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Preparing the automatic spill recovery by two unmanned boats towing a boom: Development with scale experiments

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ABSTRACT

The menace of floating spills is frequently solved using a team of ships towing a boom. This operation involves specific control and coordination aspects. Some automatic advice, on board the ships, could be helpful for the pilots. Moreover, it could be convenient to have the alternative of using unmanned boats, especially if the spill represents a danger for humans. This paper studies the control and coordination needs for automatically towing a boom, and proposes the use of unmanned boats with autonomous control. The research is supported by simulations and experiments with scaled boats towing a boom. Promising results have been obtained.

1. Introduction

The motivation of this work is related to an environmental catastrophe that happened when the ship named 'Prestige' sank near North-West Spain, throwing large quantities of crude oil to the sea, and spoiling the coast along hundreds of kilometers. From time to time, TV reports showed opportunity teams of fisher's ships towing booms. From our point of view, it seemed to be not an easy task, and we decided to build two scaled ships and to experimentally study what might happen. Based on this study, our desire was to finally arrive to fully automated recovery operations using unmanned boats or ships.

From years ago our research focused on translating mobile robotics techniques to ships on an experimental basis. Three autonomy levels were contemplated: to have a human pilot on board, to have a remotely operated unmanned ship, or to have an autonomous unmanned ship. The use of scaled ships for the last two levels is very convenient for experimental work. In case of human on board, some degree of collaboration between human intervention and automated operation could be established, the mildest automation contribution could be to offer just an advising system to the pilot. In any case, it is useful to consider the most exigent level. Therefore, the target considered in our research is to devise autonomous unmanned vehicles for the boom towing operations. This kind of marine vehicle is denoted in this article as ASV (autonomous surface vehicle).

Fig. 1 illustrates the kind of operation to be automatically performed.

Our experimental system has two ASVs and a ground station. Through a digital radio link the ground station can interrupt the autonomous behavior of the vehicles, and then be used for remote control when opportune. However this is unusual. Normally, the ground station is used for sending waypoints or other behavior specifications to the ships, before the actual operation starts, and then it remains in passive mode, just receiving data from the ships.

The operation is automatically planned before start. The system only needs information on three positions: origin, floating spill, and final destination.

Once the operation starts, the ASVs tow the boom towards the objective, minimizing the towing effort, near the objective the ASVs deploy and advance, and finally get closer, confining the spill; then the formation moves towards the destination. It is always possible to modify the plan during the operation.

The research proceeded step by step, with experimental confirmation in each phase. The first tasks were devoted to build the experimental system and to establish an adequate motion control of the ASVs. Then, formation control aspects were tackled. After that, the research focused on boom towing, with many different experiments. As expected, during the research a number of control issues appeared, mainly related to keep the formation along the planned operation. It is not the same problem as keeping a parallel formation of free ships, because of the towing effort and the physical link between ships through the boom.

The order of the article essentially reflects the sequence of steps just described. After considering the background pertinent for this research, the article introduces the experimental system, with the ASVs and the ground station, and then pays attention to the motion control of the ASVs at individual level. The article continues with a section that considers how to get a parallel formation of free (not

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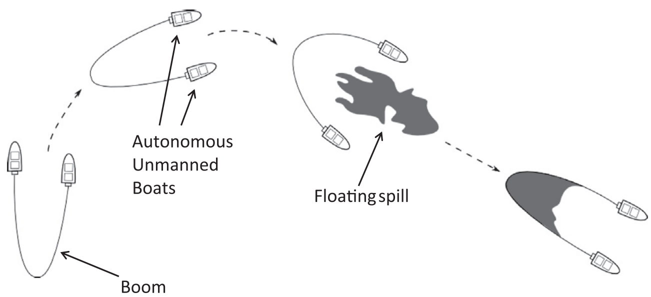

Fig. 1. An sketch of the proposed automatic spill recovery operation using two ASVs.

mutually linked) ships. Next, a subsequent section focuses on the most peculiar aspects of the article: the dynamic phenomena involved in towing, and how to maintain the parallel formation while towing. Once these aspects were under control, it was possible to design and execute fully automated operations; this is described in the sixth section. Finally, the last, short section draws some conclusions and comments immediate future work. As it will be seen along the article, the experimental results already obtained are quite encouraging.

2. Background

In their article on oil spill response planning, Zhong and You (2011) give the following details of what happened with the Deepwater Horizon disaster in the gulf of Mexico: 210 million gallons of crude oil was released affecting 180,000 km^2 of ocean surface, 39,000 personnel, 5000 vessels and 110 aircraft were involved in cleaning, over 700 km of booms were deployed.

Our research focuses on boom towing for spill recovery. A lot of information about marine spills and remediation can be accessed from 'The International Tankers Owners Pollution Federation Limited (ITOPF)' web site; in particular, the use of booms in oil pollution response is well described in one of the documents of that site, ITOPF (2014). The following special interest information items can be extracted from this document. Most conventional booms designs are not capable of containing oil against water velocities much in excess of 1 knot (0.5 ms^{-1}). There are several types of booms, from inflatable low-cost, to complex structures combining curtains, chains, and other parts. The approximate force on a 100 m length of boom with a 0.6 m skirt in a 0.5 knot current would be 375 kg. Booms should not be attached directly to towing vessels, instead towing lines of sufficient length should be used between boom ends and the ships; a typical case would be lines of 50 m for towing a 300 m boom. Vessels should be able to maintain the correct configuration of the towed boom at very low speeds.

Another source of professional information on spill recovery is the 'International Oil Spill Conference (IOSC)' repository, accessible from the web. A detailed parameter study of a boom is presented in Chung et al. (1973), including an empirical formula for determining tow-line tensions and a series of design recommendations, like that the boom length should be much smaller or much larger than the average wavelength (the study pays attention to the effect of waves on the boom dynamics). In their short contribution (Allers and Penny, 1995), it is sustained that the role of a recovery system is first to contain spilled oil and then to concentrate the oil such that skimmers may operate with efficiency; a V-shape boom geometry was recommended. A containment-recovery system is described in Glaeser (1973), with photographs and sketches; the system includes two tow-boats, the boom, and a tug between these boats towing a barge for skimming. In Nordvik et al. (1995), a full scale testing at sea is presented, with three ships towing a double-U boom; four different booms were tested, with lengths of 106.7 m, 400 m, 200 m, and a combination of several booms; it was found that the measured loads were clearly higher than those predicted by theory.

