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USV based automatic deployment of booms along quayside mooring ships: Scaled experiments and simulations

Juan F. Jimenez, Jose M. Giron-Sierra *

Arquitectura de Computadores y Automática, Universidad Complutense de Madrid, Av. Complutense s/n, 28040, Madrid, Spain

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ABSTRACT

This article explores possible uses of marine Unmanned Surface Vehicles (USV) for the fully automatic deployment of containment booms along quayside mooring ships. The task of the USV is to tow the boom along adequate trajectories. The target is the prevention of contaminant spills in harbors or near the coast, for example during crude transfers. Surrounding ships with booms is becoming a common practice. This scenario belongs to the target of our research: to transfer robotic techniques to marine applications. The article experimentally shows that the USV based automatic deployment can be done, in accordance with a suitable planning in terms of waypoints. Actually, the article presents a successful automatic deployment, with a scale USV and a 50 m long experimental light boom. For the purposes of the research a set of models, of the boom, cables, and the USV dynamics, have been established. Based on these models, a simulation platform has been developed. The platform has been employed for analyzing and planning of experiments, and for the simulation of a real scale boom deployment scenario described in the article. Some recommendations are included in the final section.

1. Introduction

Public perception is becoming more and more sensible to sea contamination issues, like in the case of pollutant spilling near the coast or in harbors. An increasing awareness of its detrimental effects is taking place (Chang et al., 2014), related to ecosystems (Hampton et al., 2003; ITOPF, 2013), health (Eykelbosh, 2014; Walker, 2017), fisheries, marine industries, and other socio-economic aspects (ITOPF, 2012; Feria-Domínguez et al., 2016). A manifestation of this concern is the growing number of publications on associated topics. So that, for instance, a survey of the oil spill literature from 1968 to 2015, (Murphy et al., 2016), detected over 11,000 related publications.

Historical records of pollutant spills usually pay attention to major incidents (ITOPF, 2017; CEDRE, 2017). In particular, the Deepwater Horizon disaster, had a significant impact (Adams, 2015; Lichtveld et al., 2016; Graham et al., 2016). However, there are other spills that occur in harbors, usually smaller but more frequent. Many regional institutions and ports have prepared contingency plans, which contemplate preventive measures to avoid the spilling of pollutants in harbor facilities. Frequently the use of containment booms is recommended. In fact, a common practice is to place booms around tankers, or other types of ships, during charge or discharge operations that might cause spills.

This article explores the possibility of an automatic deployment of containment booms around ships, using unmanned surface vehicles (USVs) for boom towing. Although this could correspond to situations in the open sea, the article focuses on scenarios with ships moored to a dock. The main point of the research is analyzing and planning of the deployment.

There are several possible procedures for boom deployment along quayside mooring ships. In this article, the deployment from a reel on shore has been chosen. Other alternatives could also be subject of study in the future.

The automatic behavior considered in this article, corresponds to a first level of autonomy. And so, it belongs to a general research trend, which is the introduction of autonomous robotized vehicles. This is entering on daily life, with the self-driving car as a clear example. Indeed, this kind of vehicles would also come to the marine scene, like surface vehicles for applications such as harbor surveillance, hydrographic monitoring, or even autonomous cargo ships (Levander, 2017).

In our case, after some years devoted to the development of autonomous surface vehicles (USVs) (Recas et al., 2004), environmental applications were deemed of great interest. Most probably it was due to the impact in our country of the Prestige disaster, (Gonzalez et al., 2006). Many volunteers tried to help, including fishermen towing

* Corresponding author.
E-mail addresses: juan.jimenez@fis.ucm.es (J.F. Jimenez), gironsi@fis.ucm.es (J.M. Giron-Sierra).

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Fig. 1. A boom around a ship for preventive purposes (Mavideniz, 2018).

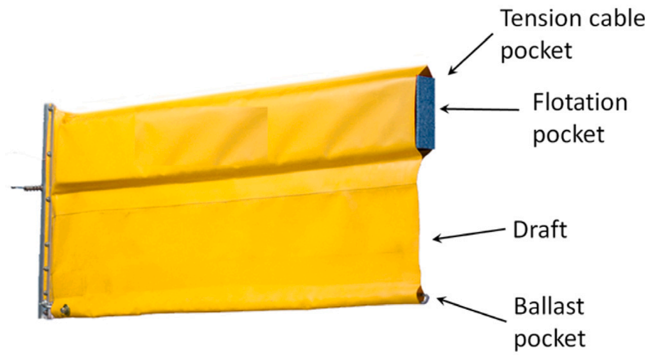


Fig. 2. Typical segment of a standard boom.

booms. Hence, our research aimed to environmental operations involving the use of booms and USVs (Jimenez et al., 2005). Some similar recent initiatives from industry can be mentioned, like SeaMachines (2019). Our general criterion is to achieve complete operations in fully automatic ways (Giron-Sierra et al., 2015). One of the reasons for this approach is that it could be difficult to have, when needed, people with pertinent expertise, while an automatic system would alleviate such need. Other advantages of robotized systems is that they can be used day and night, under most weather conditions, repetitively, and with no risk for humans in case of dangerous substances or burning.

Our research proceeded with two main activities in parallel: computer simulations, and scale experiments. In order to provide a computer environment for operation planning and analysis, a mathematical model of the boom dynamics, combined with models of the USV and the towing cable, has been developed (Jimenez and Giron-Sierra, 2018), and a simulation tool has been built. The experimental work was done using scaled boats and booms. These boats have on-board miniaturized computers for automatic (it is not remote control) operation. In some experiments, part of the shape of the boom tends to a catenary curve, which could be colloquially described as a U shape. It should be said that model ships are frequently used in automatic control studies when they include experimental work (Skjetne et al., 2005; Do and Pan, 2006).

The typical application scenario would be the case of a tanker, being desired to prevent the escape of any leakage during crude transfers, see Fig. 1. In certain circumstances, this could be an emergency response that should be accomplished as fast as possible.

At first sight, the deployment planning could be regarded as trivial. However, a basic analysis shows that currents and wind are important, implying significant changes in the USV maneuvering and in the plan itself. In particular, one of the examples suggested by experts, which is contemplated in this article, was the case of a dock by the bank of a river, near the sea so the influence of tide is relevant.

Having in mind that the harbor operations envisaged in this article, would be in general carried on by conventional USVs, not only our USV, simple waypoint steered navigation has been chosen. It is open for our future research, to include a more intelligent navigation control, since the on-board software of our USV can be easily accessed and modified.

The article has been organized as follows. Section 2 is devoted to the research background. Section 3 introduces the mathematical models of interest, which refer to the dynamics of the ship, the boom, and the towing cables. Section 4 describes the experimental framework, which is based on scaled USVs. Section 5 includes a brief, preliminary study of the boom deployment around a ship. Then, Section 6 presents a complete trial scenario, in which a boom is deployed around a zone in order to prevent the escape of pollutants (it is supposed that a ship is inside the zone). The scenario is reproduced both in simulation and with the experimental system. Section 7, is devoted to real scale simulation analysis, involving the planning of the USV path in the presence of currents. Finally, Section 8 draws some conclusions, including comments on other alternatives for automatic operation, and some ideas for future research.

