (i.e., when we go slowly, we have almost no friction). This paper proposes the use of a sailboat robot to tow large objects. It shows which control law could be used is order to *(i)* avoid loops inside the towing cable, *(ii)* avoid collisions between the robot and the towed object, and *(iii)* move the object toward the desired direction. The control law is validated on a simulation where the object to be towed has to follow a trajectory corresponding to a large circle.

1 Introduction

From an operational point of view, sailboat robots (see e.g. [20] [19] [5] [1] [4]) can be viewed as floating objects moving toward some desired waypoints and taking the energy for propulsion from its environment. A sailboat robot has to be small (otherwise it may become dangerous) and therefore cannot be used for transportation. These vessels can be used as sensors to collect measurements [22] [8], [18] for scientific surveys [15] [25] or as relays for communication [24]. They can even be used

---

Luc Jaulin
Lab-STICC/CID/IHSEV, STIC/OSM, ENSTA Bretagne, 2 Rue F. Verny, 29806 Brest, France, e-mail: `Luc.Jaulin@ensta-bretagne.fr`

Fabrice Le Bars
Lab-STICC/CID/IHSEV, STIC/OSM, ENSTA Bretagne, 2 Rue F. Verny, 29806 Brest, France, e-mail: `Fabrice.Le_Bars@ensta-bretagne.fr`

as a windmill in order to produce the required energy [14]. However, the application field remains limited and it is important to find some other domains where sailboat robots can become useful.

This paper proposes the use of sailboat robots to tow a large object (named the *load*). For such a heavy load (more than 10 times the weight of the sailboat) floating at the surface of the ocean, the trajectory is mainly governed by the wind and the currents. Now, towing the load with a sailboat will have a small impact against the wind and currents. Thus, the main propulsion of the load will be governed by the current and the sailboat can be used to influence the direction of the load perpendicular to the current. In this way, the sailboat acts as a train switch, able to move the load from one current path to another. The use of the sailboat we can expect is to move the load from one point to another taking advantage of the currents. A zero effort path has first to be found using techniques from optimal control theory and the sailboat will play the role of a regulator controlling the load around the reference trajectory. The technique is similar to the strategy used to send a space explorer outside the solar system. To achieve the goal, two subproblems need be solved (1) control the motion of the load using the sailboat, neglecting the forces generated by the currents to the load (2) finding a route consistent with the currents to bring the load to the target.

This paper investigates subproblem (1), *i.e.*, assumes that the influence of the currents/wind on the load is negligible. The paper proposes a simple and robust controller which is able to move the load from one point to another. The main difficulty for the sailboat is taking into account the wind for its own propulsion, pulling the load towards the right direction, and maintaining the towing cable straight.

The paper is organized as follows. Section 2 proposes a state space model which includes the sailboat, the load and the interaction between both. Section 3 describes the controller which tunes the rudder angle and the length of the mainsheet in order to accomplish the mission. A test-case is presented in Section 4. In this test-case, the sailboat is controlled in order to tow the load on a circular path. Section 5 concludes the paper.

2 State space model

Consider the sailboat represented in Figure 1 with one rudder and one sail. The sailboat has to tow a load using a cable which is attached both to the boat and to the load, as illustrated by Figure 2.

The model of the system including the sailboat and the load is given by the following state space equations.

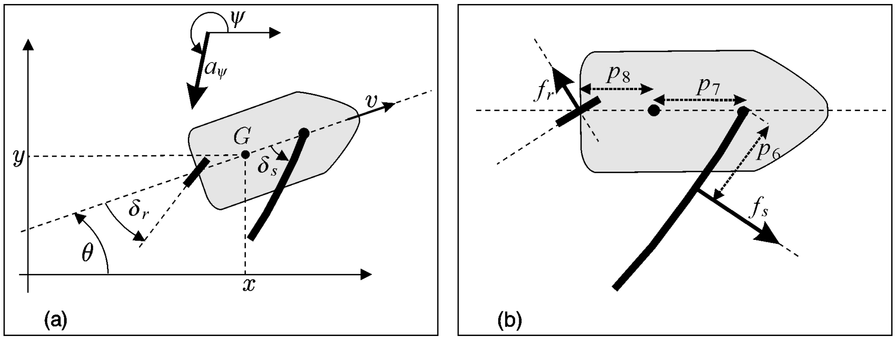

Fig. 1 Sailboat that has to tow an object.

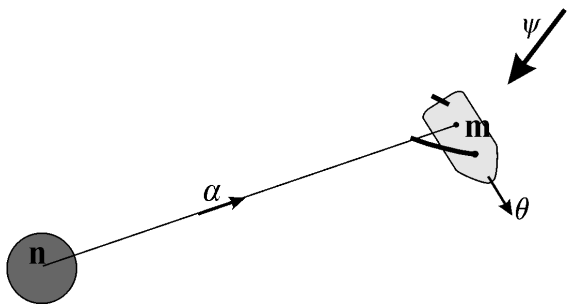

Fig. 2 The sailboat robot has to tow an heavy load. The angle α (here represented in a vector form) corresponds to the direction of the cable.