An interesting part of the information provided by IOSC, concerns reality: what can be used, how to mount an organization, what to do in case of an emergency. Two papers in particular, Hall et al. (2011) and Parson and Majors (2011) give the principal details of how a nearshore Vessel of Opportunity skimming capability was organized as part of the response to the Gulf of Mexico disaster. One of the main tactics that were decided, as represented in the photographs and drawings of these papers, is similar to the recovery operation we are considering in this article. Fishing vessels were chosen, and this was natural since fishers are familiar with cooperative tasks involved in towing a net, and the ships were designed for such tasks. By the way, a simplified model for bottom trawl fishing gears can be found in Folch et al. (2007), including balancing of forces and balancing of moments. Numerical modeling of boom and oil spill is presented in Zhu and Strunin (2002) and Violeau et al. (2007).

In the scenario proposed in this article there are several aspects of interest for the robotics and control community, since it is based on a parallel formation of two ASVs following a pertinent path. The terminology is not completely fixed in the literature, papers refer to ASVs (autonomous surface vehicles), AMVs (autonomous marine vehicles), USVs, etc. A general, important reference for dynamics and motion modeling of marine vehicles is Fossen (2002). The kind of issues that have to be solved for trajectory planning and tracking by ASVs is well reflected in Liao et al. (2014), with opportune discussion of references. The case of path tracking by a formation of ASVs is treated in Liangsheng and Weisheng (2011), which identifies three general methods of formation control (leader-follower, virtual structure, and behavior method) and another three methods for path tracking; it is said that follow-the-leader is usually preferred in the marine context. The interesting paper of Breivik and Hovstein (2008) on ASV formation control, contains also a relevant list of references.

When one observes a formation of birds, it is clear that no communication is needed, only local sensing; this is the main point in the proposal of Peng et al. (2010, 2013), for ASV formation control in the presence of uncertainties. Another aspect is collision avoidance, which is obviously important for ships; the thesis of Vintervold (2010) deals extensively with this issue within the scope of marine survey operations. Some international research projects have been launched in relation with homogeneous or heterogeneous teams of autonomous vehicles; this is the case of the GREX project, described in Aguiar et al. (2009) with numerous references. One of the diagrams in this paper shows four layers to be considered: vehicle dynamics, navigation and control, cooperation strategy, and logic-based communication. An application of GREX is marine habitat mapping.

In our scenario, there is a physical interaction of both ASVs, since they tow a boom together. Some similarities with this can be found in Arrichiello et al. (2010, 2012), where two ASVs tow a floating rope for a caging operation. Many papers on fleets of marine robots show only simulations; while a few show experimental results, like in the case of Arrichiello, et al. (2010, 2012), using two 2.1 m long ASVs on a lake. The paper of Bhattacharya et al. (2011) is also related with this experimental scenario, and includes an interesting study of rope dynamics.

There are some recent papers that offer some new alternatives for oil spill response. In Jin and Ray (2014) a swarm of ASVs, each one with cleaning capabilities, have to explore an area to find targets. In Zahugi et al. (2012) a swarm of ASVs have to surround and contain an oil spill.

Regarding to our experience, a first autonomous scaled ship was developed and tested in Recas et al. (2004), a first consideration of

ASVs confining a spill over was done in Jimenez et al. (2005), and Giron-Sierra et al. (2005). First spill over experiments were presented in Leon et al. (2006) and Giron-Sierra et al. (2006). The path planning for the ASV team was considered in Giron-Sierra et al. (2008), and a simulation environment was presented in Carrillo et al. (2008). A general view of the main steps of the oil spill recovery operation was presented in Pereda et al. (2011). A long development and experimental effort has been necessary for obtaining the results presented in this article.

3. The experimental system

Scaled ships are routinely used for research and testing, as it is the case in towing tank facilities like the 'Canal de Experiencias Hidrodinámicas de El Pardo (CEHIPAR)', near our University in Madrid. The services and experience of this facility has been quite useful for our research projects. Depending on the experimental objectives, it is convenient to use larger or smaller scales for the ships, and to stay indoors (for instance a basin with wavemaker), or go to larger open air environments, like for instance a dam. In the case of the proposed spill recovery operation, the objective of the experiments is to visualize real behaviors, which are more related to maneuvering. Therefore, observation should be easy and so it is convenient to use small scale ships. In this way, although the recovery operation needs space, requiring open air environments, it has been possible to do the experiments under visual reach.

The experimental system that has been developed for the research has two scaled ASVs and a ground station. It is a distributed robotic system in which there is no central brain controlling the robots, nor humans doing remote control. Each ASV decides its own actions. Once the operation was initiated, the ASVs are able to complete it without contact with the ground station.

Both ASVs are similar: a scaled zodiac with outboard motor. Fig. 2 shows a photograph of one of the ASVs. The hull is a 1/15 scaled Wiking made by Kehrer Modelbau, Berlin. The vessel measures 0.8 m long and weights 3.9 kg once batteries and electronics were on board. The propulsion system is based on a 700-Neodyn DC electric motor. Maximum speed is about 1.8 m/s. The ship has no rudder, heading control is done by moving the outboard motor with a RC servo. The ASV is equipped with two boxes containing the servo, the on-board miniature computer, a digital compass, and the interface electronics for speed control.

The on board electronic system includes a small board we developed and built, with an ARM microcontroller, a GPS receiver, and a digital radio link. The GPS patch antenna, and the digital compass are external to the board. Fig. 3 shows a block diagram of the on board electronic system.

