Proceedings of the 2018 Winter Simulation Conference
M. Rabe, A. A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson, eds.

MODELLING THE AUTOMATIC DEPLOYMENT OF OIL-SPILL BOOMS: A SIMULATION SCENARIO FOR SEA CLEANING

Juan Jiménez
José María Girón-Sierra

Universidad Complutense de Madrid
Departamento de Arquitectura de Computadores y Automática
Facultad de Físicas. Ciudad Universitaria. 28040 Madrid

ABSTRACT

Booms are extensively used for confining oil spilled at sea and for carrying it away from sensitive areas or toward a gathering point. The success of booming operations depends on effective boom deployment, which, in turn, is conditioned by the state of the sea – wind, tides, currents, and waves – and its effects on the spill spreading shape and speed. Planning the boom deployment beforehand could help overcome problems derived from sea condition. Besides, the employment of Unmanned Surface Vehicles (USVs) for towing spill recovery booms represents an interesting alternative to the use of ordinary vessels, and it could lead to a fully automatic oil spill recovery system. A basic tool has been developed in Python to simulate the deployment of booms towed by USVs. The aim is to explore simple trial scenarios, working out information that helps to prototype real USV-boom systems and to plan automatic deployments.

1 INTRODUCTION

According to the United Nations Review on Maritime Transport 2017 (United Nations 2017), the seaborne tanker trade – crude oil, refined petroleum products, and gas – reached a total volume of 3.1 billion tons during 2016 and, according to the U.S. Energy Information Administration, the total offshore oil production approached to 25.5 million barrels per day this same year. Although in recent times there have been global efforts to make oil production and transportation safer – mainly by hardening the legislation – the ever-present risk of oil spills cannot be ignored (ITOPF 2018).

When an accident takes place at sea and an oil spill occurs, it is important to counteract as fast and efficiently as possible. There are a number of possible actuations, such as *in situ* oil burning or the use of chemical or biological countermeasures. Depending on the features of the disaster, some of them could be more suitable for the situation than others. In any case, these measures require a previous evaluation of their potential impact on the environment. For this reason, responders still rely heavily on technology such as oil spill containment booms and skimmers.

Booms can be used in many different ways, depending on the area affected (ITOPF 2014). In coastal waters they could be deployed to protect sensible zones from the oil. They can also be deployed in berthing facilities, around tankers, during the loading or unloading process or during other high-spill-risk operations. When an accident takes place on open sea, it is common to use heavy-duty offshore booms, towed by two ships. The ships have to move jointly in order to contain and concentrate the floating oil. Then, a skimmer is used for physically recovering oil from the sea surface and for pumping it into a suitable storage container, like, for instance, a floating barge. Figure 1 shows an image of two vessels towing a boom.

Both, boom deployment and boom towing involve the performance of maneuvers that require skillful crews. These are not always available – or they might not be enough – when an emergency arises. Besides,

978-1-5386-6572-5/18/$31.00 ©2018 IEEE

Figure 1: Two ships towing an oil-spill recovery boom.

a non-stop working schedule could be desirable to reduce the damages as much as possible. But, human crews need to rest; thus, in most cases, it is not possible to hold a non-stop schedule.

The increasing development of autonomous vehicles during the last decade lets envision the automatic deployment and towing of oil spill booms, carried out by Autonomous Surface Vehicles (USVs). This could help to alleviate the hindrances already described. Autonomous systems could be replicated until reaching a suitable number of units and could work in a non-stop fashion as far as they would be properly refuelled. Some boom towing experiments, carried out by scale USVs have been reported by Giron-Sierra et al. (2015).

From the point of view of control systems, automatic boom deployment or towing are interesting and challenging scenarios. We can consider a set of successive layers to describe them easier.

A first ground layer concerns the design of USVs able to tow a boom. The engine and the steering system should have power enough to let the USVs move and maneuver under the external strain exerted by the boom. On top of this ground layer, a basic control layer is necessary for the auto-guidance – heading and speed control – of the USV.

In the case of more than one USV involved in the boom towing operation, the USVs have to coordinate their manoeuvres. Otherwise, the whole system could end up out of control and the boom broken. A suggestive approach to carry out the coordination among USVs is the application of cooperative control strategies (Arrichiello et al. 2006; Mas and Kitts 2014). They could be implemented as a new control layer on top of the basic control layer.

Lastly, a planning layer would be very convenient, to define optimal or a least suboptimal trajectories for the boom deployment. This layer could be distributed among the USVs taking part on an oil spill recovery action or it could be implemented in a central base station.

An important question still remains: How may we transfer the experience of well-trained crews to USVs? A first approach to be considered is the use of simulations to reproduce the deployment of spill booms. Simulations help to understand the effect of the boom on the USV movement, the magnitude of the strains involved in the towing process, and the control actions necessary to perform safe maneuvers. The experience acquired by simulation can then be employed for designing control strategies on real scenarios. Besides, the information obtained can also help in the USV design and to select the most suitable boom features and dimensions.

The following sections of this paper describe a tool developed in Python to simulate the deployment of booms towed by USVs. First, we briefly describe the equations used for modeling the dynamics of the USV and the boom. Then, some details of the simulation tool implementation are presented. Lastly, we show and discuss basic simulation examples and draw some conclusions.