$$\left\{\begin{array}{llcl}
\text{(i)} & \dot{\mathbf{m}} & = & v.\mathbf{u}_\theta + p_1 a_\psi \mathbf{u}_\psi - f_c \mathbf{u}_\alpha \\
\text{(ii)} & \dot{\theta} & = & \omega \\
\text{(iii)} & \dot{v} & = & \frac{f_s \sin\delta_s - f_r \sin u_1 - p_2 v.|v| - f_c \cos(\alpha-\theta)}{p_9} \\
\text{(iv)} & \dot{\omega} & = & \frac{f_s(p_6 - p_7\cos\delta_s) - p_8 f_r \cos u_1 - p_3 \omega v}{p_{10}} \\
\text{(v)} & \dot{\mathbf{s}} & = & \frac{f_c.\mathbf{u}_\alpha - p_{12}.\|\mathbf{s}\|.\mathbf{s}}{p_{11}} \\
\text{(vi)} & \dot{\mathbf{n}} & = & \mathbf{s}
\end{array}\right. \tag{1}$$

where the link variables are given by

$$\begin{cases} (a)\ \mathbf{w}^{\mathrm{ap}} = & \begin{pmatrix} a_\psi \cos(\psi-\theta) - v \\ a_\psi \sin(\psi-\theta) \end{pmatrix} \\ (b)\ \psi^{\mathrm{ap}} = & \mathrm{atan2}(\mathbf{w}^{\mathrm{ap}}) \\ (c)\ \gamma_{\mathrm{s}} = & \cos\psi^{\mathrm{ap}} + \cos u_2 \\ (d)\ \delta_s = & \begin{cases} \pi + \psi^{\mathrm{ap}} & \text{if } \gamma_{\mathrm{s}} \le 0 \\ -u_2\ \mathrm{sign}(\sin\psi^{\mathrm{ap}}) & \text{otherwise} \end{cases} \\ (e)\ f_s = & p_4 \|\mathbf{w}^{\mathrm{ap}}\| \sin(\delta_s - \psi^{\mathrm{ap}}) \quad \text{(force on the sail)} \\ (f)\ f_r = & p_5 v \sin u_1 \quad \text{(force on the rudder)} \\ (g)\ f_c = & \exp(\|\mathbf{m}-\mathbf{n}\| - L_0) \quad \text{(force on the cable)} \\ (h)\ \alpha = & \mathrm{atan2}(\mathbf{m}-\mathbf{n}) \end{cases}$$

This model is close to the models developed in [11] and [14] except that it incorporates the load (object to be towed). The following describes all variables involved in this model.

Inputs. The sailboat has two inputs. The first input $u_1 = \delta_r$ is the angle between the rudder and the sailboat. The second input u_2 corresponds to the length of the mainsheet. More precisely, u_2 corresponds to the absolute value of the maximal angle δ_s that could reach the sail when the mainsheet is tight.

State variables. The state variables occurring in the proposed model (1) are $\mathbf{m}, \theta, v, \omega, \mathbf{s}, \mathbf{n}$ where $\mathbf{m} = (m_x, m_y)$ are coordinates of the robot, θ is its heading, v is its speed along the main axis, ω is its angular speed. The state variables associated with the load should also be included, i.e., the position $\mathbf{n} = (n_x, n_y)$ and the speed $\mathbf{s} = (s_x, s_y)$ of the load.

Parameters. In the model, p_1 is the drift coefficient, p_2 is the tangential friction, p_3 is the angular friction, p_4 is the sail lift, p_5 is the rudder lift, p_9 is the mass of the boat and p_{10} is the mass moment of inertia. The distances p_6, p_7, p_8 are represented in Figure 1. Also add the mass of the load p_{11}, the friction coefficient p_{12}. All parameters p_i are assumed to be known exactly. Two other quantities should also be considered as parameters: the speed a_ψ of the wind and its direction ψ. All quantities are expressed using the international unit system.

Link variables. These variables are used to shorten the expression of the state equations. *(a)* The vector $\mathbf{w}^{\mathrm{ap}}$ corresponds to the apparent wind expressed in the robot frame. *(b)* The angle of $\mathbf{w}^{\mathrm{ap}}$ (in the robot frame) is denoted by ψ^{ap}. *(c)* The coefficient γ_{s} is positive if the mainsheet is tight. *(d)* When the mainsheet is not tight, the angle of the sail δ_s, is equal to $\pi + \psi^{\mathrm{ap}}$ and it behaves as a flag. Otherwise, the angle corresponds to $\pm u_2$. *(e)* f_s represents the force of the wind on the sail, *(f)* f_r is the force of the water on the rudder. *(g)* The force on the cable is obtained from the expression of the potential energy of an elastic cable: $E_p = \exp(\|\mathbf{m}-\mathbf{n}\| - L_0)$, where L_0 is the nominal length of the cable. *(h)* α is the angle of the cable which is assumed to be straight.

State equations. The first equation *(i)* of (1) expresses that the boat follows its heading $\mathbf{u}_\theta$, where $\mathbf{u}_\theta = (\cos\theta, \sin\theta)^{\mathrm{T}}$, but always loses some advance with respect to the wind $a_\psi \mathbf{u}_\psi$ (where $\mathbf{u}_\psi = (\cos\psi, \sin\psi)^{\mathrm{T}}$ is the direction vector of the wind and a_ψ is the speed of the wind). The motion of the boat is also influenced by the cable through the term $f_c \mathbf{u}_\alpha$ where $\mathbf{u}_\alpha = (\cos\alpha, \sin\alpha)^{\mathrm{T}}$. Equations *(iii)* and *(iv)* are obtained using the Newton laws applied to the boat. Equation *(v)* corresponds to the Newton law applied to the load.