Note that the PWM ('Pulse Width Modulation') signals are well established standards, so they can be as well used for large servos and powerful speed controllers. In the case of real scale boats, the same PWM signals would be able to control the speed and heading. Likewise, real scale boats can employ the same compass and GPS we are using in our ASVs. Therefore, our electronic system could equally be used in real scale ships.

The on board control software is written in plain C. It consists in a main control loop, which receives data from the on board sensors and computes values for speed and heading control signals. The control loop is periodically executed, 10 times per second. Fig. 4 shows an overview of the ASV feedback control, based on two proportional-integral-derivative (PID) controllers. The references for the control are the desired path and velocity. The GPS and the digital compass give the pertinent information about position, speed and heading angle.

The software for the ground station has also been developed in C. Any experiment involves four steps: preparation, setup, execution, and analysis of results. The ground station is used for the setup, and for real-time data acquisition during experiments. The setup consists in a series of specifications related to the desired path and the motion control parameters (for instance, the speed). During experiments, the ASVs send to the ground station the data needed for experiment monitoring and for analysis of results. Fig. 5 shows a sketch of the interaction between ground station and ships.

Of course, in case of unexpected problems, the operator can take manual control of the ASVs. Note also that it is possible for the ground station to handle several teams of ASVs towing booms.

The digital radio link being used can reach up to 5.6 km, provided the antenna was 10 m over the ground. The experiments we made were less than 200 m far from the ground station.

A simulation environment has been developed, with two objectives: experiments preparation, and analysis of results. One of the

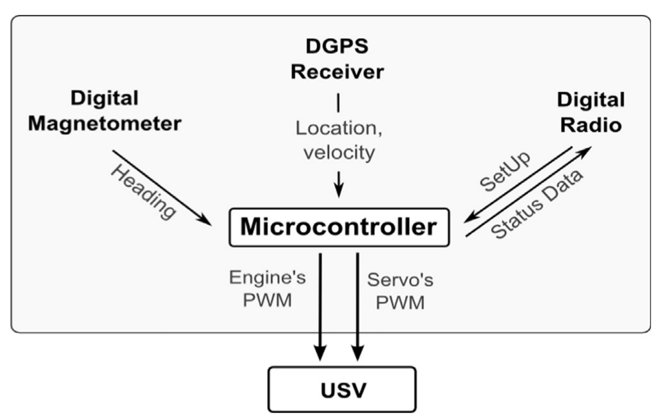

Fig. 3. Block diagram of the on board electronic system.

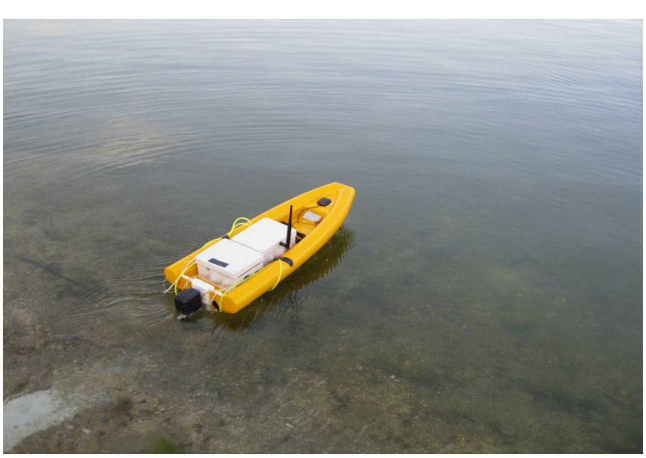

Fig. 2. Photograph of one ASV.

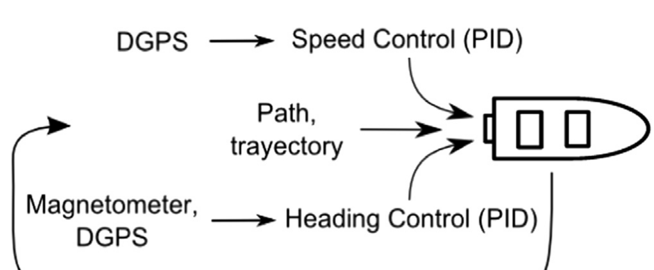

Fig. 4. An overview of the ASV motion control system.

options of the simulation environment is to use Google Maps as background when plotting GPS traces of the ASVs motion.

4. Individual navigation control

A conventional specification of paths to be followed by the ships, consists in a list of waypoints. However, in the case of circular arcs a series of waypoints is not a good idea. Hence, we decided to use Dubins paths, which are composed of lines and circular arcs, as depicted in Fig. 6. This is a classic method in mobile robotics (La Valle, 2006). A path is specified by a series of centers and radii.

The heading control is based on a lateral error and a heading error. The lateral error is measured with respect to the desired path. The situation, when the ship should follow a line, is described in Fig. 7.

The position of the boat cog (center of gravity), denoted in Fig. 7 as '*C*', is projected onto the specified path, giving the point '*P*'. The distance between '*P*' and '*C*' is the lateral error, 'e_{lat}'. The previous '*P*' point is kept as '*ref*'. The current heading angle with respect to the North is '$curr_h$'. The path leads to a specified waypoint, '*W*': During parallel formations it is desired to keep a constant lateral error, so the ship moves parallel to the path. This implies a required heading angle, '*h*', with respect to the North. Errors with respect to this required angle may appear; Fig. 7 shows a situation in which there is a heading angle error, 'e_h'.

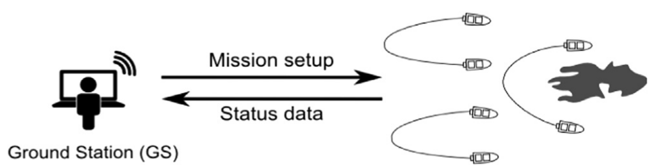

Fig. 5. Interaction between ground station and ASVs.