2. Background

2.1. Booms for contaminant spills

Booms are typical components of the equipment for marine pollution response. They can be used in several ways (ITOPF, 2014). For example, a boom can be statically placed as a kind of floating wall. Or the boom can be dynamically operated, like in the case of towing it with two ships. Usually the booms have ballast (for example, a chain) at the bottom to maintain a vertical posture. Part of the boom is on the surface, while most of the boom is submerged. Most booms are composed of a series of connected segments, like the one shown in Fig. 2.

There are many models of booms, with different combinations of freeboard and draft sizes. In case of having to withstand currents or being towed, the tensile strength specification is important. In order to avoid oil escape, low speeds, about 1 knot, are recommended for towing (ITOPF, 2014). The weight of light booms could be less than 2 kg/m, while heavy booms could have more than 17 kg/m. Draft dimension ranges approximately from 30 cm to 100 cm.

For the application considered in this article, an easy to extend curtain light boom would be appropriate. Actually, some of our initial experiments were done with a 30 cm draft and 3 kg/m real scale boom, in order to obtain data on towing force for modeling purposes.

The deployment of a boom could be more or less a matter of routine. In certain emergencies, it should be fast. There are boom reels to be used on the shoreline, or on board special ships. It also would be possible to have the boom folded in a suitable way. During the deployment, in addition to a ship towing the boom (if this is the case), other ships or boats would be helpful for lateral pushing of the boom in order to place it along a convenient curve. It would require coordination of activities from the people involved in the deployment.

The length of tankers could be as much as 415 m, although there are many in the range 100 m–200 m.

In an interesting account of what happened with the Deepwater Horizon spill, (Hall et al., 2011), it is mentioned that vessels of opportunity were recruited, and fishermen's expertise was important. This was also the case with the Prestige oil spill in 2002, (Gonzalez et al., 2006). Clearly, people accustomed to trawling would be good for boom towing. Actually, Parson and Majors (2011) proposes an effective oil response system based on fishing vessels. As it will be cited later on, opportune information on towing and required forces can be obtained from the fishing context.

With respect to literature on oil pollution response, a synthesis of major oil response methods and materials was presented in Ventikos et al. (2004). The book (Fingas, 2012) covers current oil spill cleanup techniques. A short review of other information sources is contained in Giron-Sierra et al. (2015).

2.2. USV navigation control

The course control of ships is a classic research topic. Reference books on it are Fossen (1994, 2002, 2011). A review of course keeping control of USVs, by Azzeri et al. (2015), has recently appeared.

For the USV to tow a boom around a ship, a suitable path should be specified and then the USV should follow the path. This is a question belonging to the mobile robots context. A most cited book on path planning is LaValle (2006). A number of path-following control methods have been introduced. Some of these methods were evaluated by Sujit et al. (2013). It was particularly useful for our work the contributions of (Breivik and Fossen, 2004) for paths composed of circles and lines. Both the trajectory planning and the path-following control of USVs is studied in Liao et al. (2014). An overview of USV status can be found in Liu et al. (2016).

Some surveys of available unmanned surface vehicles can be easily reached in Internet. Let us mention in particular (Bertram, 2008; Motwani, 2012; Liu et al., 2016).

3. Mathematical modeling

This section is devoted to introduce a model of the boom dynamics, a maneuvering model of a USV, and a model of the towing cables. Based on these models, a simulation environment has been implemented.

With the simulation tool, it is possible to observe the dynamic behavior of the boom, the evolution of its shape during deployment, to estimate tensions and forces, and to take into account currents and winds.

Needless to say, the models try to be simple and sufficiently approximate. In the actual form, the models, in special the model of the boom, require moderate computational efforts. The models are open enough as to be changed if necessary.

3.1. Boom model

Let us concisely introduce the boom model. A more extended description of this model, and some possible applications, can be found in Jimenez and Giron-Sierra (2018).

It is assumed that the boom is composed of a series of interconnected links. Each link has a length $2l$ and inertial mass m_l. Fig. 3 shows a schematic view of the boom with the links represented as line segments. The bold dots correspond to the center of mass of each link. The central part of the figure focuses on two consecutive links. For those links, the figure depicts the normal $\vec{n}_i$ and parallel $\vec{p}_i$ unitary vectors, which are employed in the boom equations. Also, the position vectors $\vec{r}_i$, $\vec{r}_{i+1}$ of the center of mass of those two links are shown.

The total mass of a link is represented on the $\{x, y\}$ system as the following diagonal matrix:

$$\mathbf{M_{Ai}} = \begin{pmatrix} m_l + m_a \cos(\theta_i) & 0 \\ 0 & m_l + m_a \sin(\theta_i) \end{pmatrix} \tag{1}$$

where m_a is the added mass in the direction normal to the link.

Suppose that the boom has a total number of m links. The dynamics of the ith link is described as follows:

$$\vec{T}_{i,i+1} - \vec{T}_{i-1,i} - \vec{F}_{ri} = \mathbf{M_{Ai}} \cdot \vec{a}_i \tag{2}$$

$$\left(\vec{T}_{i,i+1} \cdot \vec{n}_i + \vec{T}_{i-1,i} \cdot \vec{n}_i\right) l - A\omega_i = I \cdot \alpha_i \tag{3}$$

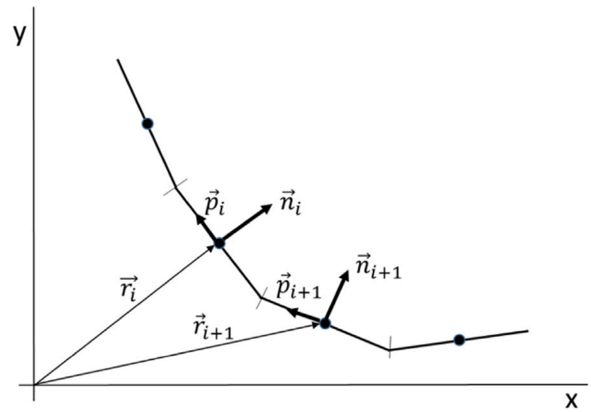


Fig. 3. Boom layout showing the main elements used in the boom model.

where $\vec{F}_{ri}$ represents the linear and quadratic resistance forces against the link velocity $\vec{v}_i$, using the coefficients s, s_2, q and q_2,

$$\vec{F}_{ri} = \left(|\vec{v}_i \cdot \vec{n}_i| s + |\vec{v}_i \cdot \vec{p}_i| q\right) \frac{\vec{v}_i}{|\vec{v}_i|} + \left(|\vec{v}_i \cdot \vec{n}_i| s_2 + |\vec{v}_i \cdot \vec{p}_i| q_2\right) \vec{v}_i \tag{4}$$

and $A\omega_i$ represents a resistance momentum proportional to the link angular velocity.

The linear motion of the link center of mass is described by Eq. (2), while the link rotational motion around its center of mass is described by Eq. (3). Notice that the strains were denoted by pairs of indexes, $i, i+1$, corresponding to the strain in the hinge that joints link i with link $i+1$.