Note that this model for the sailboat could be made more realistic by adapting the modeling tools described by Fossen in the context of marine vessel [6] to sailboats (see [28]). To the authors' best knowledge a model with a sailboat towing a load has never been proposed before.

3 Controller

There exist different approaches to control sailboat systems [10] [27] [9] [3] [7] [2] [16] [26]. This section proposes a pragmatic approach (as in [12] [17]) to have a simple controller for the towing sailboat, with few parameters and easy to debug. The system to be controlled is composed of two subsystems: the load and the sailboat. The sailboat can be interpreted as a complex actuator which is able to generate forces that will influence the motion of the load. To find the controller we decompose into six steps described as follows. **(a)** Since the load is typically a second order system moving on a plane, we first propose a basic proportional control to move it toward the desired direction. **(b)** The proportional control is adapted to make the load move with respect to a desired vector field. **(c)** We introduce a new concept of segment for a sailboat which consists of an arc where the robot can move maintaining the cable taut. **(d)** Unfeasible segments are projected to get the nearest feasible segment. **(e)** The heading of the boat is oriented in order to pull the cable as much as possible. **(f)** Control the rudder and the sail in order to have the right heading. Once all these six steps are described, we propose a controller implementation.

(a) Moving the load with a proportional control. Consider a load moving at the surface of the water. Assume that the load can be pull with respect to the direction α^* A proportional like control pulls toward the desired direction α_0, but also corrects by pulling proportionally to the heading error. More precisely, the proportional control is given by

$$\alpha^* = \alpha_0 + \sin\left(\alpha_0 - \text{atan2}(\dot{\mathbf{n}})\right). \tag{2}$$

Here $\alpha_0 - \text{atan2}(\dot{\mathbf{n}})$ represents the heading error of the load and the sine function eliminates the 2π discontinuities. Note that, for this application, it is the sailboat which pulls. It has its own dynamics and cannot pull toward arbitrary direction at anytime.

(b) Vector field. The desired dynamics for the load is described by a vector field [21] [23]. Classically, a vector field is a function from $\mathbb{R}^n$ to $\mathbb{R}^n$ (since the load moves in the plane, $n = 2$). This vector field associates with a position (n_x, n_y) of the load, the vector (speed and direction) to be followed. Now, in a sailboat context, the amplitude of the vector has no meaning: we do not want to control our speed to a given value. Instead, the boat has to do its best to go to the right direction and to go as fast as possible. As a consequence, a vector field will be a function from $\mathbb{R}^2$ to $[-\pi, \pi]$. It associates to a position $\mathbf{n}$ of the load, the direction α_0 to be followed. The corresponding vector is $(\cos\alpha_0,\ \sin\alpha_0)$. The proportional control (2) can be used to make the load going in the direction α_0. Again here, we do not consider that the load is towed by a sailboat and that all directions for α^* are not possible.

(c) Feasible segment. We now consider that the load is towed by a sailboat. Assume that the cable is long and that the speed of the load is small with respect to the speed of the boat. To maintain the cable taut, the boat has to move in a circle of radius L_0 centered in $\mathbf{n}$ (see Figure 3). Define a *segment* as an arc of this circle with an half angle ζ_0. A segment is identified by its middle angle $\bar{\alpha}$ as shown by Figure 3. A segment is feasible if the two directions (direct and indirect) along this arc are feasible. A segment with angle $\bar{\alpha}$ is thus feasible if

$$|\sin(\bar{\alpha}-\psi)| \leq \cos(\zeta+\zeta_0),$$

where ζ is the close hauled angle of the sailboat (typically $\zeta = \frac{\pi}{4}$). When the boat decides to follow a segment, it has to scan this segment back and forth. A Boolean state variable $\varepsilon \in \{-1,1\}$ has thus to be introduced so that the controller knows in which direction it is scanning the selected segment. When $\varepsilon = 1$ the segment is scanned in the direct trigonometric sense. The value for ε is allowed to change only once the boat has reached the border of the segment, *i.e.*, when $\cos(\bar{\alpha}-\alpha) < \cos\zeta_0$. In such a case, ε takes the value 1 if $\sin(\bar{\alpha}-\alpha) > 0$ and -1 otherwise.

(d) Projection. Recall that the projection $\bar{x}$ of a point x onto a subset $\mathbb{X}$ of a metric space corresponds to one point of $\mathbb{X}$ which minimizes its distance to x. A point x may have several projections. Now, for simplicity, we assume that projection is unique.

Proposition. Given a set of angles $\mathbb{B} = \{\beta \text{ such that } \cos|\beta| > \cos\beta_0\}$ where $\beta_0 \in \left[0, \frac{\pi}{2}\right]$, the projection $\bar{\alpha}$ of an angle α onto $\mathbb{B}$ (*i.e.*, the closest angle in $\mathbb{B}$ to α) is obtained using the following analytical expression

$$\bar{\alpha} = \text{atan2}\left(\min\left(|\sin\alpha|, \sin\beta_0\right).\text{sign}\left(\sin\alpha\right), \max\left(|\cos\alpha|, \cos\beta_0\right).\text{sign}\left(\cos\alpha\right)\right), \tag{3}$$

where atan2(y,x) returns the horizontal angle of the vector $(x,\ y)^{\mathrm{T}}$.