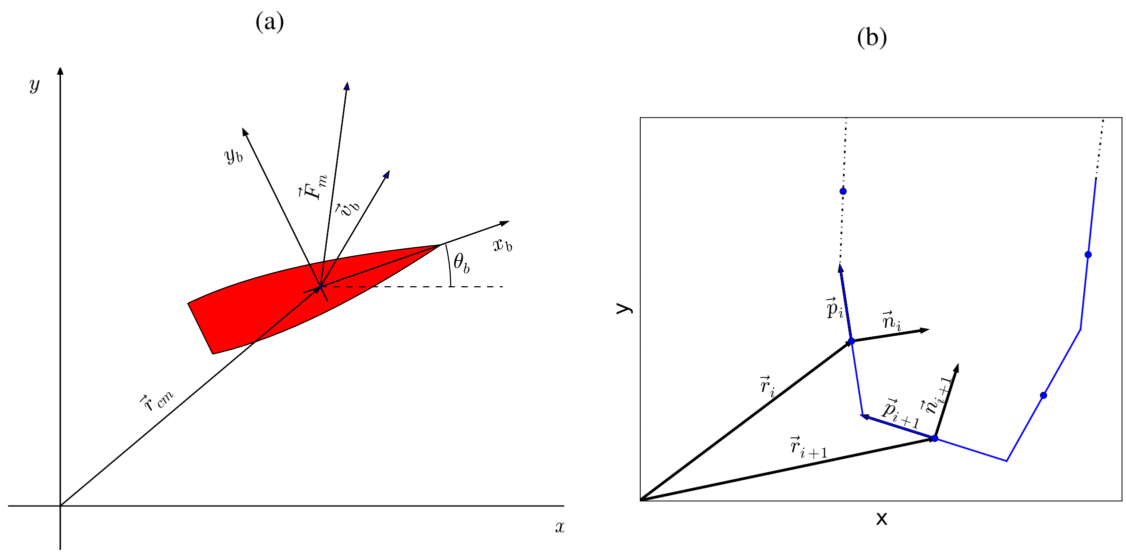

Figure 2: USV and boom layouts, showing the main elements used in their models. (a) USV layout, (b) Boom layout.

2 MODEL EQUATIONS

This section briefly describes the equations used for modelling the USV and the boom dynamics. A detailed explanation can be found in the paper by Jiménez (2016).

2.1 USV Equations

We use for the USV a 2D simplified manoeuvring model of a ship of length l_s, mass m_b and moment of inertia I_b (Fossen 2002). It has been conceived as a dynamical model which considers a generic propulsion force F_m applied to the ship's center of mass. Besides, a generic bearing moment M is applied to the ship.

In addition to the propulsive force and moment, the model considers also the resistance opposed by the water to the ship movement. Such resistance has been modeled as a two-terms force. One term is proportional to the ship speed and the other one is proportional to the squared speed. Coefficients μ_l and μ_{l2} take into account the ship contribution to the resistance in the length direction. The lateral resistance is modeled proportional to the ship length and to a second pair of coefficients, namely, μ_t and μ_{t2}.

Added masses m_A have also been modeled in an oversimplified way, following a similar approach to that employed for resistance. One constant coefficient is used to represent the added mass in surge direction and another one for the added mass in sway direction. Effects of added masses in ship turning are neglected.

External forces applied to the USV by tides or streams are taken into account subtracting the speed of the water from the speed of the USV and using this relative speed in the resistance terms just described in the previous paragraph. The model considers also the existence of a single external force F_e, applied to a single point on the ship hull and its corresponding moment M_e. This force can be used for modeling the existence of external strains such as those due to the presence of devices towed by the ship. Figure 2a shows the coordinate reference systems (CRSs) and forces employed to describe the dynamics of the USV.

The following equations may be applied to obtain the ship's linear acceleration components on the repose CRS and the angular acceleration, using the forces and momenta applied to the ship.

$$\begin{aligned}(m_b + m_{A\|}\cos(\theta_b) - m_{A\perp}\sin(\theta_b))\cdot a_{bx} = \\ F_{mx} - \mu_l\left[v_{bx}\cos(\theta_b) + v_{by}\sin(\theta_b)\right]\cos(\theta_b) \\ +\mu_t l_s\left[v_{by}\cos(\theta_b) - v_{bx}\sin(\theta_b)\right]\sin(\theta_b) \\ -\mu_{l2}\left[v_{bx}\cos(\theta_b) + v_{by}\sin(\theta_b)\right]|\vec{v}_b|\cos(\theta_b) \\ +\mu_{t2} l_s\left[v_{by}\cos(\theta_b) - v_{bx}\sin(\theta_b)\right]|\vec{v}_b|\sin(\theta_b) + F_{ex}\end{aligned} \tag{1}$$

$$\begin{aligned}(m_b + m_{A\|}\sin(\theta_b) + m_{A\perp}\cos(\theta_b))\cdot a_{by} = \\ F_{my} - \mu_l\left[v_{bx}\cos(\theta_b) + v_{by}\sin(\theta_b)\right]\sin(\theta_b) \\ -\mu_t l_s\left[v_{by}\cos(\theta_b) - v_{bx}\sin(\theta_b)\right]\cos(\theta_b) \\ -\mu_{l2}\left[v_{bx}\cos(\theta_b) + v_{by}\sin(\theta_b)\right]|\vec{v}_b|\sin(\theta_b) \\ -\mu_{t2} l_s\left[v_{by}\cos(\theta_b) - v_{bx}\sin(\theta_b)\right]|\vec{v}_b|\cos(\theta_b) + F_{ey}\end{aligned} \tag{2}$$

$$I_b\alpha_b = M - \mu_a l_s\omega_b - \mu_{a2} l_s\omega_b|\omega_b| + M_e \tag{3}$$

2.2 Boom Equations

The boom equations are derived from an oversimplified model of the dynamic of a boom 'link'. Each boom 'link' is considered as a rigid floating long and thin structure. Boom links are joined together building up the complete boom layout. They can move and rotate provided that the joints among the links remain connected.