Eqs. (2) and (3) are valid for all links except for those located at the ends of the boom. The ends of the boom will be connected to external towing forces. Therefore, for the last link on the left of the boom,

$$\vec{T}_{1,2} - \vec{F}_{left} - \vec{F}_{r1} = \mathbf{M_{A1}} \cdot \vec{a}_1 \tag{5}$$

$$\left(\vec{T}_{1,2} \cdot \vec{n}_1 + \vec{F}_{left} \cdot \vec{n}_1\right) l - A\omega_1 = I \cdot \alpha_1 \tag{6}$$

and for the link located at the right end,

$$\vec{F}_{right} - \vec{T}_{m-1,m} - \vec{F}_{rm} = \mathbf{M_{Am}} \cdot \vec{a}_m \tag{7}$$

$$\left(\vec{F}_{right} \cdot \vec{n}_m + \vec{T}_{m-1,m} \cdot \vec{n}_m\right) l - A\omega_m = I \cdot \alpha_m \tag{8}$$

The equations above do not form a complete set. It is necessary to add a closing condition. Such a condition can be that the links should remain connected (not separated). Therefore:

$$\vec{r}_i - l \cdot \vec{p}_i - l \cdot \vec{p}_{i+1} - \vec{r}_{i+1} = 0 \tag{9}$$

for any consecutive pair of links.

By taking derivatives twice, an expression was obtained that combines linear and angular acceleration, supplying the additional equation needed:

$$\vec{a}_i + l \cdot \vec{p}_i \omega_i^2 + l \cdot \vec{n}_i \alpha_i + l \cdot \vec{p}_{i+1} \omega_{i+1}^2 + l \cdot \vec{n}_{i+1} \alpha_{i+1} - \vec{a}_{i+1} = 0 \tag{10}$$

In order to solve the equations set (from Eq. (2) to Eq. (10)), first split them into $\{x, y\}$ coordinates, and remove linear and angular accelerations. Then, rewrite the equations, grouping on the right-hand side those terms with strain components. In this way, the system can be expressed in matrix format as:

$$\mathbf{H} \cdot \vec{T} = \vec{b} \tag{11}$$

where $\mathbf{H}$ is a sparse matrix that depends on link poses and parameters (inertial mass and moment). The non-zero entries are located in the six central diagonals: the main diagonal, the three upper diagonals, and the two lower diagonals. $\vec{T}$ is a vector of strain components,

$$\begin{pmatrix} \cdots T_{i-1,ix} & T_{i-1,iy} & T_{i,i+1x} & T_{i,i+1y} & T_{i+1,i+2x} & T_{i+1,i+2y} \cdots \end{pmatrix}^T \tag{12}$$

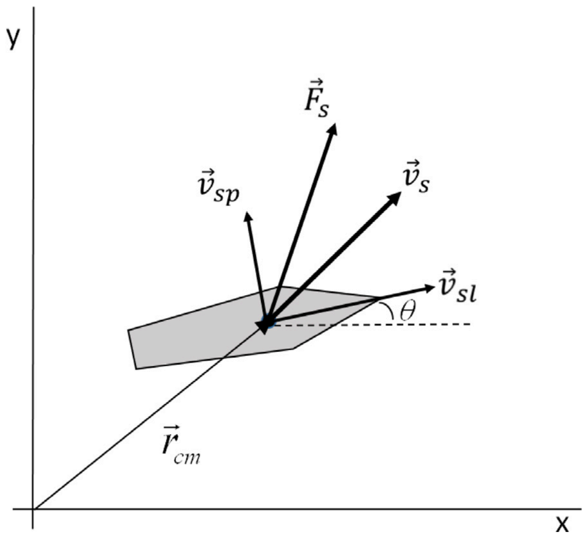


Fig. 4. Main variables o the USV mathematical model.

The right-hand side term, $\vec{b}$ represents a vector of independent terms containing resistance and inertial forces.

The iterative solution of the equations starts by an initial disposition of the links, and forces acting on the boom tips. Then, the strains are computed. Then the linear and angular accelerations can be obtained.

The links at ends of the booms require another calculation way, since they are attached to the boom only by one side. It may happen that the left tip of the boom was attached to a boat or a bollard, or be free, etc.; and similarly with the right tip.

3.2. Towing cables

Assume that the boom is attached to the USV by means of cables. It is possible to consider the cable stress as a function of its stretching, $\Delta d = d - d_0$, over its nominal length d_0.

$$T_{cbl} = \begin{cases} 0 & if\ \Delta d < 0, \\ \frac{E}{d_0}\Delta d & if\ \Delta d \geq 0 \end{cases} \tag{13}$$

where E represents the Young's elasticity module.

The distance between the tip of the boom and the center of mass of the USV, is given by Eq. (14) if the USV is on the left side of the boom, or by Eq. (15) if it is on the right side.

$$d_l = |\vec{r}_{cm} - \frac{\vec{l}_s}{2} - \vec{r}_1 - l \cdot \vec{p}_1|^2, \quad \text{SoL (Ship on the Left)} \tag{14}$$

$$d_r = |\vec{r}_m - l \cdot \vec{p}_m - \vec{r}_{cm} + \frac{\vec{l}_s}{2}|^2, \quad \text{SoR (Ship on the Right)} \tag{15}$$

Fig. 4 shows the definition of variables for the USV, of length l_s. It is supposed that the boom is attached to the USV aft. The Δd is obtained by subtracting d_0 from the proper expression above (d_l or d_r).

The direction of the cable stress is:

$$\vec{u}_{cbl} = \frac{\vec{r}_{cm} - \frac{\vec{l}_s}{2} - \vec{r}_1 - l \cdot \vec{p}_1}{d_l}, \quad \text{SoL} \tag{16}$$

$$\vec{u}_{cbl} = \frac{\vec{r}_m - l \cdot \vec{p}_m - \vec{r}_{cm} + \frac{\vec{l}_s}{2}}{d_r}, \quad \text{SoR} \tag{17}$$

Based on these expressions, the forces on the ship's stern and the boom tips can be computed:

$$\begin{aligned} &\vec{F}_e = T_{cbl} \cdot \vec{u}_{cbl}, \ \text{SoL} \\ &\vec{F}_e = -T_{cbl} \cdot \vec{u}_{cbl}, \ \text{SoR} \\ &\vec{F}_{left} = T_{cbl} \cdot \vec{u}_{cbl} \\ &\vec{F}_{right} = T_{cbl} \cdot \vec{u}_{cbl} \end{aligned} \tag{18}$$

The equations introduced so far can be used to get the instantaneous values of the strains acting on the boom links. From these values, linear and angular accelerations can be obtained. Speeds can be computed by numerical integration of accelerations. And from numerical integration of speeds, positions and orientations can also be calculated.

The approach already introduced could be characterized as Newtonian, (Jimenez et al., 2005). Other approaches could be also possible, like in Bhattacharya et al. (2011), Kim et al. (2013).

3.3. USV model

The mathematical model considers a USV with inertial mass m_s, and inertial moment about the USV center of mass I_s. A propulsion force $\vec{F}_s$ and a bearing moment $\vec{T}_s$ are applied to the center of mass. The model is generic, for several types of vessels.