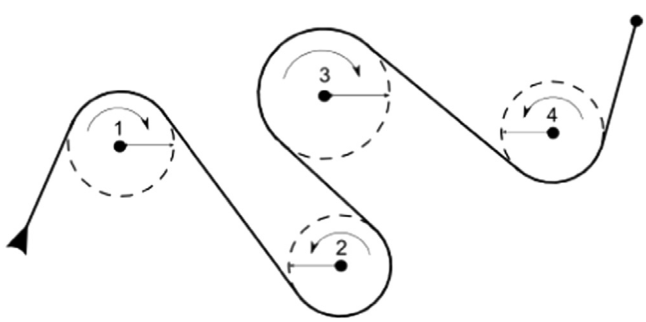

Fig. 6. Example of a Dubins path.

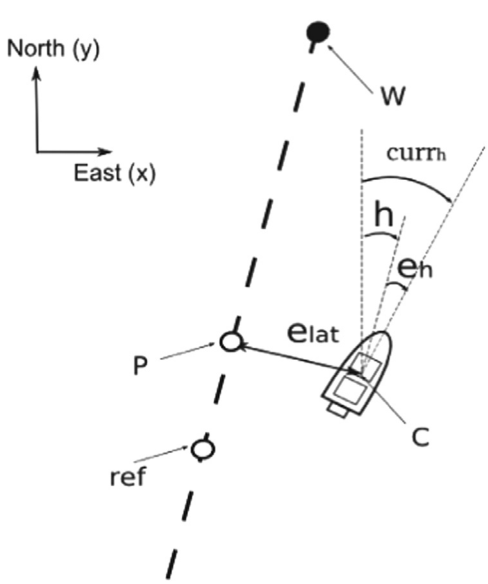

Fig. 7. Control variables corresponding to a straight path segment.

Based on Fig. 7, one has that

$$\tan(h) = \frac{-(W_x - ref_x)}{(W_y - ref_y)} \tag{1}$$

where W_x and W_y are the *x* and *y* coordinates of the point '*W*', and so on with the rest of points considered. Notice that counter-clockwise angles are taken as positive.

Therefore, the angle '*h*' can be simply computed, like for instance in MATLAB using the function *atan*2(.).

Another computation of interest concerns the distance between '*P*' and '*C*'. If one express the line joining '*ref*' and '*W*' as

$$ax + by + c = 0 \tag{2}$$

with

$$a = (W_y - ref_y);\ b = -(W_x - ref_x);\ c = -(aW_x + bW_y) \tag{3}$$

Then, the distance between '*P*' and '*C*' can be obtained with

$$D = \frac{|aC_x + bC_y + c|}{\sqrt{a^2 + b^2}} \tag{4}$$

For the computation of the position of '*P*', one could use an equivalent expression of the line (2):

$$y = mx + k \tag{5}$$

with

$$m = \frac{(W_y - ref_y)}{(W_x - ref_x)};\quad k = W_y - mW_x \tag{6}$$

Then

$$P_x = \frac{C_x + mC_y - mk}{1 + m^2} \tag{7}$$

$$P_y = mP_x + k \tag{8}$$

(notice that *m* can be expressed in function of tan(*h*)).

When following a circular arc, the situation is as depicted in Fig. 8.

In the case of the arc, one would take into account the angle 'β', which can be computed from

$$\tan(\beta) = \frac{(C_y - W_y)}{(C_x - W_x)} \tag{9}$$

The position of '*P*' would be

$$P_x = W_x + r \times \cos(\beta) \tag{10}$$

$$P_y = W_y + r \times \sin(\beta) \tag{11}$$

Now, one obtains '*h*' with

$$h = \left| -\frac{\pi}{2}Q + \arctan\left(\frac{P_y - W_y}{P_x - W_x}\right) \right| \tag{12}$$

where the parameter '*Q*' has one of the three values shown in Fig. 8.

Once '*h*' is obtained, it is possible to compute the errors:

$$e_{lat} = \sqrt{(C_x - P_x)^2 + (C_y - P_y)^2} \tag{13}$$

$$e_h = |h - curr_h| \tag{14}$$

One of our first experiments was devoted to check the individual navigation control. It was repeated several times, on different days, on a pond. A Dubins path was defined using two semi-circumferences. Before experiments the simulation environment was employed for off-line testing, with good results. During experiments, data from the ASV was acquired by the ground station. After experiments, the simulation environment was used to represent the GPS traces on a Google Map image of the pond. Videos were also made, which confirm the GPS traces. Fig. 9 shows the GPS trace of an experiment where the boat accomplished two complete laps.

Fig. 10 shows a plot of experimental data, GPS and vehicle attitude, corresponding to the experiment shown in Fig. 9. Note that the two semi-circumferences have been highlighted in colors.

One of the semi-circumferences has 15 m radius, and the other 10 m radius. Along the experiment, the propulsion force was step-wise increased because it was opportune to get data for ship dynamics modeling. Fig. 11 shows the experimental data acquired from the ship. In order to smooth vibrations induced by water ripples, a 5th order Butterworth filter with 1 Hz cutoff frequency (the Matlab filter 'butter(5, 0.2)') has been applied to all data vectors, except for the propulsion force. As indicated by colors (the same as in Fig. 10), the data correspond to having cycled two times along the closed path.

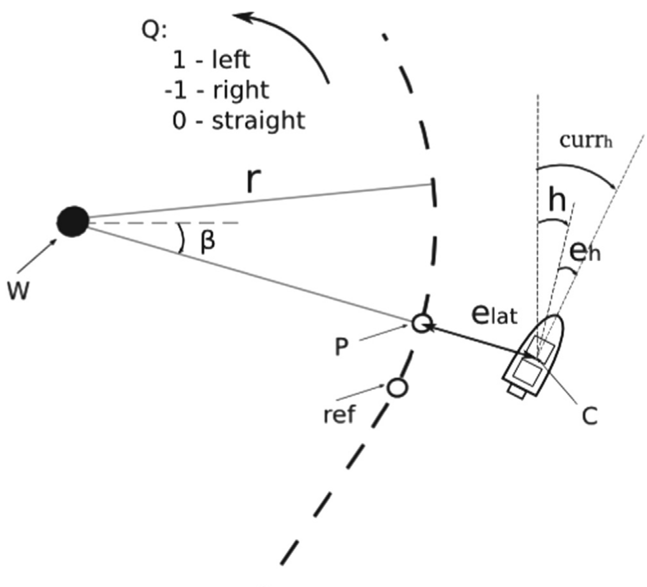

Fig. 8. Control variables corresponding to a circular arc path segment.