Figure 2b shows a schematic view of the boom where the boom links have been represented as concatenated segments, The dots represent the location of the links' centers of mass. Also, the figure presents the layout of the normal $\vec{n}_i$ and parallel $\vec{p}_i$ unitary vectors, employed in the boom equations. Lastly, vector $\vec{r}_i$ represents the position vector of the links' centers of mass.

In a first approach, each boom link is considered under the action of the strains applied to its ends. Resistive forces are also taken into account, as in the previously described case of the USV. Added masses are considered only in the direction normal to the link. In the repose CRS, the total link mass is represented by a diagonal matrix:

$$m_{Ai} = \begin{pmatrix} m_l + m_{la}\cos(\theta_i) & 0 \\ 0 & m_l + m_{la}\sin(\theta_i) \end{pmatrix} \tag{4}$$

The following equations describe the dynamics of a link i of length $2l$, whatsoever. Henceforth, the boom will be considered as composed by a total number of m links,

$$\vec{T}_{i,i+1} - \vec{T}_{i-1,i} - \vec{F}_{ri} = m_{Ai}\vec{a}_i \tag{5}$$

$$\left(\vec{T}_{i,i+1}\cdot\vec{n}_i + \vec{T}_{i-1,i}\cdot\vec{n}_i\right) l - M_{ri} = I\alpha_i \tag{6}$$

where $\vec{F}_{ri}$ represents linear and quadratic resistance forces,

$$\vec{F}_{ri} = (|\vec{v}_i\cdot\vec{n}_i|s + |\vec{v}_i\cdot\vec{p}_i|q)\frac{\vec{v}_i}{|\vec{v}_i|} + (|\vec{v}_i\cdot\vec{n}_i|s_2 + |\vec{v}_i\cdot\vec{p}_i|q_2)\vec{v}_i \tag{7}$$

and M_{ri} represents linear and quadratic resistance momenta.

$$M_{ri} = A_1\omega_i + A_2\omega_i|\omega_i| \tag{8}$$

Equation (5) describes the movement of the (i) link's center of mass, while Equation (6) describes the rotation of the link around its center of mass. Notice that strains are denoted by pairs of letters $i, i+1$ corresponding to the strain in the hinge that joints link i with link $i+1$.

These equations are valid for all the links of the boom except for those located at the ends of the boom. These links have a tip connected to the next link while the other tip is free. These tips can be attached to a boat through a towing cable, remain free, or, in general, be under the influence of an external force: $\vec{F}_{left}$ for the link located at the left boom end and $\vec{F}_{right}$ for the link located a the right one.

So, for the link located at the boom left end,

$$\vec{T}_{1,2} - \vec{F}_{left} - \vec{F}_{r1} = m_{A1} \cdot \vec{a}_1 \tag{9}$$

$$\left(\vec{T}_{1,2} \cdot \vec{n}_1 + \vec{F}_{left} \cdot \vec{n}_1\right) l - A\omega_1 = I\alpha_1 \tag{10}$$

and for the link located at the right end,

$$\vec{F}_{right} - \vec{T}_{m-1,m} - \vec{F}_{rm} = m_{Am} \cdot \vec{a}_m \tag{11}$$

$$\left(\vec{F}_{right} \cdot \vec{n}_m + \vec{T}_{m-1,m} \cdot \vec{n}_m\right) l - M_{ri} = I\alpha_m \tag{12}$$

The set of equations described above does not form a complete set. It is necessary to add a closing condition. This condition establishes that the links should remain connected. To fulfil this condition is enough to impose (Figure 2b) that,

$$\vec{r}_i - l\vec{p}_i - l\vec{p}_{i+1} - \vec{r}_{i+1} = 0 \tag{13}$$

for any consecutive pair of links, and taking time derivatives twice we obtain,

$$\vec{a}_i + l\vec{p}_i\omega_i^2 + l\vec{n}_i\alpha_i + l\vec{p}_{i+1}\omega_{i+1}^2 + l\vec{n}_{i+1}\alpha_{i+1} - \vec{a}_{i+1} = 0 \tag{14}$$

Equations (5), (6), (9), (10), (11), (12) and (14) form a complete set of equations and it is possible to solve them numerically to obtain the movement of the boom. To solve the equations, first, a new system, containing only the strains applied on the hinges, is derived from the equations for two consecutive links and eliminating accelerations $a_i, \alpha_i, a_{i+1}, \alpha_{i+1}$.

Such a system can be expressed in matrix form as $H \cdot T = b$, where H is the $2 \cdot m \times 2 \cdot m$ coefficient matrix of the system, T represents a column vector with the components of the strains

$$(\ldots\ T_{i-1,ix}\ T_{i-1,iy}\ T_{i,i+1x}\ T_{i,i+1y}\ T_{i+1,i+2x}\ T_{i+1,i+2y}\ \ldots)^T,$$

and b is a vector of independent terms.

The previous equations allow us to obtain the strains applied to an inner boom link. The links located in the boom ends should be described in another way, as far as they are attached to the boom only by one side. This affects the two first and the two last equations of the system for the boom strains, $H \cdot T = b$.

Assuming that external forces $\vec{F}_{left}$ and $\vec{F}_{right}$ are applied to the ends of the boom, the two first and the two last equations of the system can be obtained from Equations (9), (10) and (11), (12), following the same development used for an inner link. Obviously, if an end of the boom is left free, the previous equations are still valid just taking $\vec{F}_{left} = 0$ or $\vec{F}_{right} = 0$, depending on the released boom end.