The accelerations would be:

$$m \cdot \vec{a}_s = \vec{F}_s - \vec{F}_r + \vec{F}_e \tag{19}$$

$$I_s \cdot \vec{\alpha}_s = \vec{T}_s - \vec{T}_r + \vec{T}_e \tag{20}$$

where the terms F_e and M_e correspond to towing action, and the terms F_r and M_r correspond to resistance against ship motion. Given the inertial components of the USV velocity v_s, the corresponding components in body axes can be obtained with:

$$\begin{pmatrix} v_{sl} & v_{sp} \end{pmatrix}^T = \mathbf{R}(\theta)^{-1} \cdot \begin{pmatrix} v_{sx} & v_{sy} \end{pmatrix}^T \tag{21}$$

being $\mathbf{R}(\theta)$ a standard 2D rotation matrix.

The components of the resistance force $\vec{F}_r$ in body axes, are modeled as follows:

$$F_{rl} = \mu_l \cdot v_{sl} \tag{22}$$

$$F_{rp} = \mu_p \cdot v_{sp} \tag{23}$$

Then, the components of the resistance force $\vec{F}_r$ in inertial axes can be obtained with:

$$\begin{pmatrix} F_{rx} & F_{ry} \end{pmatrix}^T = \mathbf{R}(\theta) \cdot \begin{pmatrix} F_{rl} & F_{rp} \end{pmatrix}^T \tag{24}$$

Finally, the resistance to rotation has been modeled as the following momentum:

$$\vec{T}_r = \mu_a \cdot \vec{\omega}_s \tag{25}$$

were $\vec{\omega}_s$ is the angular velocity of the ship, and μ_a is a resistance coefficient.

4. Experimental framework

This research involved frequent experimentation along several years, as the weather permitted it. Initial experiments were devoted to develop and test the experimental system, which includes equipment and software. Afterwards, the experimental work focused on modeling needs concerning the USV model and the booms. As said before, once the mathematical models were established, a simulation environment was built. Based on this environment, it was possible to prepare new experimental scenarios with boom towing, in order to investigate path-planning. The experiments were also important for observation of dynamical behaviors and phenomena, which in certain situations were somewhat surprising. In turn, experiments have been useful as a validation reference for the simulation.

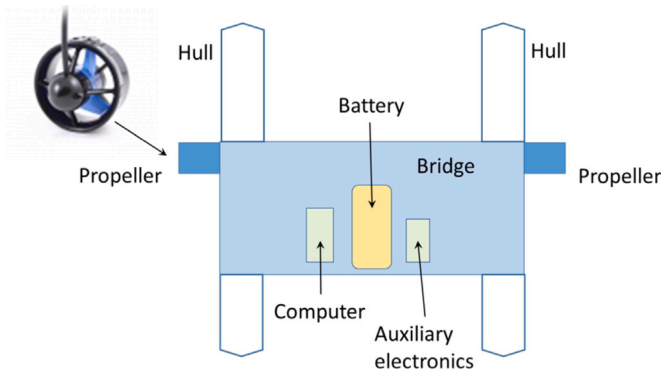


Fig. 5. Schematic top view of the USV.

4.1. Details of the USV

A common scene you can see in harbors is a ship being towed by a tug. What it is wanted from a tug is propulsion power and good maneuvering capabilities.

Taking into account the needs of experiments related to towing, a small twin-hull catamaran-type USV has been built in our laboratory. Each hull has an associated propeller, with 34.8 N maximum propulsion force (quite more of what is needed for our boom towing experiments). Both propellers are independently controlled. The ships course is governed by differences in propeller forces.

Denote as $\vec{F}_R$ the propulsion force of the propeller on the right side, $\vec{F}_L$ the propulsion force of the propeller on the left side. The sum of these forces gives the total propulsion force $\vec{F}_s$. Their difference would be $\vec{F}_{dif} = \vec{F}_R - \vec{F}_L$. There is a slip angle, that can be approximated with:

$$sin(\beta) = \vec{F}_{dif} / \vec{F}_s \tag{26}$$

(see Pandey and Hasegawa (2015) for a more detailed modeling).

In body axes, there would be two forces caused by propulsion:

$$\vec{F}_{sl} = \vec{F}_s \cdot cos(\beta) \tag{27}$$

$$\vec{F}_{sp} = \vec{F}_s \cdot sin(\beta) \tag{28}$$

The length of the USV hulls is 80 cm. The bridge is 70 cm wide and 50 cm long. In order to provide large torques for USV spinning, the propellers are placed by the external side of the hulls.

Figs. 5, 6, show an schematic top view of the boat design, and a photograph of the USV. The digital radio antenna is mounted on the ship superstructure. A more detailed view of one of the two propellers is shown in Fig. 7.

The propellers chosen for the boat are the T200 thrusters from Blue Robotics (Robotics, 2018). The T200 thruster has been modeled in Nielsen et al. (2018). By means of a RC electronic speed control (ESC) device, the propulsion force of the thrusters is controllable with conventional pulse-width modulated (PWM) signals. This kind of signals is widely used in the radio-control community. In fact, the same PWM signals that are used for our small ship could be used at any ship scale, even large sizes, for governing the propulsion power through adequate electronic interfaces.

One of the initial activities of the research has been to test the behavior of the USV under manual control from a RC console, measuring the USV position and speed with an on-board GPS. Speeds well over 2 m/s can be easily reached, with low energy consumption. For the boom towing experiments this speed can be lowered, by just using PWM signals with narrower width. Notice that the recommended speed, at real scale, for boom towing is around 0.5 m/s.

The miniature digital computer is based on a STM Nucleo board (by STMicroelectronics) (STM, 2018). This board has an ARM Cortex

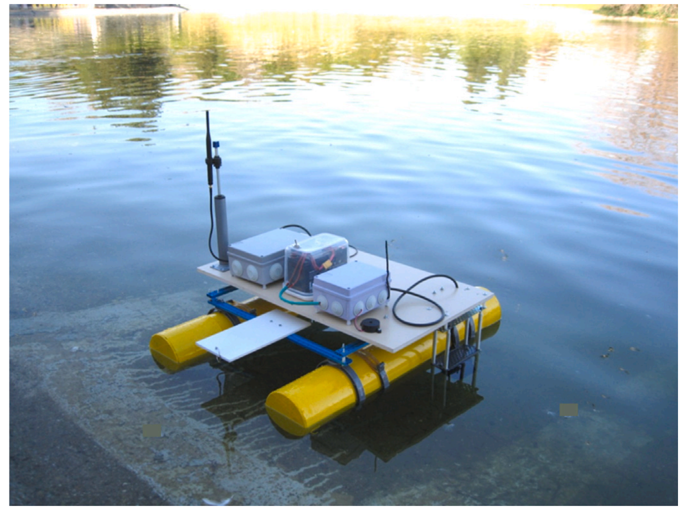


Fig. 6. A photograph of the USV.

Fig. 7. The right-hand side propeller.

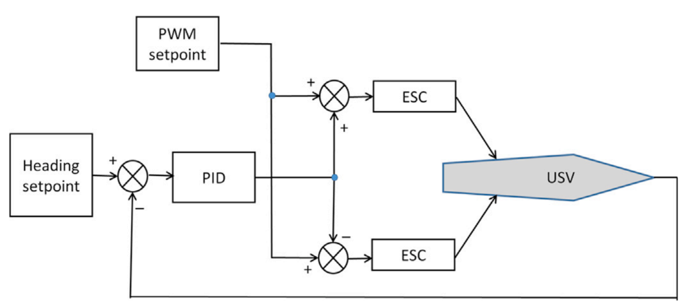


Fig. 8. Block diagram of the USV course control.