Fig. 9. GPS trace of an individual navigation control experiment along a specified Dubins path.

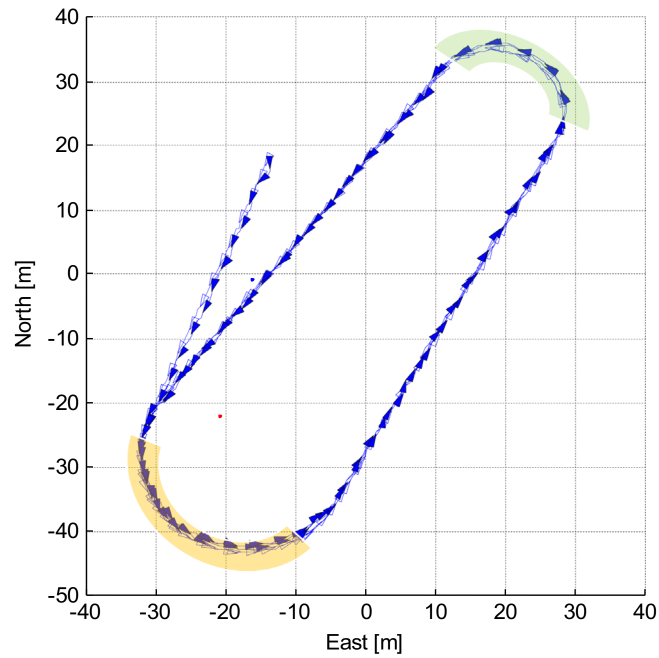

Fig. 10. Computer representation of experimental GPS and attitude data.

Unlike cars, it happens that ships have sway motion, mostly noticeable when turning. This is the reason of the lateral error increasing in the curves. The effort to attenuate this lateral error causes the heading errors that can also be observed (the ship's attitude tries to point to the arc center). Note also that an increase of the force above 4.5 does not mean much increase of the speed, since the resistance to advance increases non-linearly.

5. Parallel formation

In order to establish a parallel formation, we consider a central path, a longitudinal error that should be zero, and two lateral distances (two '$bias_x$') that should be constant. A follow-the-leader strategy has been chosen. The leader moves with a constant propulsion force. Fig. 12 illustrates these aspects.

The central path is specified as before, a Dubins path. Through the digital radio link, the ASVs exchange information on their current position and velocity; this is important for obtaining a zero longitudinal error, e_{lon}, by adequate control of speed. Fig. 13 depicts the situation in a straight segment of the path. Notice that lateral errors may appear with respect to the intended $bias_x$ values.

When the formation follows a circular arc, both ASVs must have the same angular velocity: the interior ASV must move slower than the exterior ASV. Fig. 14 shows the aspects that must be considered by the control. Note that sway should be considered. The longitudinal error must be computed along the curved path.

It is necessary to consider speed limits of the ships ($v_{\min}$, $v_{\max}$). Both the turning radius 'R' and the separation between ships should comply with the following expression:

$$w = w_1 = w_2 \rightarrow \frac{v}{R} = \frac{v_1}{R - bias_x} = \frac{v_2}{R + bias_x} \quad (15)$$

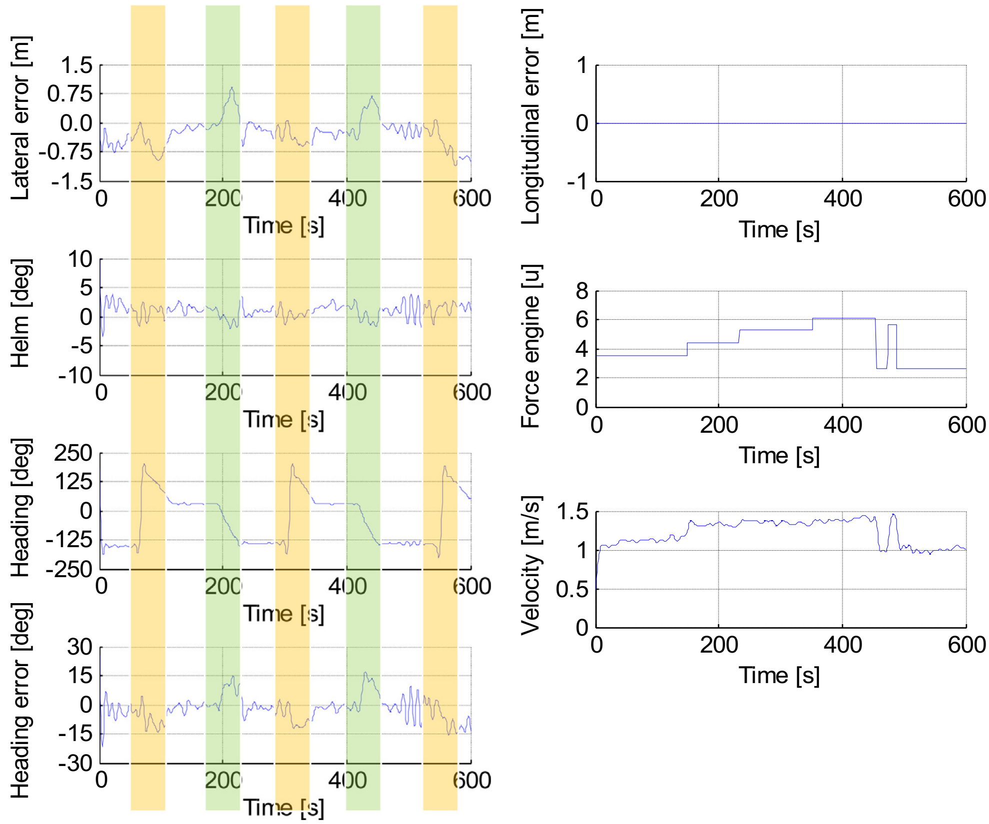

Fig. 11. Experimental ASV data along two laps.