2.3 Towing Cables

The boom is attached to the towing ships by means of towing cables. It is possible to consider the stress in the cable as a function of its stretching $\Delta d = d - d_0$ over its nominal distance d_0,

$$T_{cbl} = \begin{cases} 0 & if \Delta d < 0, \\ \frac{E}{d_0}\Delta d & if \Delta d \geq 0 \end{cases} \tag{15}$$

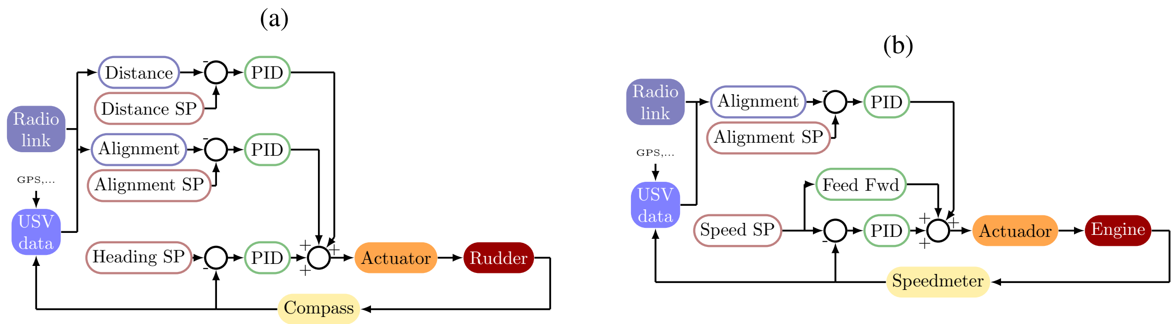

Figure 3: Cooperative control systems. Acronym SP stands for Set Point, (a) Heading control, (b) Speed control.

where E is Young's elasticity module (neglecting the effect of cable section change).

The strain of the cable can be obtained calculating the distance between the points the cable is attached to, usually the aft of the towing ship and the corresponding end of the boom,

$$\begin{aligned} d_l &= |\vec{r}_{cm} - \frac{\vec{l}_s}{2} - \vec{r}_1 - \vec{p}_1|^2, \quad \text{SoL (ship on the left)} \\ d_r &= |\vec{r}_m - \vec{p}_m - \vec{r}_{cm} + \frac{\vec{l}_s}{2}|^2, \quad \text{SoR (ship on the right)} \end{aligned} \tag{16}$$

and subtracting the length of the towing cable from this distance. Of course, the direction of the stress can be obtained as the direction of the cable itself,

$$\begin{aligned} \vec{u}_{cblr} &= \frac{\vec{r}_{cm} - \frac{\vec{l}_s}{2} - \vec{r}_1 - \vec{p}_1}{d_l}, \quad \text{SoL} \\ \vec{u}_{cbll} &= \frac{\vec{r}_1 - \vec{p}_1 - \vec{r}_{cm} + \frac{\vec{l}_s}{2}}{d_r}, \quad \text{SoR.} \end{aligned} \tag{17}$$

Now it is possible to identify the forces applied to the aft of the ships and to the boom ends in Equations (1), (2), (3), (9), (10), (11), and (12) namely,

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

2.4 Cooperative Control

Whenever two ships take part in the towing of a boom, it is necessary for them to act in a coordinated way. In a first approach, they should navigate at the same speed, aligned and keeping a constant distance between them. In the case of an automatic towing, carried out by USVs, such coordination can be achieved applying cooperative control strategies.

Figures 3a and 3b depict heading and speed control systems on board a USV model. Both control systems act using information supplied for the USV-mate(s) and have to deal with several set points (SP) simultaneously. Data from other USVs are gathered using a radio link. These data comprise the state variables of the sender, i.e., position, speed, and heading. Each USV has a kinematic model of its mate(s) and can estimate its movement between two consecutive radio data receptions.

In the context of multi-agent systems, cooperation is often linked to the concept of decentralised coordination (Wooldridge 2009). In the present case, the cooperation is implemented at a lower level. Each USV is aware of its mate situation just in order to achieve its own set points.

```
>>> uno.listar()

 USV parameters:
-------------------------------------------------------------
ide      :identification number                    1
thewjmax :Maximum water-jet/rudder turn angle  0.52
Ac       :Distance from the rudder axis to CoM 10.0
mb       :USV mass                             1000.0
mA       :added mass                           [ 0.  0.]
mul      :damping linear coefficient  (surge)  1000.0
mul2     :damping quadratic coefficient(surge) 0.0
Ib       :Inertia moment                       1000.0
mua      :damping coefficient (yaw)            1000.0
mua2     :damping quadratic coefficient(yaw)   0.0
ls       :length                               2.0
mut      :damping linear coefficient(sway)     10000.0
mut2     :damping quadratic coefficient(sway)  0.0
pmax     :maximum engine power                 36750.0
Tsf      : time constant of the USV engine     0.1
Tsw      : time constant of USV guiding system 0.1
tipo     : type of USV propulsion system       waterjet
cfr      : form factor for rudder guided USVs  100
------------------------------------------------------------
variables and their meaning (values are omitted)
------------------------------------------------------------
pb       :position
vb       :speed
vr       :speed relative to water
ab       :acceleration
alfab    :angular acceleration
wb       :angular speed
theta    :heading
Fm       :exerted force
setl     :engine setpoint
setw     :heading setpoint
thewj    :waterjet/rudder orientation
M        :moment applied to the USV
tiempo   :USV simulation time
------------------------------------------------------------
```

```
>>> cd1.listar()

 boom parameters
----------------------------------------------------------
esl   :number of elements                        10
s     :element surface                           2.0
s2    :element thick                             0
q     :damping coefficient (transverse)          0.1
q2    :damping quadratic coefficient (transverse)0
A     :damping coefficient (turning)             10.0
Anch  :Tip(s) anchored to the dock               [ 0.  0.]
L     :half length of an element                 0.5
m     :element mass                              1.0
mA    :element added mass coef. (transverse)     0
Fd    :force applied to the boom right end       [ 0.  0.]
Fi    :force applied to the boom left end        [ 0.  0.]
I     :moment of inertia                         0.08333
mtr_s :method to calculate the strains matrix    <bound method
 cadena.mtrb_s of <boom.cadena instance at 0x0B884710>>
----------------------------------------------------------
 Variables and their meaning (values are omitted)
-----------------------------------------------------------
normal:unit vector normal to the elements
para  :unit vector parallel to the element
cms   :elements center of mass
v     :elements speed
vr    :element speed ref. water
vmod  :element speed norm
a     :element acceleration
per   :element external perturbation
alfa  :element angular acceleration
w     :element angular speed
T     :strains
M     :strain matrix
B     :Independent terms to calculate T, from M*T = B
----------------------------------------------------------
```

Figure 4: List of attributes for classes `barco` and `cadena`.