Proof. The projection $\bar{y}$ of a real y onto an interval $[-b,b]$ is $\bar{y} = \min(|y|, b)\cdot\text{sign}(y)$. The projection $\bar{x}$ of a real x onto the complementary of the interval $[-a,a]$ is $\bar{x} = \max(|x|, a)\cdot\text{sign}(x)$. To obtain formula (3), it suffices to project $\sin\alpha$ onto $[-\sin\beta_0, \sin\beta_0]$ and $\cos\alpha$ on the set $[-1, -\cos\beta_0] \cup [\cos\beta_0, 1]$. The corresponding angle (obtained using *atan2*) is the projection. ■

Figure 4 gives an illustration of the projection onto the set $\{\beta \text{ such that } \cos|\beta| > \cos\beta_0\}$.

For $\beta = 0.5$, the graph of the projection function (3) is given by Figure 5.

(e) The robot has to pull. If the segment $\bar{\alpha}$ is fixed, the robot now has to be controlled in order to follow its segment. At first glance, it could be thought that the robot has to follow the direction $\bar{\theta} = \alpha + \varepsilon\frac{\pi}{2}$. Now, for such a direction, the boat does not pull anything, as illustrated by Figure 6 (a),(c). To pull the load, the robot has to look at outside the circle as in Figure 6 (b),(d). The desired heading for the boat will thus be chosen as $\bar{\theta} = \alpha + \varepsilon$ instead of $\bar{\theta} = \alpha + \varepsilon\frac{\pi}{2}$.

(f) Heading control. To control the low level actuators (here the rudder and the length of the mainsheet), a heading controller similar to [13] is used. This heading

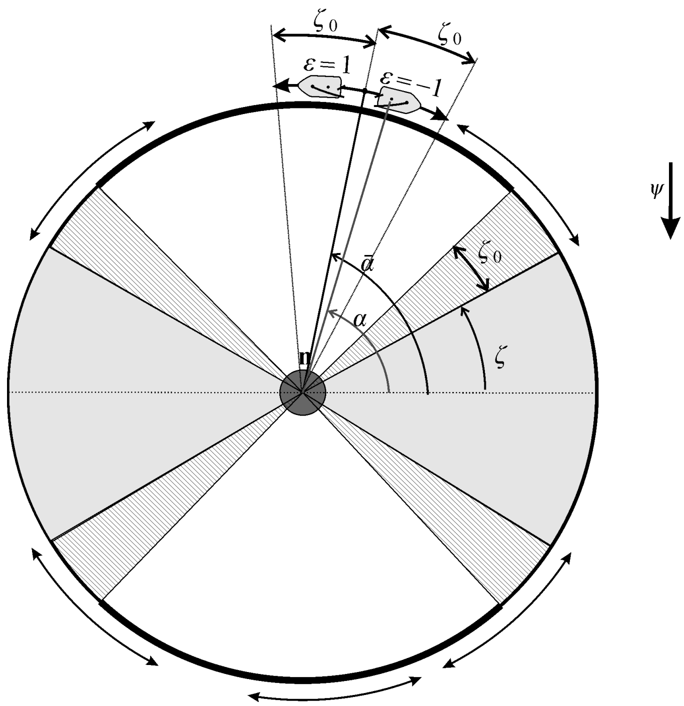

Fig. 3 Six segments are represented. Since none of them intersects the gray sectors, they are all feasible, *i.e.*, the boat can move back and forth, on each segment.

control is given by

$$u_1 = \begin{cases} \frac{\pi}{4}.\mathrm{sign}\left(\sin\left(\theta - \bar{\theta}\right)\right) & \text{if } (\cos\left(\theta - \bar{\theta}\right) \leq 0) \\ \frac{\pi}{4}.\sin\left(\theta - \bar{\theta}\right) & \text{otherwise} \end{cases}$$

$$u_2 = \frac{\pi}{2}.\left(\frac{\cos\left(\psi - \bar{\theta}\right) + 1}{2}\right).$$

Here, to avoid doing any loop, always tack with the cable on the back, *i.e.*,

$$u_1 = \begin{cases} \frac{\pi}{4}.\mathrm{sign}\left(\sin\left(\alpha - \bar{\theta}\right)\right) & \text{if } (\cos\left(\theta - \bar{\theta}\right) \leq 0) \text{ (tacking)} \\ \frac{\pi}{4}.\sin\left(\theta - \bar{\theta}\right) & \text{otherwise.} \end{cases}$$

Controller. The resulting controller is as follows

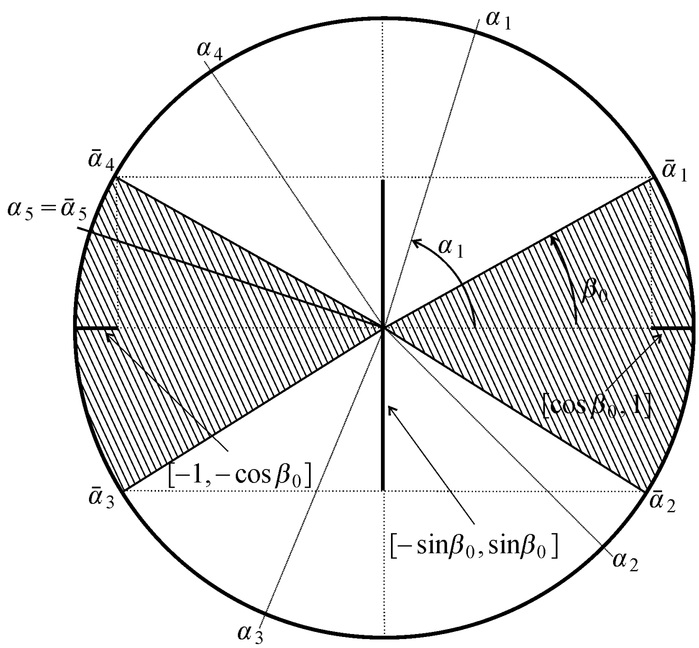

Fig. 4 Illustration of the projection on the set of angles represented by the hatched sectors. The α_i are projected into $\bar{\alpha}_i$. Since α_5 is inside the section, $\alpha_5 = \bar{\alpha}_5$.