4M digital microcontroller and many input/output pins. Some of these pins have been selected for including in the control system miniature devices for GPS, digital compass, and a digital radio link.

The on-board control software is written in C. The main task of this software is to compute the suitable propulsion forces, according to the information from sensors about current heading, location and velocity. Desired forces are transmitted to the ESC devices, via PWM signals generated by the ARM microcontroller.

The on-board navigation control includes, implemented in software, a digital proportional–integral–derivative (PID) controller. Fig. 8 shows the block diagram of the course control. This control is handled by a

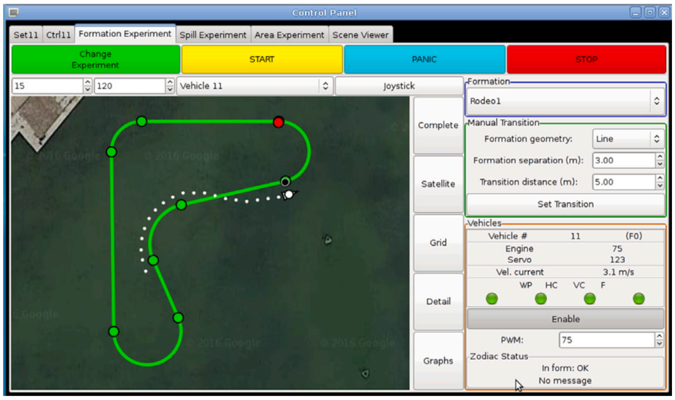


Fig. 9. One of the Ground Station screens during an experiment.

Table 1
USV model parameters.

$l_s = 0.3$ m	$m = 7$ kg
$\mu_l = 17.08$ N s/m	$I = 0.2$ kg m
$\mu_t = 40$ N s/m	$\mu_a = 2.2$ N m s^2

higher level algorithm, which regularly updates the heading setpoint, for waypoint-based steering.

4.2. The ground station

A ground station (GS) has been developed as part of the experimental system. It is used before experiments to transmit to the USV setup data, like speed, desired trajectory and PID parameters. The desired trajectory is specified by waypoints. The GS has Start/Stop commands to begin/stop the experiments.

During experiments, the GS remains passive, with no intervention on the USV behavior. The only task of the GS during experiments is to gather digital radio data sent by the USV for real-time monitoring. These data are also saved in a file for off-line study of results. While moving, the USV sends to the GS her compass and GPS data and the PWM values generated for speed and course control. It is always possible to take manual control of the USV using a Joystick. Fig. 9 shows one of ground station screens during an experiment. This screen can be used for formation experiments with several USVs, but in this case it is used for a single vehicle. The left panel shows the desired path in green and the USV motion as a white trail.

The GS program has been developed in C++, using the GTK++ environment for GUI implementation. The GS hardware is a conventional portable computer coupled through USB to a digital radio chip (another Xbee unit (DIGI, 2018)), which in turn is connected to an antenna.

4.3. USV model parameters

A series of experiments were done for estimation of the USV model parameters.

The first experiments were done following a straight path at different speeds, in order to estimate the USV friction coefficient in the direction of surge.

A second series of experiments were devised to make the USV follow circular paths of specified radii, and measuring period times. The friction coefficients of the model in the sway direction were estimated. Also, the spinning friction coefficient was estimated.

As a result of these experiments, the parameters of the USV model were estimated to be as given by Table 1:

Fig. 10. A view of the pond from its southern corner and pointing North.

4.4. Boom towing: Estimation of forces

In theory ITOPF (2014), the towing force (in N) is given by:

$$F_T = q\, v^2 \tag{29}$$

with $q = 1000A$ (A is the area perpendicular to the flow).

When towing a boom with two ships, the boom takes a catenary form. The area perpendicular to the flow will depend on the distance between boom tips, or, in other words, how wide is the mouth.

A first experimental light boom, 15 m long, was made by chaining a series of cylindrical floats. The boom cable is a conventional polypropylene rope, flexible and light. Based on experiments towing the boom with two scaled boats (that were used years ago in another research (Giron-Sierra et al., 2015)), and comparing velocities with and without towing, it was estimated that the drag of the boom is in the order of conventional booms, considering equivalences from scale 1/15 to real scale (see Lloyd (1989) for scaling).

From initial experiments on boom towing, it was noticed that if the USV tries to turn while towing the boom, the boom opposes to it. It could be regarded as a course stabilization influence from the boom. It was also experimentally noticed that the boom was quite sensitive to wind gusts.

4.5. Automatic navigation experiments

Most of our experiments were carried out in a 100 m ×70 m pond near our University. Fig. 10 shows a picture of the pond. The border of the pond is not a vertical wall, but instead a kind of beach with a soft slope.

A top view (Google Maps) of the pond was chosen and saved as an image (Fig. 11). The ground station displays the real-time GPS data from the USV, as color traces on this image. Besides, the GPS data obtained from experiments, are saved by the ground station as a file and can be retrieved afterwards for analysis and display (using MATLAB).

Before using any boom, it is convenient to check the automatic behavior of the USV alone. The preparation of an experiment involves the specification of a path in terms of waypoints. The USV will turn around waypoints following curved trajectories (not necessarily touching the waypoints, some tolerance is allowed). Based on the mathematical model of the USV dynamics, these trajectories can be predicted and displayed by our simulation environment.

The simulation is also useful for the tuning of the PID course controller.

Several paths, from simple to more complicated, were planned and the corresponding USV trajectories were predicted, for the USV not towing any boom. Subsequent experiments in the pond confirmed a satisfactory automatic navigation of the USV, in reasonable agreement with the simulation predictions. For instance, Fig. 12 shows the GPS trace of the USV motion (red curve with triangles) in an experiment

Fig. 11. Satellite view of the pond (Google Maps).

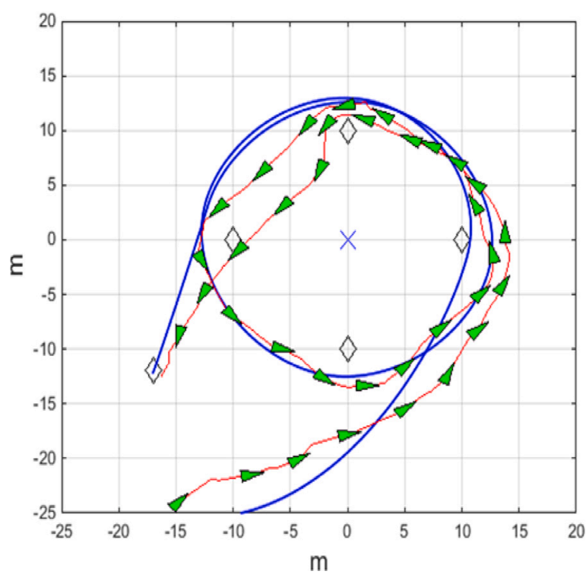


Fig. 12. One of the USV automatic navigation experiments: USV simulation (blue) versus real GPS trace of the USV (green with triangles). The diamonds correspond to the waypoints. The USV is not towing any boom yet.