This approach proves useful for dealing with basic maneuvers. It is fully reactive and alleviates the computational load in the USV on-board equipment.

3 SIMULATION TOOL IMPLEMENTATION

Equations (1) to (18) form a complete set, i.e., after integration they are suitable to describe the time evolution of USVs and boom states, provided the initial conditions are known.

Numerical integration of these equations is the core of the system simulation. Departing from some configuration of the system at initial time t_0 and selecting an integration step Δt, the motion equations for the USVs and the boom are integrated step by step until a final simulation time t_f is reached. It is interesting to notice that in each integration step the simulation has to calculate the strains in the hinges between consecutive boom links by solving the system $H \cdot T = b$ already described. The computational effort grows with the length of the boom.

We have chosen Python to develop the simulation environment. There are several reasons for this. First, it is a scripting language that allows us fast prototyping and testing. Second, the use of Python's modules Numpy and Scipy gives access to suitable algebraic numerical routines. In addition, the Matplotlib module provides a rather good set of tools for graphical representation.

The simulation relies on two basic classes: the class `barco` to instantiate software models of USVs and the class `cadena` to instantiate software models of booms. Figure 4 shows the lists of attributes defined for both classes.

Class `barco` defines two kinds of attributes for USV objects: USV parameters and USV variables. USV parameters represent design features and USV variables are used for describing its state.

The three main procedures belonging to the class `barco` are:

- `movimiento(.)`, which defines and integrates the dynamical equations of a USV instance. It also can simulate the transmission of the USV's state to other USVs.

- `controlador(.)`, which implements speed and heading USV controllers. It can be configured for single USV navigation or for cooperative boom towing.
- `propulsion(.)`, which implements the USV propulsion and bearing systems. At present, there are only two possible choices. The first one combines the use of a normal propeller and a rudder. The second one is intended to simulate outboard or water-jet propulsion systems.

There are other auxiliary procedures, to perform graphical representations of the USV and its trajectory, to make changes between CRSs, to obtain lists of attributes, and lastly, a procedure for path-planning based on Bezier's curves.

Likewise, the class `boom` defines a set of attributes to represent boom features and boom state and it implements two main procedures:

- `movimiento(.)`, which deals with the dynamical equations of the boom.
- `mtr_s(.)`, which calculates the strain values between the boom links.

The actual procedure implemented by `mtr_s` varies depending on the length of the boom and the boom end's conditions. For booms with more that 30 links the procedure uses algorithms for sparse matrices manipulation. The boom end's conditions can be: free, hitched to a USV by a towing cable, or moored to a dock. Cables for towing or mooring are considered part of the boom and their features can be included as parameters when calling the boom class constructor.

To complete the simulation toolbox, there are functions to include maps of tides or streams and functions for path planning using Dubing's paths.

Simulations are performed following the scripting philosophy of Python. Thus, the code is written using scripts to define the classes and functions just described. We also employ a script template, which is adapted in each case to the specifications of the scenario under study. The code is available in GitHub (https://github.com/juanjimenez/pyships).

4 SOME SIMULATION RESULTS

4.1 Individual Control

One interesting application of simulations is the study of different control strategies. In previous sections we have pointed out that it is necessary to coordinate the control actions of USVs when they are towing a boom together. We can design a simple scenario to test it.

The initial conditions of the simulated experiment are as follows: a boom 20m long composed of twenty links of 1m each extends on all its length in east-west direction, except for the first and last links which are pointing northwards. Each of these boom-end links is hitched to a USV heading north, using a 5m long towing cable. The whole system is at rest when the USVs start to tow the boom. Each USV tries to keep its north course and to reach a stable speed of 1m/s, using its own control system and ignoring the actions of the other USV. There is no action to maintain a constant distance between both USVs.

Figure 5 shows the two possible results of the scenario. Both figures show the successive dispositions (traces) of the two USVs, represented by triangles, and the boom, represented by a black line with dots to mark the center of the boom links. The lines on the boom's tips are the towing cables. These traces are represented every ten seconds.

Figure 5a depicts an expected result, the system under the action of individual heading control systems is stable and has an asymptotically stable equilibrium point: both USVs suffer a lateral shift due to the strain induced in them by the boom and their trajectories tend to converge. Figure 5b shows a more hypothetical result: the bearing systems of the USVs reach a saturation point and are not able to counteract the torque caused for the boom on the USVs. The system as a whole becomes unstable and ends up with the USVs pulling the boom in opposite directions. Of course, in real situations, it is more likely that the boom would be broken before reaching this final situation.