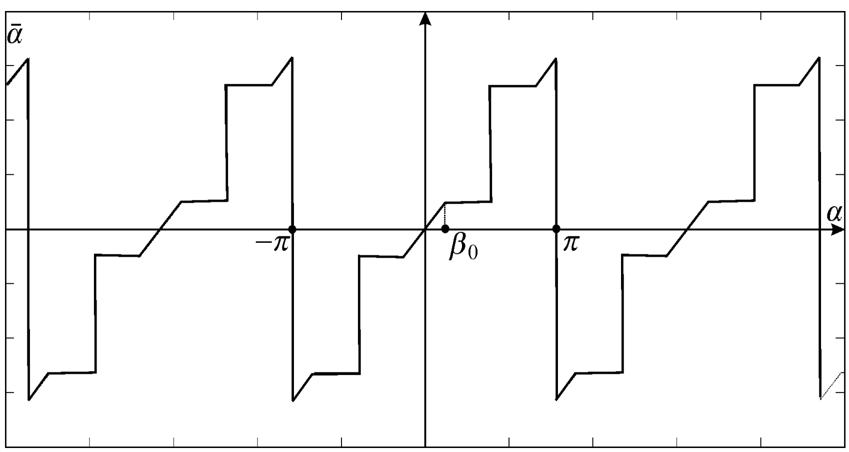

Fig. 5 Graph of the angular projection function. The frame box is $[-10, 10] \times [-4, 4]$

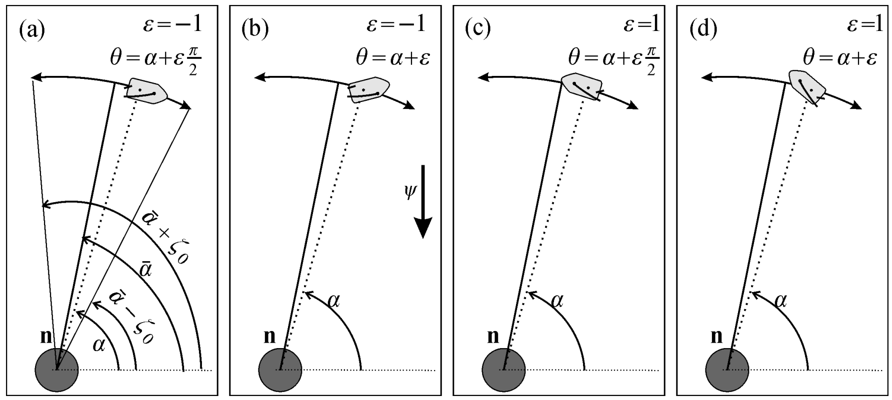

Fig. 6 (a),(c) the boat follows the segment but does not pull the cable; (b),(d) the boat pulls the load

Controller. in: $\mathbf{m}, \mathbf{n}, \dot{\mathbf{n}}, \theta, \psi$; out: u_1, u_2; inout: ε
1 $\alpha_0 = \text{ field}(\mathbf{n})\,;\ \alpha^* = \ \alpha_0 + \sin(\alpha_0 - \text{atan2}(\dot{\mathbf{n}}))\,;$
2 $\tilde{\alpha} = \alpha^* - \psi;\ \beta_0 = \frac{\pi}{2} - \zeta - \zeta_0;$
3 $\bar{\alpha} = \psi + \text{atan2}\begin{pmatrix} \max\left(\left|\cos\tilde{\alpha}\right|, \cos\beta_0\right).\text{sign}\left(\cos\tilde{\alpha}\right) \\ \min\left(\left|\sin\tilde{\alpha}\right|, \sin\beta_0\right).\text{sign}\left(\sin\tilde{\alpha}\right)\end{pmatrix};$
4 $\alpha = \text{atan2}(\mathbf{m} - \mathbf{n});$
5 if $\cos(\bar{\alpha} - \alpha) < \cos\zeta_0$ then $\varepsilon = \ \text{sign}(\sin(\bar{\alpha} - \alpha));$
6 $\bar{\theta} = \alpha + \varepsilon;$
7 if $(\cos(\theta - \bar{\theta}) \leq 0)$ then $u_1 = \frac{\pi}{4}.\text{sign}\left(\sin\left(\alpha - \bar{\theta}\right)\right)$ else $u_1 = \frac{\pi}{4}.\sin\left(\theta - \bar{\theta}\right);$
8 $u_2 = \frac{\pi}{2}.\left(\frac{\cos\left(\psi - \bar{\theta}\right) + 1}{2}\right).$

The inputs of the controller are the position $\mathbf{m}$ of the boat, the position of the load $\mathbf{n}$, its speed $\dot{\mathbf{n}}$, the heading of the boat θ and the direction of the wind ψ. The output of the controller are the rudder angle u_1 and the length u_2 of the mainsheet. There is only one binary state variable $\varepsilon \in \{-1, 1\}$. From $\mathbf{n}, \dot{\mathbf{n}}$, Step 1 computes the direction α^* we want to pull from the desired vector field **(b)**. This direction is obtained using the proportional control law **(a)**. Since α^* may be unfeasible, Steps 2 and 3 project (see **(d)**) this angle to get the nearest feasible direction $\bar{\alpha}$. This direction gives the segment **(c)** to be followed back and forth. When the boundary of the segment is reached the scanning direction ε changes at Step 5. The desired heading is corrected at Step 6 in order to pull the cable (see **(e)**). Steps 7 and 8 correspond to the low level control **(f)** for the rudder and the sail.