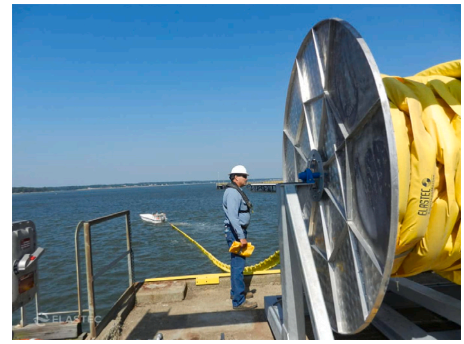


Fig. 13. Example of boom deployment from an on-shore reel (Elastec, 2018).

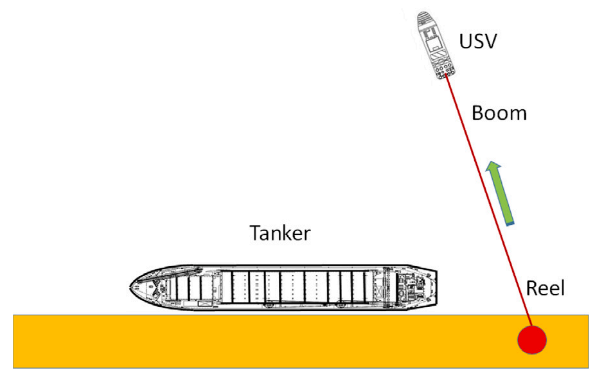


Fig. 14. Basic initial boom deployment concept.

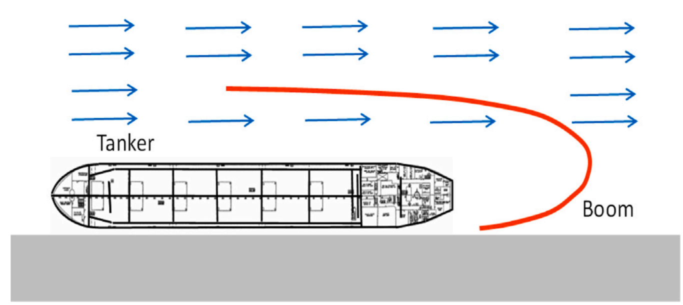


Fig. 15. A case of boom deployment against current.

with a cross of four waypoints (marked as black diamonds). The curve in blue is the USV trajectory prediction based on the mathematical model. Of course, the prediction does not know the actual perturbations found by the USV this day (in particular, there is some underwater pumping machinery near north-west of the pond and close to the surface, for water filtering).

5. Preliminary analysis of the boom deployment

The scenario being studied in this article is a boom to be towed from shore, near the tanker. The boom could be folded, or contained in a reel. The USV has to tow the boom and deploy the boom around the tanker. Fig. 13 shows a picture, that gives an example of on-shore reel with a boom. Recently, a similar system, with a reel, a toboggan, and an USV, has been introduced, with the USV coming from the reel to a receiving station (SPMarine, 2019).

At first sight the boom deployment could be judged a simple task. However if one does not want the boom to brush against the tanker during the deployment, things become more complicated. In absence of auxiliary boats, or devices that could help to separate the boom from the tanker, it would be required to pull completely the boom from shore, towing the boom relatively far from the tanker. After the complete boom has been put on the water, it may be necessary to adapt the boom geometry to the tanker. Fig. 14 illustrates how the first step of the deployment could be, before matching the boom to the tanker.

Then, it becomes pertinent to think about what can be expected from wind and currents. This environmental part of the situation might be convenient, as far as it helps to get a suitable shape for the boom being towed. Fig. 15 illustrates a favorable case. The USV moves from right to left (counterclockwise), towing the boom.

Taking as reference Fig. 15, suppose that the current takes the opposite sense. This would throw the boom against the tanker, unless the USV tried to harness the situation, which could become quite difficult. In such a case, it would be recommended to have another boom, near the bow of the tanker, and try the boom deployment from bow to stern.

There is an important remark to do, although it is evident. Towing a boom longitudinally takes much less force, than towing it transversely.

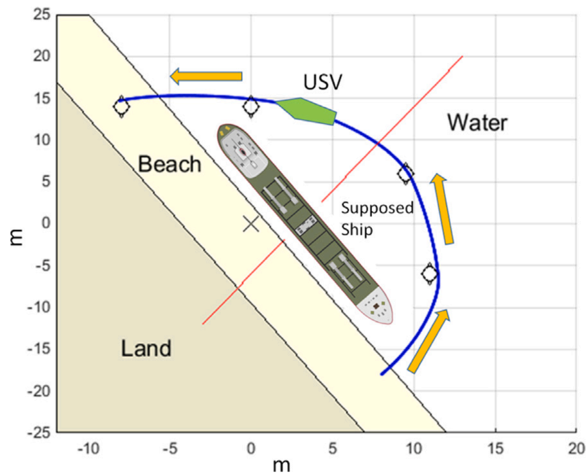


Fig. 16. The experimental plan for placing the boom around a supposed ship. The waypoints are represented as black diamonds.

Fig. 17. Photograph of the 50 m experimental light boom just when a deployment experiment finished.

Fig. 18. GPS trace of the USV (yellow curve) during a boom deployment.

In particular, as soon you have a U shape, towing forces would become larger, depending on the mouth dimension.

Let us consider the possible size of involved forces. The information from shipbuilders usually gives data on engine power; how this power transforms into propulsion force depends on gears and propellers. For instance, a 1000 kg weight rescue zodiac with a 44.74 kW engine could have 3.53 kN propulsion force, or with a gearbox 4.71 kN propulsion force.

For a boom with a mouth 100 m wide and draft 0.30 m, and a velocity relative to the water of 1 m/s, the required towing force would be 30.02 kN.

Looking at the usual ships for towing tasks, there are river tugs, 13 m long, with 34.32 kN bollard pull (Manor-Marine, 2017). High seas tugs could have from 88.26 kN to 882.59 kN bollard pull (Damen, 2017). Latest trends in harbor tugs were described by Artyszuk (2013).

Fishing ships offer another context with experience in towing. It is estimated (Prado and Drémière, 1990) that 74.57 kW trawlers would have about 9.80 kN bollard pull. This last reference also says that trawlers with 15–20 m length, and 74.57–149.13 kW would be used for nets with 20–30 m mouth opening. The speed of net hauling in coastal waters is in the range 15–40 m/min. Indeed, nets and booms are not the same concerning resistance to motion.

6. Scaled experiments of boom deployment around a ship

A basic study has been made, with our USV towing a experimental boom. The scenario considered was a simple deployment around a (supposed) ship. Fig. 16 shows how it was conceived. The first part is devoted to tow the boom away from the coast. While the boom moves, the U shape builds up, and so taking the boom towards the coast could mean a larger effort. For this reason, the last part of the trajectory tries an oblique approach to the border. Since our experiments are done in a pond, it is assumed that there are no currents; however, wind could have a significant effect.

The plan itself is expressed as a series of four waypoints. The curve depicted on the figure corresponds to the USV trajectory, as predicted by simulation (based on the USV model).

One of the main targets of the experiment is to confirm the predictions from our simulation system. Videos and pictures were taken; and the GPS traces of the USV during boom towing were acquired and saved. Another important target, is to provide an opportunity of direct observation of what may happen during the boom deployment.