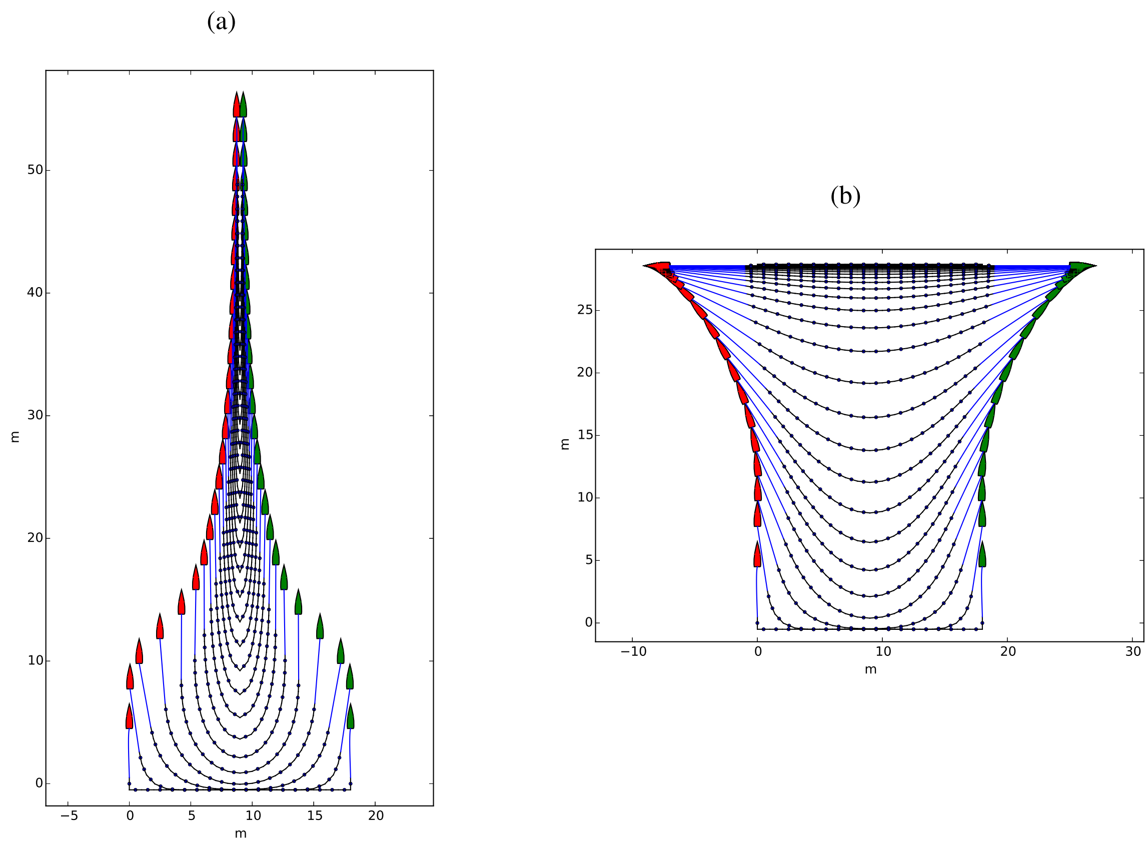

Figure 5: Two undesirable situations the system may end up, when only individual control is applied to the towing USVs, (a) Non actuators saturation, (b) Actuators saturation

Looking at both results, we can conclude that the equilibrium point of the system has a finite basin of attraction, limited by the saturation of the USV actuators. In any case, the simulation results indicate that it is not possible to tow the boom without coordinating the actions of the USVs.

4.2 Cooperative Control

As a second example, we are going to include in the scenario the cooperative control described in Section 2.4. USVs and boom parameters are set to the values shown in Figure 4. In addition, we will use a longer boom: 200m. The initial conditions of the simulation are very similar to those used in the previous example: the boom extends on all its length in east-west direction and it is hitched to two USVs using 5 m long towing cables. The USVs start up from repose and have to reach a steady navigation state with 45^oNE course, 1m/s speed and have to keep a constant distance of 20m between them.

Figure 6 depicts the resulting traces of the simulation, every ten seconds. The USVs are initially represented at $[0,5]$, and $[200,5]$. The cooperative control system balances four variables: the USVs' speeds, their heading and, also, the alignment and distance between them. Initially, the major control effort tries to reduce drastically the distance between the USVs. The result is that they sail directly towards each other. As the distance between them decreases, the effort for the parallel alignment dominates and, gradually, they begin to turn towards their final heading. Eventually, both USVs stabilise their bearing, reaching the prescribed steady navigation state.

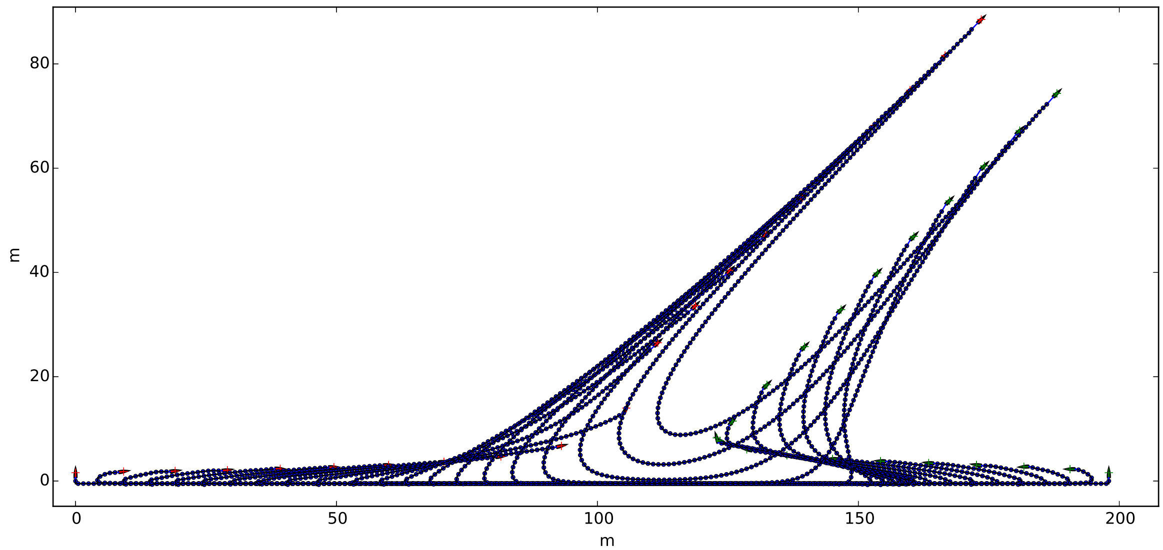

Figure 6: Two USV towing a 200m boom. Final heading: 45^oNE. Final speed:1m/s. Time between system traces: 10s