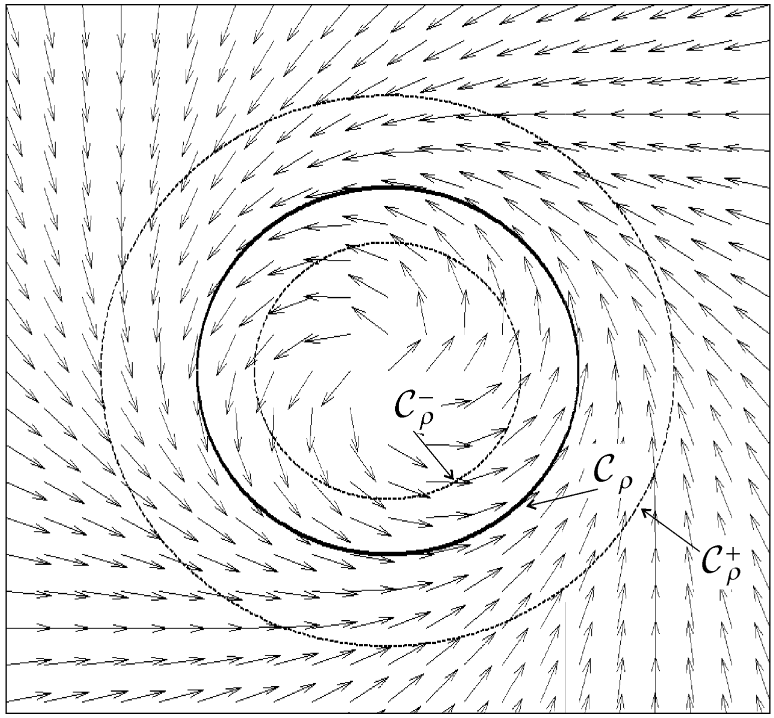

Fig. 7 The limit cycle $\mathscr{C}_\rho$ of this vector field is the bold circle.

4 Test-case

Assume that the load has to follow a circle $\mathscr{C}_\rho$ with radius ρ. Thus choose a vector field so that the circle $\mathscr{C}_\rho$ corresponds to a limit cycle of the field. An expression of such a vector field in given by

$$\varphi(\mathbf{n}) = \text{atan2}(\mathbf{n}) + \frac{\pi}{2} + \text{atan}\left(\frac{\|\mathbf{n}\| - \rho}{\delta}\right),$$

where δ is the required accuracy (typically the GPS accuracy). Figure 7 shows such a vector field. Taking two circles bracketing the limit circle $\mathscr{C}_\rho$ (such as the two dotted circles $\mathscr{C}_\rho^-, \mathscr{C}_\rho^+$ of Figure 7), the corresponding dynamical system, is captured by the corridor delimited by these two circles. This is the case even for small uncertainties.

For simulation, the same coefficients as [17] are used for the sailboat. For the cable, a length of $L_0 = 50$m is chosen. The mass of the load is $p_{11} = 2000$Kg. The friction coefficient of the load is $p_{12} = 10$ Kg.s.m^{-1}. For the controller, a segment with half radius $\zeta_0 = 0.2$rad is applied. For the initialization, the load is placed at the center of the circle. For a circle with radius $\rho = 150$m, the trajectories painted in

Figure 8 are obtained. This figure illustrates the desired circle $\mathscr{C}_\rho$ for the load (dotted circle), the trajectory of the load (bold curve), and the trajectory of the sailboat (thin curve). The trajectory of the boat is mainly composed of many segments (*i.e.*, arcs with half angle $\zeta_0 = 0.2\text{rad} \simeq 11\,\text{deg}$). The big arcs (with angle around $\frac{\pi}{2}$) correspond to situations where the load wants to go perpendicular to the wind and thus two different projections exist in (3). The sailboat thus has to alternate between these two projections.

Remark. Figure 8 contains some arcs that would not be considered as feasible. See, e.g., at the very top (before the trajectory of the towed load finishes the circle). The sailboat is performing a large arc windwards. This phenomenon is due to the model we considered: the dynamic of the boat and that of the load are considered almost independent. More precisely, in the unfeasible arcs, the boat is in a closed hauled mode whereas the cable maintains it and the arc. This makes the boat going upwind (which is not possible). In practice, the switching would require tacking. ■

For a circle with radius $\rho = 500$m, we get the simulation illustrated by Figure 9. Note that now, due to the zoom out effect, the trajectory for the load looks much more accurate. Once the initialization has been performed and that the load has reached the desired circle, the distance of the load to the circle is always less than 20m.