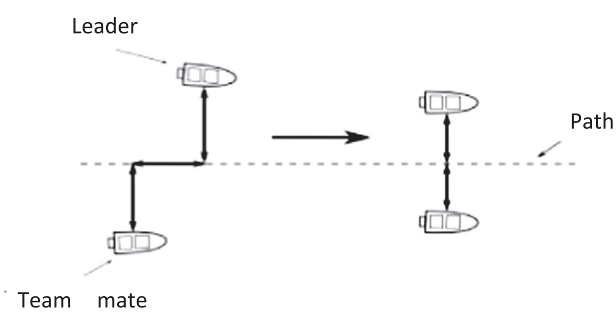

Fig. 12. Basic aspects of the parallel formation.

The formation velocity along the central path, v, should permit flexibility between ASVs speed limits. Since at significantly low speeds the heading control is lost (too small torque), it is recommended to devise arcs with large radii. At the same time, it is important that the external ASV does not reach its maximum speed; radius and mutual separation are linked by:

$$v_{\text{int}} \geq v_{\text{min}} \Rightarrow R \geq \frac{v \times bias_x}{v - v_{\text{min}}} \tag{16}$$

$$v_{ext} \leq v_{\text{max}} \Rightarrow 2 \times bias_x \leq \frac{(v_{\text{max}} - v) \times R}{0.5 \times v} \tag{17}$$

During our experiments, it has been noticed that it is convenient that the external ASV was the leader. In case of changing the direction of the curve, formation roles must be exchanged (this is automatically done in our actual implementation). A main reason for the external ASV be the leader is that the internal ASV is prone to turning fluctuations due to her lower control authority; supposing that the internal ASV was the leader, these

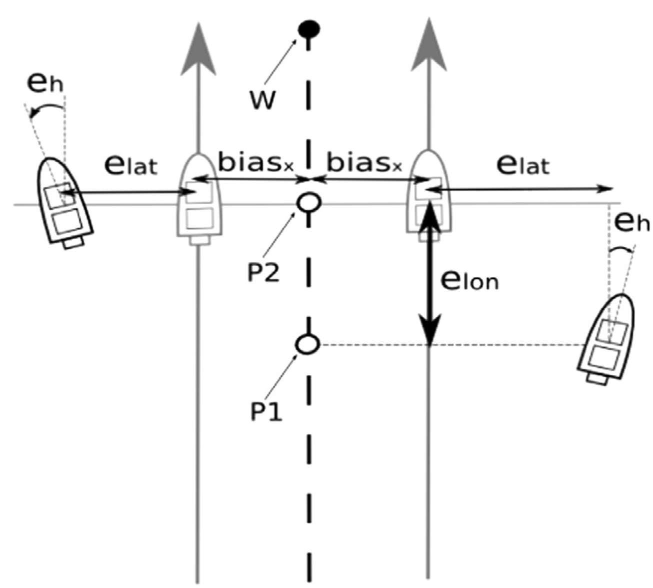

Fig. 13. The situation during a straight path segment, the leftmost boat is the leader.

fluctuations would be amplified (as tangential) and become difficult to follow by the external boat.

6. Towing

When both ships tow a boom, a number of peculiar issues must be solved in order to have fully automatic operation. Our research arrives here to a novel zone in the context of robotic automatic control.

Suppose that the boom is attached to the stern of the ships, and that the boom has a V shape. Fig. 15 depicts the forces that would appear on the leftmost ship when towing. The boom force F_B can be decomposed into F_T and F_P. A torque, T_P, would be exerted on the ship, due to the perpendicular force F_P, and the ship would turn, unless some counteracting action was applied. The distance between ships would increase as they advance. One could easily assume that human pilots will spontaneously react in order to keep a prescribed mutual distance. However, this is not the case with ASVs, they do not include any control law for this. Actually, unmanned vehicles are mostly prepared for individual action, and not for teamwork involving physical interaction.

In order to acquire experience with the boom towing scenario, a simple, floating boom was made and was attached to our scaled boats. Fig. 16 shows a photograph of the system. There is a third, white boat attached to the center of the boom, in opposite direction; this is a R/C boat that is used to drive the system to desired initial positions at the pond, and then remains passive during towing (it can also be used to simulate the friction increasing as oil spill becomes trapped by the boom).

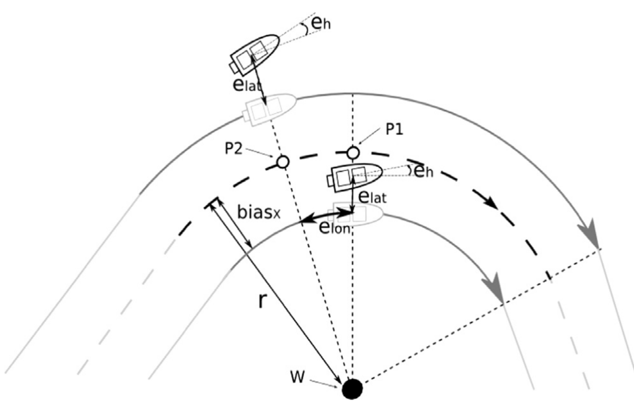

Fig. 14. The situation during a circular arc.

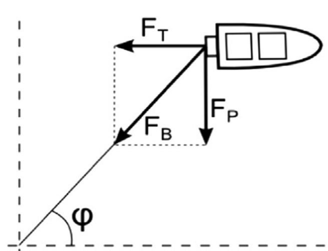

Fig. 15. Forces due to towing a V-shape boom.