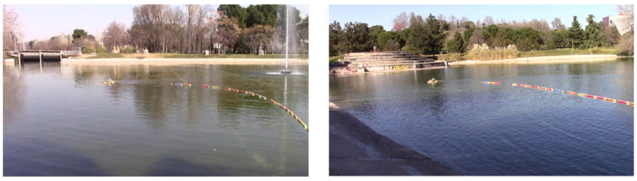
A light experimental boom was made especially for this experiment. The boom was 50 m long. Supposing that the boom draws a perfect semi-circle with a 10 m radius, it is only necessary 31.4 m of boom. However, more length should be allowed for other USV trajectories.

The experiment was made several times, with a fixed PWM setpoint (Fig. 8). Fig. 17 shows a picture of the result after one of the experiments. The USV should not approach the border, by the end of the experiment, in order not to run aground on the submerged beach.

The GPS trace of the USV along the deployment experiment is shown in Fig. 18 with respect to the satellite view of the pond.

Fig. 19 shows two photographs taken along one experiment. The first photograph, Fig. 19(a), was taken with the camera pointing to East side of the pond. It corresponds to the USV starting to pull the boom from shore, heading left from the pond jet (which means a danger for the USV). As the USV passes by the first waypoint, the U shape starts to develop. The second photograph, Fig. 19(b) now with the camera pointing North-East, was taken after some time, near the end of boom deployment, and shows the USV driving towards the shore. A video of the experiment is available (the link is given at the end of the article).

Fig. 20 compares the predicted motion of the USV while towing the boom (simulation), and what happened in reality (USV GPS trace). There was some south-east wind during the experiment.



(a) separating from shore while starting the U shape (b) the USV approaching to the shore, for ending the boom deployment

Fig. 19. Initial and final phases of boom deployment.

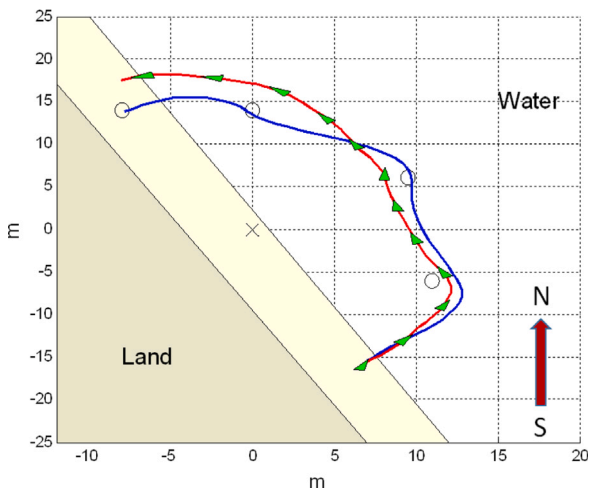


Fig. 20. Comparison of simulation and experiment: simulation of the USV motion while towing the boom (blue), GPS trace of the USV along the boom deployment experiment (red with triangles).

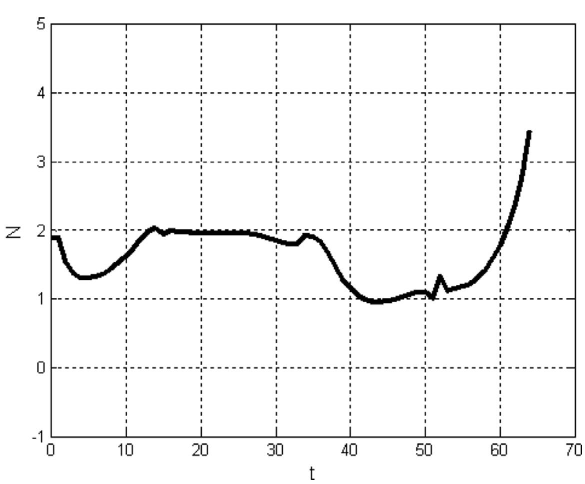


Fig. 21. Cable tension along the boom deployment.

By using the simulation, it is possible to compute the evolution of the cable tension along the boom deployment, which is shown in Fig. 21. The maximum value gives an important information on what tensile performance the cable should have. There is a significant tension growth near the end of the experiment, as the length of the deployed boom comes near its 50 m limit.

Notice that the information on cable tension, obtained with our simulation tool, is important for determining what propulsion force the USV should provide for adequate boom towing. The sharp peak in tension, by the end of deployment, suggests that adding a tension sensor

Table 2
Boom model parameters.

Link length = 0.7 m	I = 0.002 kg m
Link mass = 0.05 kg	m_a = 0.01 kg
μ_l = 0.05 N s/m	μ_{l2} = 0.15 N s^2/m^2
μ_t = 0.05 N s/m	μ_{t2} = 0.2 N s^2/m^2
μ_w = 0.015 N m s^2	

would be welcome, since it would give opportunities for extending the on-board control to take care of speed and thrust along the deployment.

Table 2 gives the boom parameters that have been used for the boom dynamics simulation.

7. Real scale simulation experiments for boom deployment planning

A clear advantage of simulation is that many different experiments, perhaps difficult to achieve in reality, can be done just with some computational effort. Another added value is that simulation can provide a lot of data, otherwise difficult to acquire in real-time. An example of this second aspect is that with simulation it is possible to follow in detail, as a sequence of snapshots, the changing shape of the boom as the deployment progress. Of course videos can be taken during real experiments, but numerical data would be really cumbersome to get (perhaps using GPS devices in each link of the boom).

This section is mainly devoted to boom deployment planning, with results at real scale obtained in simulation. The objective is to establish an adequate sequence of waypoints for the USV, in order to have an acceptable boom deployment around the target tanker.

In order to simplify the boom deployment planning, it could be assumed that when the USV turns around a waypoint, it follows approximately a circular arc. Therefore, USV paths can be built by connecting two types of pieces: arcs of circles, or straight line segments. In his pioneering work, Dubins showed that a car-like mobile robot with a given initial position and heading can arrive to a target final position and heading with exactly three sequentially connected such pieces (Dubins, 1957). The Dubins paths are the shortest paths for the car-like case (a nonholonomic vehicle). There are many papers focusing on this approach for several applications, like for example (Breivik and Fossen, 2004; Yong and Barth, 2006; Fossen et al., 2015).

The result of a path planning for a certain experiment (real or simulated), is a list of waypoints. In the case of a real experiment, this list is given to the Ground Station, which in turn transmit it to the USV. The USV navigation control takes care of going along the specified path, from one to another waypoint.

In a scenario with a long tanker and a relatively narrow river, it could be not possible to try the plan used in our scale experimental study (previous section).

Another basic planning for our boom deployment is sketched in Fig. 22. The idea is to have a narrow U mouth, also keeping the USV far from the farthest bank of the river. The first waypoint is placed near the tanker's stern. The second waypoint is relatively far (at right side of the figure). This waypoint is placed there in order to completely deploy the boom. The USV would have the hardest towing work when going from the third to the fourth waypoint, which marks the end of the operation. The figure shows the prescribed path, and captures one of the instants of the boom deployment.

Once the plan was specified, a deployment simulation was run. The results are presented in Figs. 23 and 24.

Fig. 23 shows the evolution of towing cable tension at the tip of the boom nearer to the USV. The turnings around waypoints can be easily identified, since tension decreases there. After the third waypoint, tension increases sharply because the USV effort on the boom becomes more perpendicular to the boom.