5 Conclusion

This paper has presented a controller for a sailboat robot for towing an heavy load along a desired trajectory. To our knowledge, this problem has never been considered before. The controller is simple to implement (about 10 lines of C++ code) and only includes easy-to-tune parameters (such as the length of the cable or the angle of the segments). The feasibility and the robustness of the controller has been tested on some simulations. It remains to validate the principle on experiments involving an actual sailboat robot (towing a zodiac, for instance). Note that the controller could also be used for towing objects that are not as large as addressed in the paper: in practical application a sailing robot could be used to tow a floating or submerged sensing device.

All C++ codes associated with the test-case can be found at

`www.ensta-bretagne.fr/jaulin/tracteur.html`

References

1. Brière, Y.: The first microtransat challenge, `http://web.ensica.fr/microtransat`. ENSICA (2006)

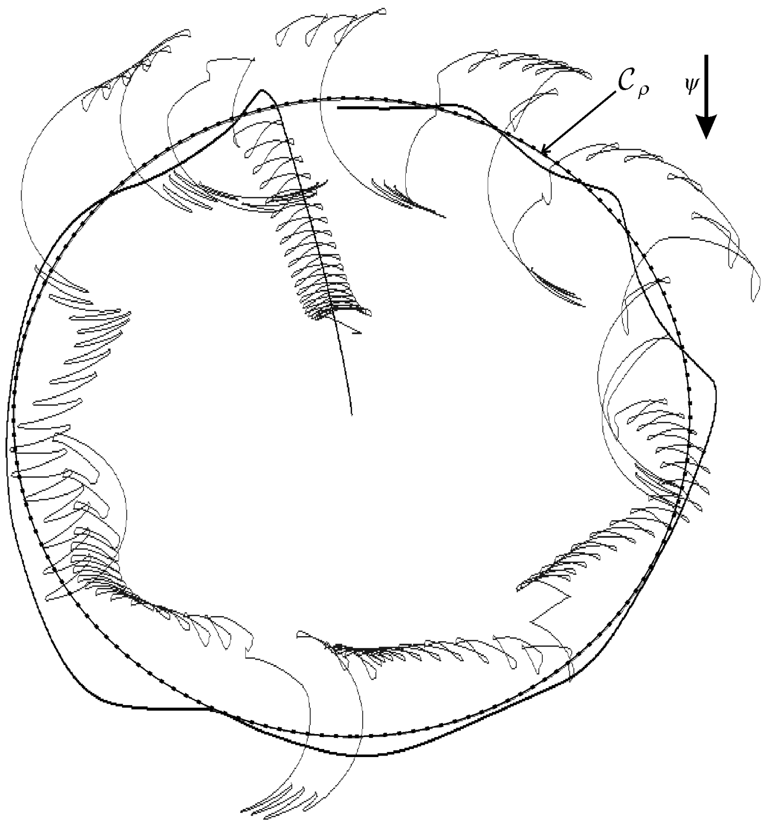

Fig. 8 The load (bold curve) follows the desired path (dotted circle). The sailboat trajectory is mainly composed with small arcs (or segments) in order the keep the cable taut. The starting point for the load is the center of the target circle.

2. Cabral, H., Alves, J., Cruz, N., Valente, J., Lopes, D.: MPL - A Mission Planning Language for Autonomous Surface Vehicles. In: 6th International Robotic Sailing Conference. Springer, Brest, France (2013)
3. Cabrera-Gamez, J., Isern-Gonzalez, J., Hernandez-Sosa, D., Dominguez-Brito, A.C., Fernandez-Perdomo, E.: Optimization-Based Weather Routing for Sailboats. In: 5th International Robotic Sailing Conference. Springer, Cardiff, UK (2012)
4. Cruz, N., Alves, J.: Ocean sampling and surveillance using autonomous sailboats. In: International Robotic Sailing Conference. Austria (2008)
5. Erckens, H., Büsser, G., Pradalier, C., Siegwart, R.: Navigation Strategy and Trajectory Following Controller for an Autonomous Sailing Vessel. IEEE RAM **17**, 47–54 (2010)
6. Fossen, T.: Guidance and Control of Ocean Vehicles. Wiley, New York, NY (1995)
7. Gal, O.: Multi-agents Decision Making Concept for Multi-missions Applications in Marine Environments. In: 6th International Robotic Sailing Conference. Springer, Brest, France (2013)
8. Gorgues, T., Ménage, O., Terre, T., Gaillard, F.: An innovative approach of the surface layer sampling. Journal des Sciences Halieutique et Aquatique **4**, 105–109 (2011)