Let us denote as PFC the control parameters that worked well for the parallel formation. In our first experiments using a parallel formation for towing, PFC were used again. However, repeated experiments showed that the distance between ships always increased. On each ship, after any small turning caused by F_P, the heading control takes back the ship to the correct attitude, but the mutual distance already increased a little, and so there is an accumulative phenomenon. Fig. 17 shows GPS traces during one of the experiments that confirm that separation increases along time.

Perhaps this increasing separation problem has been also found by other authors, Arrichiello et al. (2010, 2012), making difficult to actually perform towing experiments.

In response to the increasing separation problem, the control of the lateral error was made more aggressive, with good experimental results. This confirms a general control rule: the feedback should be directly related to the variable of interest, which, in this case, is the mutual distance of ships. Let us denote as TwC the control parameters for towing.

There is still another aspect that should be mentioned. If one continues with the experiment that uses PFC – as depicted in Fig. 17 – once a certain mutual distance is reached, the ships rapidly go to a tug-of-war situation, as sketched in Fig. 18.

Based on Fig. 15, and supposing the formation velocity was constant independently of φ, a basic analysis can be done as follows. Consider first that the boom opposes to the motion a certain force; this force reaches a maximum value, that will be denoted as F_Q, if $\phi = 90^{\circ}$ (in this case, the boom V shape becomes a straight line). Given a value of φ, the longitudinal force F_T that is needed for towing the boom, would be:

$$F_T = F_Q \times \sin \varphi \tag{18}$$

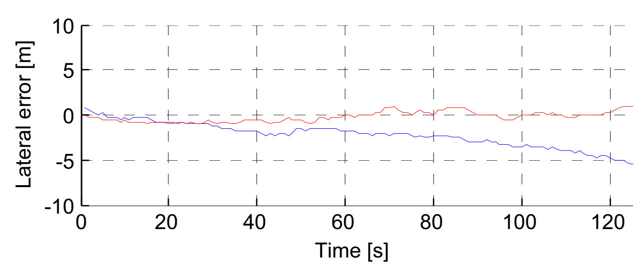

Fig. 17. Experimental lateral error data showing increasing distance as the ASVs tow the boom.

Fig. 16. The two ASVs towing the boom.

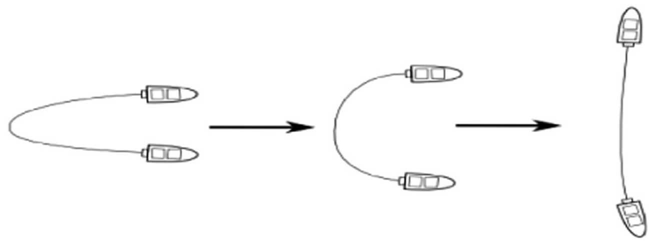

Fig. 18. The system evolves to a tug-of-war situation.

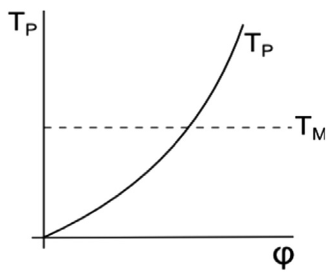

Fig. 19. The torque T_P in function of φ. Both T_P and T_M intersect at the critical angle.

Continuing with the decomposition of forces shown in Fig. 15, there would be a perpendicular force F_P:

$$F_P = F_T \times tg\varphi = F_Q \times \frac{\sin^2\varphi}{\cos\ \varphi} \quad (19)$$

The force F_P causes a torque T_P. In order to counteract T_P, the ship has to exert a certain opposite torque. This torque can reach a certain maximum value T_M.

Fig. 19 shows a plot of T_P in function of φ. There will be a certain value of φ, which we call the *critical angle*, for which T_P and T_M intersect. The important fact is that above the critical angle, the ship will be unable to counteract T_P.

Therefore, it is important to have a moderate angle φ, and so it is recommended to use somewhat long ropes between the ships and the boom.

Coming back to the experiment described in Fig. 17, it should be said that this experiment ended in a tug-of-war situation. Fig. 20 shows the GPS traces and the ASVs attitude along the complete experiment. A colored bar has been added to highlight when the critical angle was reached.

The behaviors of the lateral error and the heading error of the ASVs are plotted in Fig. 21.

Notice in the lower plot, Fig. 21, that the heading control was correct until the critical angle was reached.

To give an idea of the boom drag, it has been estimated as 3.5 kg when the mutual distance between ships is 6 m and the speed was 0.5 m/s. This force represents approximately for each ship a half of her propulsion force. In order to compare with a real scale zodiac, one could take for example the RIBO 420 rescue boat, by Survitecgroup (2014), which is 4.20 m long. This boat, with a good engine has 355 kg maximum towing force. Applying scaling rules (R^3 for forces, with R=scale ratio) it results that the scaled up drag force of our boom would be 506.5 kg, so it would take from each towing boat – supposing two boats – more than half her towing force. In other words, our boom has significant drag, and the small zodiac used in our experiments has strong towing force.

7. Automatic capture of a spill over

After the experiments related to boom towing with a parallel formation of ASVs, our work focused on the spill recovery

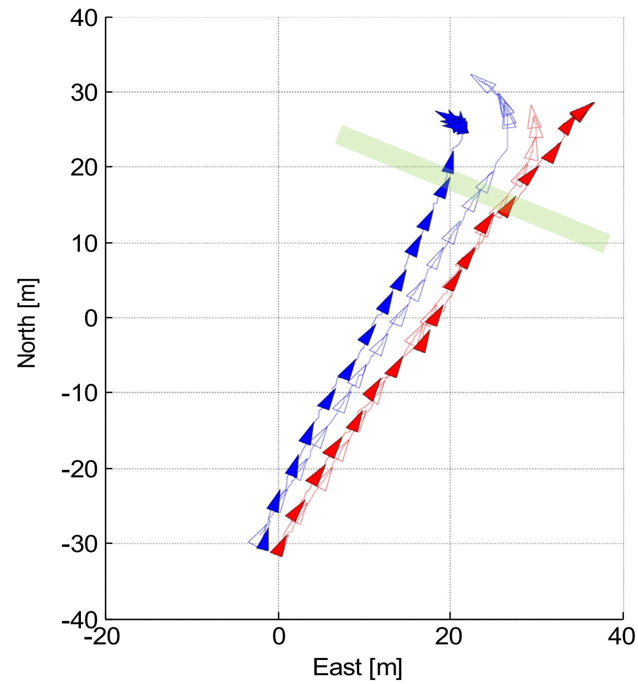

Fig. 20. A boom towing experiment, with tug-of-war final situation.