To complete the analysis of this scenario, Figure 7 shows the time evolution of most relevant variables during the boom-towing process. Figure 7a shows the stress supported by the towing cables. During, roughly, the first 80*s* the strain is low and it increases slowly. It corresponds to the first stages of the process, when both USVs are approaching each other. Most part of the boom remains at rest, even though, gradually new links at both ends are joining the movement. Figure 7d corroborates the results; we can see a fast turning of both USVs during the first seconds of the simulation. The port USV takes course 0rad, which means it takes an eastwards course. The starboard USV takes course π *rad*, which means it takes a westwards course.

Between seconds 80 and 120 and centered around second 100, there is a clear transition. The strain exerted on the port USV increases and the strain exerted on the starboard USV decreases to zero. If we take a look on Figure 7b, the reason is clear: the port USV's speed increases and the starboard USV's speed decreases. Figure 7c shows that the USVs have reached the distance set-point of 20m. So, the speed controllers make the port USV accelerate and the starboard slow down in order to align them. At the same time, Figure 7d shows how both USVs turn again towards their set-point course 0.78rad, i.e., 45^oNE.

From second 120 to 200, the USVs are sailing steadily keeping their course, distance, and alignment. Nevertheless, the speeds have not reached a steady value yet. We can see the reason looking at Figure 6. The last traces of the USVs-boom system are not completely symmetrical. Moreover, the USVs are sailing aligned and with a common course before the central section of the boom starts to move. Looking at Figure 7a, we can see their effect in the strain. For both USVs the strain increases, as new boom links start to move. But, due to the asymmetric boom layout, the starboard USV needs to pull stronger. Eventually, when all the boom is moving and its layout becomes more symmetrical, the speeds of the USVs tend to reach their set point.

Coming back to the cooperative control system, there are two interesting remarks. First, the system is able to stabilize the USV movement without taking any measurement of the boom strength. The forces exerted by the boom are managed as perturbations. This suggests that the control system would be able to govern the USVs in more realistic scenarios, for instance high seas, provided the USVs had been suitably designed to carry out their task.

Second, the proposed cooperation schema, albeit rather simple, is enough for towing the boom and performing simple maneuvers. Nevertheless, the system would require a higher-level coordination system