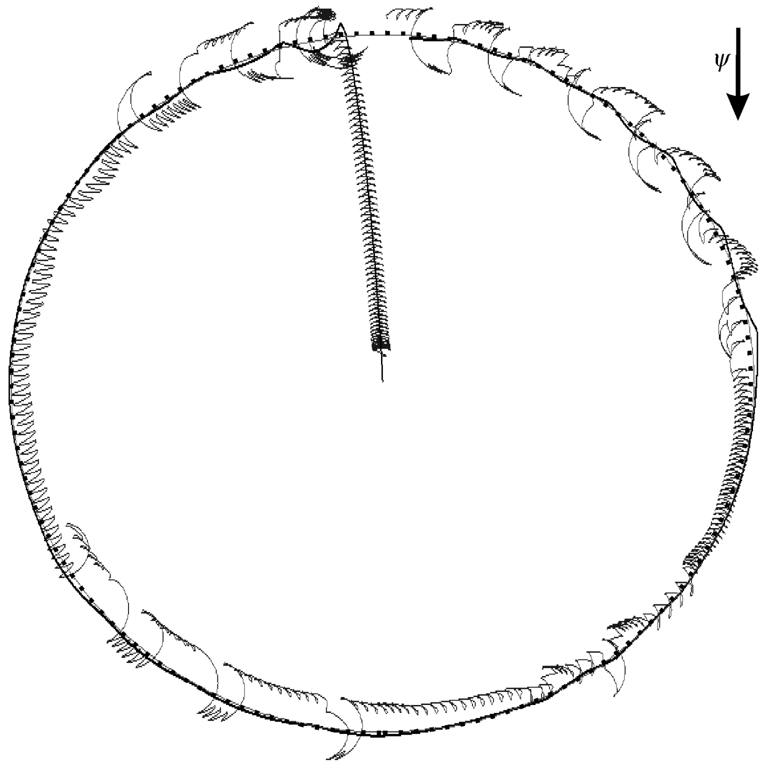

Fig. 9 Trajectories of the load and the sailboat, when the radius of the circle to be followed is $\rho = 500$m.

9. Guillou, G.: Architecture multi-agents pour le pilotage automatique des voiliers de compétition et extensions algébriques des réseaux de petri. PhD dissertation, Université de Bretagne, Brest, France (2011)
10. Herrero, P., Jaulin, L., Vehi, J., Sainz, M.A.: Guaranteed set-point computation with application to the control of a sailboat. International Journal of Control Automation and Systems **8**(1), 1–7 (2010)
11. Jaulin, L.: Représentation d'état pour la modélisation et la commande des systèmes (Coll. Automatique de base). Hermès, London (2005)
12. Jaulin, L., Le Bars, F.: A simple controller for line following of sailboats. In: 5th International Robotic Sailing Conference, pp. 107–119. Springer, Cardiff, Wales, England (2012)
13. Jaulin, L., Le Bars, F.: An Interval Approach for Stability Analysis; Application to Sailboat Robotics. IEEE Transaction on Robotics **27**(5) (2012)
14. Jaulin, L., Le Bars, F.: Sailboat as a windmill. In: 6th International Robotic Sailing Conference. Springer, Brest, France (2013)
15. Klinck, H., Stelzer, R., Jafarmadar, K., Mellinger, D.K.: AAS Endurance: An Autonomous Acoustic Sailboat for Marine Mammal Research. In: 2th International Robotic Sailing Conference. Matosinhos, Portugal (2009)
16. Langbein, J., Stelzer, R., Fruhwirth, T.: A Rule-Based Approach to Long-Term Routing for Autonomous Sailboats. In: 4th International Robotic Sailing Conference. Lübeck, Germany

(2011)
17. Le Bars, F., Jaulin, L.: An experimental validation of a robust controller with the VAIMOS autonomous sailboat. In: 5th International Robotic Sailing Conference, pp. 74–84. Springer, Cardiff, Wales, England (2012)
18. Miller, P., Sauze, C., Neal, M.: Development of ARRTOO: A Long-Endurance, Hybrid-Powered, Oceanographic Research Vessel. In: 6th International Robotic Sailing Conference. Springer, Brest, France (2013)
19. Miller, P.H., Hamlet, M., Rossman, J.: Continuous improvements to USNA sailbots for inshore racing. In: 5th International Robotic Sailing Conference, pp. 49–60. Springer, Cardiff, Wales, England (2012)
20. Neumann, T., Schlaefer, A.: Feasibility of basic visual navigation for small sailboats. In: 5th International Robotic Sailing Conference, pp. 13–22. Springer, Cardiff, Wales, England (2012)
21. Petres, C., Ramirez, M.R., Plumet, F.: Reactive Path Planning for Autonomous Sailboat. In: IEEE International Conference on Advanced Robotics, pp. 1–6 (2011)
22. Sauze, C., Neal, M.: An Autonomous Sailing Robot for Ocean Observation. In: proceedings of TAROS 2006, pp. 190–197. Guildford, UK (2006)
23. Schmitt, S., Le Bars, F., Jaulin, L., Latzel, T.: Obstacle Avoidance for an Autonomous Marine Robot - A Vector Field Approach. In: 7th International Robotic Sailing Conference. Springer, Irland (2014)
24. Stelzer, R., Dalmau, D.E.: A study on potential energy savings by the use of a balanced rig on a robotic sailing boat. In: 5th International Robotic Sailing Conference, pp. 89–93. Springer, Cardiff, Wales, England (2012)
25. Stelzer, R., Jafarmadar, K.: The Robotic Sailing Boat ASV Roboat as a Maritime Research Platform. In: in Proceedings of 22nd International HISWA Symposium on Yacht Design and Yacht Construction. Amsterdam, The Netherlands (2012)
26. Stelzer, R., Proll, T., John, R.: Fuzzy Logic Control System for Autonomous Sailboats. In: in Proceedings of IEEE International Conference on Fuzzy Systems. London, UK (2007)
27. Xiao, K., Sliwka, J., Jaulin, L.: A wind-independent control strategy for autonomous sailboats based on voronoi diagram. In: CLAWAR 2011 (best paper award). Paris (2011)
28. Xiao, L., Jouffroy, J.: Modeling and nonlinear heading control of sailing yachts. IEEE Journal of Oceanic Engineering (2013)