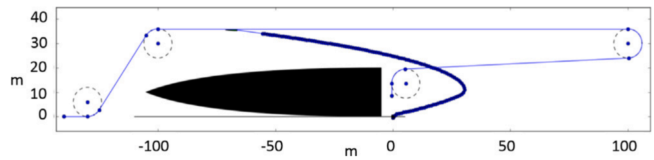


Fig. 22. Basic planning of the boom deployment for a river port; a particular instant of the boom deployment is also visualized.

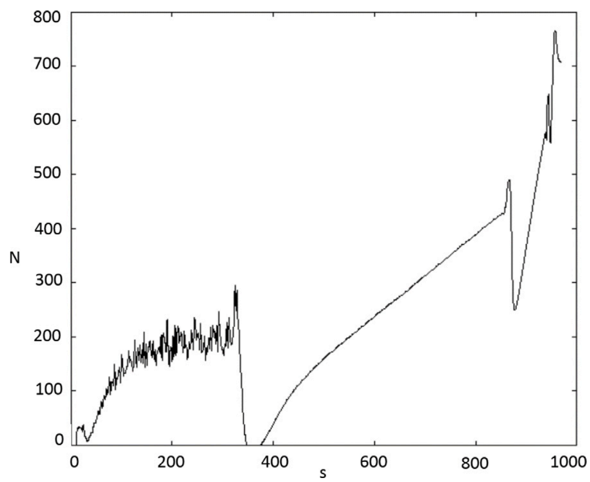


Fig. 23. Evolution of cable tension.

Table 3
USV model parameters.

$L = 5$ m	$m = 350$ kg
$\mu_l = 100$ N s/m	$I = 1000$ kg m
$\mu_t = 1000$ N s/m	$\mu_a = 1000$ N m s^2

The first part of the cable tension evolution, has a jagged profile. The simulation takes into account, as specified in the scenario definition, that the boom was folded at the initial point, on shore. The link by link unfolding, due to USV towing, means a complicated dynamics that translates to brisk changes in resistance to towing. It is even possible, with the simulation, to study in detail the unfolding process, if required for any reason. For the pond scaled study, the experiments, and simulation, started with the boom already extended on the border, so the initial part of tension curve was smooth.

The complete evolution of the boom deployment is shown in Fig. 24.

The parameters of the USV model being used in the simulation, were the following (see Table 3):

Table 4 gives the parameters of the boom model.

The simulation was developed in the Python language. The simulation code is available from Internet. It should be said that it requires large computation work, taking around one day for scenarios like the one selected in this section.

Table 4
Boom model parameters.

Link length = 1 m	$I = 0.16$ kg m
Link mass = 2 kg	$m_a = 1$ kg
$\mu_l = 0.003$ N s/m	$\mu_{l2} = 0.01$ N s^2/m^2
$\mu_t = 20$ N s/m	$\mu_{t2} = 100$ N s^2/m^2
$\mu_w = 2$ N m s^2	

8. Conclusion and comments

In this article the automatic boom deployment around a quayside moored ship has been explored. The deployment was done by means of an USV towing the boom and following an adequate path.

Considering that in real applications, the boom deployment would be done with a conventional USV, this article adhered to a basic USV waypoint steering navigation.

Several aspects of the planning were been considered, including forces and sizes, dynamic behavior of the boom, USV trajectories, etc. The research involved the development of a experimental system with a ground station, USVs, scale booms, and measurement devices. A series of experiments were made to show the successive steps of the research.

A main result of the research was to experimentally show that the automatic boom deployment with an USV can actually be done.

The article included the modeling of the boom dynamics that, together with a model of the USV and a model of the towing cable, which provided a comprehensive simulation environment. This environment was shown to be a useful tool for boom deployment planning in different scenarios, exemplified by a tanker moored in a river (Section 7 of the article). Part of the research activity has been oriented to provide experimental confirmation of the simulation prediction capabilities.

Both wind and currents can be considered by the simulation. Given a particular application case, with specific location boundaries and a concrete type of USV and boom, a series of plans could be established, for different currents, winds and tanker sizes. The results could be expressed in tabular format, with waypoint lists for each case.

From experimental observation it would be recommended for the development of a real scale USV, to incorporate the type of thrust vectoring available on tugs. Likewise, it would convenient to add auxiliary lateral maneuvering thrusters (for instance, near the bow). It would be preferred to use propellers for low-speed, high-torque operation. Another point is that adequate support should be given for human supervision and intervention, when needed. In our case, it was easy to visually follow the experiments; however, in real scale, it would be advisable to add cameras, perhaps drones, and real-time visualization on the ground station.

Probably, rather than deploying the boom from an off-shore reel, it would be better to design the USV for having a reel on-board, or at least a platform for a folded boom, and deploy the boom from the USV. This

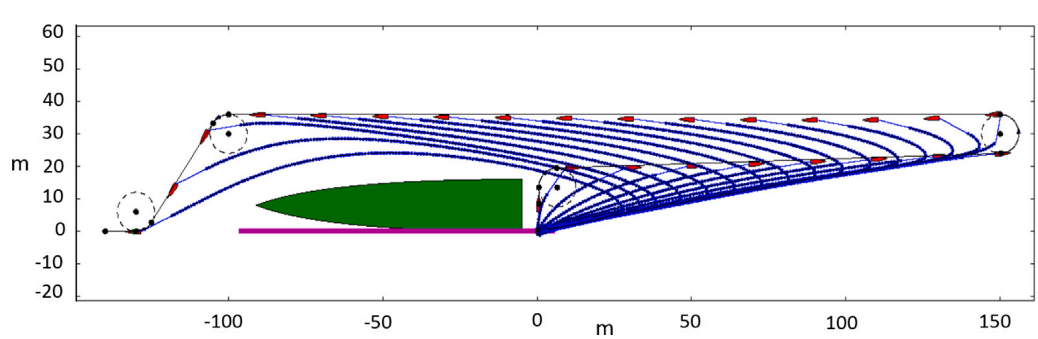


Fig. 24. Complete view of the boom deployment.

would represent a new research problem from the USV control point of view, since the dynamic characteristics of the USV would change along the deployment.

Concerning future research, since our USV is open for on-board software changing, more intelligent USV control can be investigated. For instance, optimization of trajectories, use of a tension sensor for thrust control, and control actions for avoiding deviations with respect to the prescribed path (large perturbations could appear during deployment).

We have in mind to use an aerial unmanned vehicle for looking at the boom shape from above, as it is deployed. In case of having, actually, an oil spill, this would be convenient for suitable guidance of the USV in order to encircle the spill. That is an interesting scenario for cooperative robotics.

Future work on the scenario treated in this article will focus on automatic planning flexibility, for tackling changes of tanker size, and wind and current conditions (perhaps re-planning if these conditions change). These are steps towards increased level of autonomy.

The simulation code can be accessed at:

GIT https://github.com/juanjimenez/pyships

Two videos of experiments at the pond are available from:

https://www.youtu.be/e2xQJVh71Y0

https://www.youtu.be/-p5uz-F-akY

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Juan F. Jimenez: Conceptualization, Formal analysis, Software, Methodology. **Jose M. Giron-Sierra:** Conceptualization, Investigation, Resources, Validation.

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