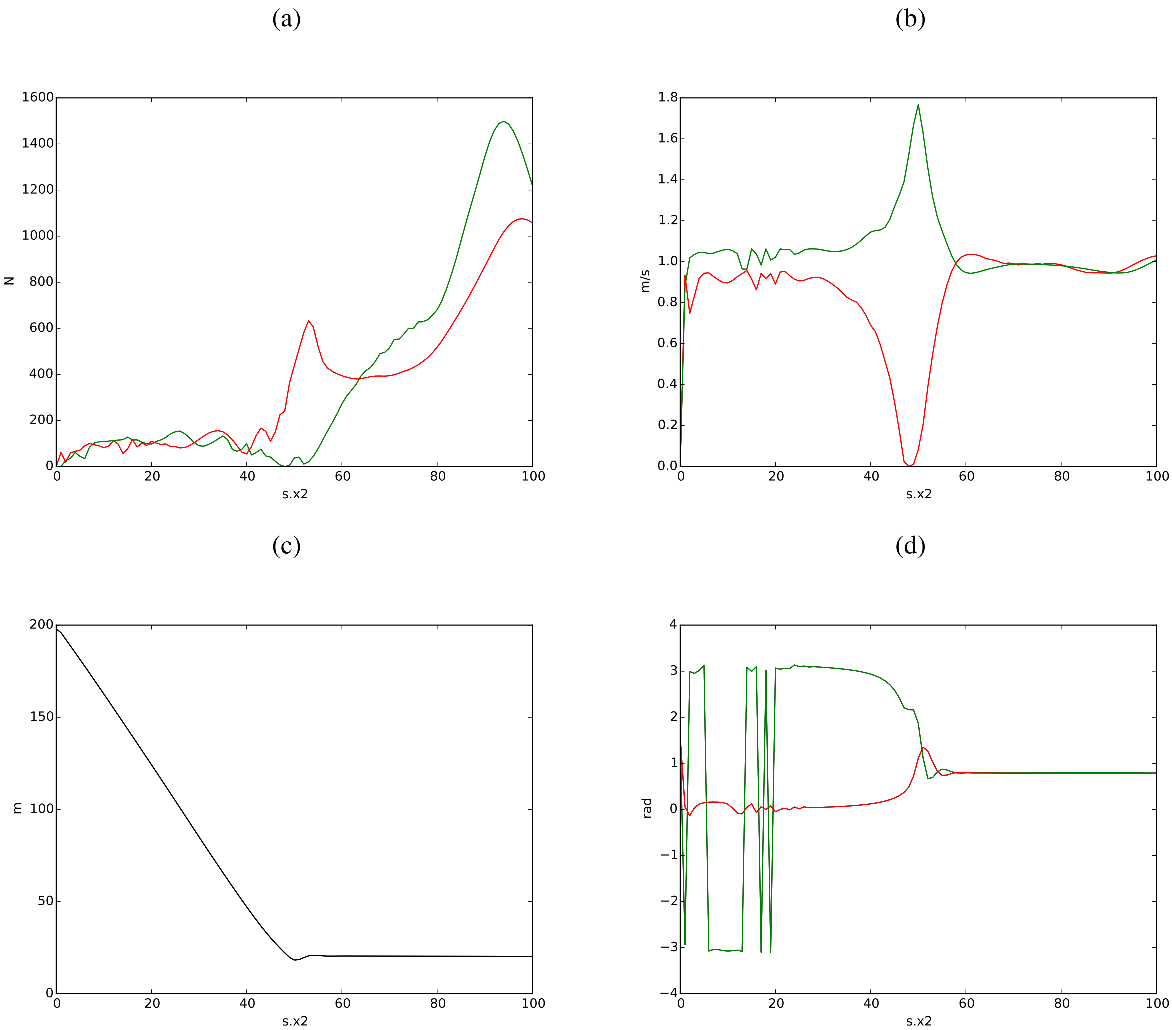

Figure 7: Time evolution of principal system variables for the two USVs boom towing scenario, (a) Towing cables strain, (b) Speed, (c) Distance, (d) Heading

for updating the set points defined for the USVs, according to the state of the mission. For instance, the common course for both USVs should be modified according to the fuel leak position distance, which is likely to change during the USVs approach. Also, the USVs should navigate close to each other when they are far from the slick and they should split wider when they are arriving to the slick, in order to take in as much oil as possible.

Lastly, it is worth noticing that this higher coordination system could be implemented in a decentralized and cooperative way, allowing the USVs to dynamically coordinate their activity. Modeling this coordination requires another kind of simulation, where maneuvers are considered just as feasible or infeasible, leaving apart the dynamic details of maneuvers.

5 CONCLUSIONS AND FUTURE WORK

The paper presents a simulation tool to model the behavior of recovery oil spill systems consisting of oil spill booms and USVs to tow the booms. The aim is to aid both, in the design of automatic recovery systems and in the planning of feasible maneuvers to recover or contain the spilled oil.

The design of the control system represents an important aspect of the system design. In this paper, a cooperative control system is proposed and an example of its performance presented. This is a major contribution that facilitates the collaboration between the USVs.

The simulation tool allows for prototyping USVs by testing their performance and towing capacity in many different scenarios. It would be the first step to develop real automatic spill oil recovery systems that can undertake sea cleaning-tasks in a faster and more efficient way. Basic maneuvers, whenever they prove feasible, would be the basis for dealing with complete oil-spill recovery scenarios: First, coordinating the couple of USVs that tow a boom and then coordinating groups of couples of towing USVs.

Future goals will be (i) to improve the USV control system for dealing with situations where the system has reached unstable situations and it is no longer possible to recover it with the standard control system, (ii) to modify USV and boom classes to include new features such as 6 DOF USV models, seekeeping, etc. and (iii) to perform new experiments with scaled USVs and booms to improve the accuracy of the simulation.

REFERENCES

Arrichiello, F., S. Chiaverini, and T. Fossen. 2006. "Formation Control of Marine Surface Vessels Using the Null-Space-Based Behavioral Control". In *Group Coordination and Cooperative Control*, edited by K. Y. Pettersen et al., 1–19. Berlin, Heidelberg: Springer.

Fossen, T. I. 2002. *Marine Control Systems*. Trondheim, Norway: Marine Cybernetics AS.

Giron-Sierra, J. M., A. T. Gheorghita, G. Angulo, and J. F. Jimenez. 2015. "Preparing the Automatic Spill Recovery by two Unmanned Boats Towing a Boom: Development with Scale Experiments". *Ocean Engineering* 95:23–33.

ITOPF 2014. *Use of Booms in Oil Pollution Response*. Technical information Paper no. 3. Technical report, The International Tanker Owners Pollution Federation Limited.

ITOPF 2018. *Oil Tanker Spill Statistics 2017*. Technical report, The International Tanker Owners Pollution Federation Limited.

Jiménez, J. 2016. *Notes on the Development of a Model for Spill Boom Towing*. Technical report, Universidad Complutense de Madrid.

Mas, I., and C. Kitts. 2014. "Cooperative Tasks Using Teams of Mobile Robots". In *IAENG Transactions on Engineering Technologies*, edited by H. K. Kim et al., 83–99. Dordrecht, The Netherlands: Springer Science+Business Media.

United Nations. 2017. *Review of Maritime Transport*, UNCTAD/RMT/2017. United Nations.

Wooldridge, M. J. 2009. *An Introduction to MultiAgent Systems*. 2nd. ed. Chichester, UK: John Wiley & Sons Ltd.

AUTHOR BIOGRAPHIES

JUAN JIMÉNEZ is a professor in the Department of Computer Architecture, Systems Engineering and Automatic Control at Complutense University of Madrid. His current research interests are focused on Distributed Control Systems and Cooperative Control Systems. He was a scientific researcher in Centro Nacional de Investigaciones Metalurgicas (CSIC) (1993-2003). He is IEEE member. His e-mail address is juan.jimenez@fis.ucm.es.

JOSÉ MARÍA GIRÓN-SIERRA is a professor in the Department of Computer Architecture, Systems Engineering and Automatic Control at Complutense University of Madrid. His current research interests include applied automatic control and simulation: ships, airplanes, spacecrafts, robotics, logistics, process control, high-speed ships, simulation, real-time remote monitoring and control, optimization based on genetic algorithms, and estimation with neural networks. He is IEEE member. His e-mail address is gironsi@fis.ucm.es.