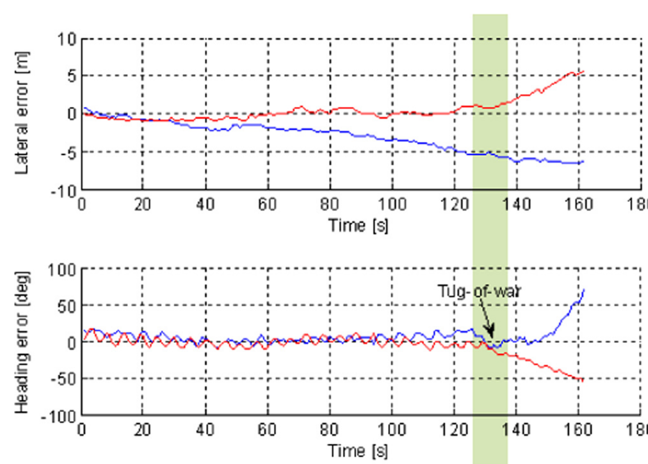

Fig. 21. Lateral and heading errors of the ASVs during the complete experiment.

operation already sketched in Fig. 1. In order to minimize the towing effort, the ships should approach the spillover keeping a mutual short distance. Near the spillover, the ships should increase this distance, in order to deploy the boom. Then, the ships should advance for spillover trapping. Finally, both ships should converge to a closer mutual distance, for spillover confinement and subsequent towing.

A series of experiments were done for exercising the three confinement steps: deployment, advance, closing. Fig. 22 shows GPS traces and ASVs attitude during one of the spillover confinement experiments.

Notice that two colored bands have been included in Fig. 22 to highlight two transitions. During the first transition, which is 10 m long, the distance between ASVs increases from 3 m to 6 m. The second transition is the opposite, the mutual distance decreases from 6 m to 3 m, along 10 m of central path. The transitions start at ‘transition points’, which are part of the operation definition, together with the Dubins waypoints. Transitions should allow for smooth

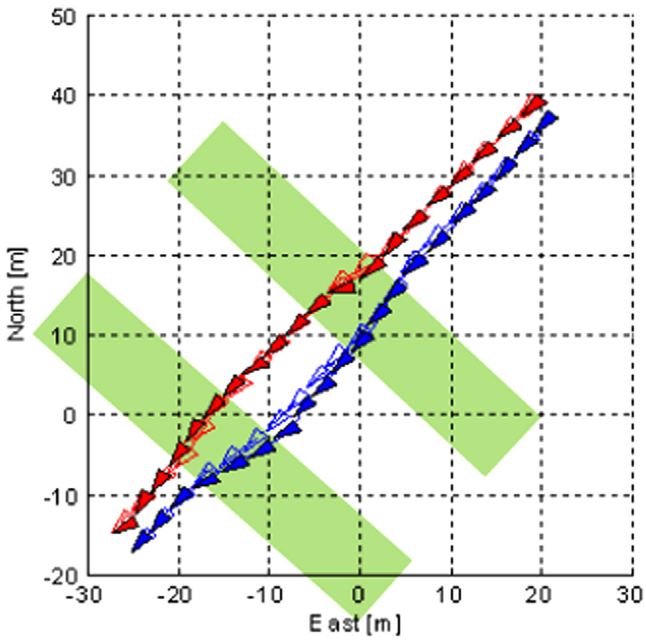

Fig. 22. A spillover confinement experiment.

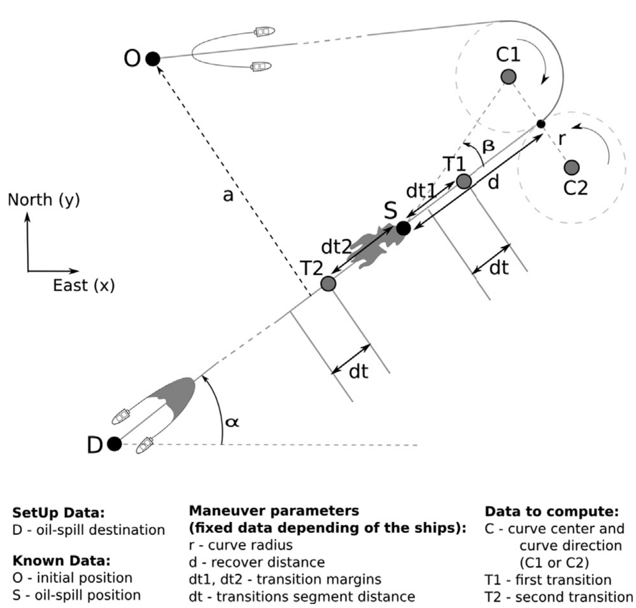

Fig. 23. Details of the automatic operation planning.

deployment of the boom. During transitions the lateral bias is linearly changed, so mutual distance would linearly increase or decrease under control. Of course the mutual distance during the central step must be limited, not to exceed the critical angle.

Once the correct execution of the spillover confinement was experimentally confirmed, an automatic planning of the complete operation has been achieved. This planning only needs to know where are the origin, the spillover, and the final destination. Fig. 23 shows the details considered by the planning. The general idea was to devise a straight trajectory of the formation towards the destination just after the spillover confinement.

Among the aspects that the planning has to consider, the radius and center of the Dubins waypoint must be appropriate for the ASVs parallel formation turning, also letting enough distance before the first transition point so the formation could stabilize after the curve. The equations to be computed by the planning comprise two main phases:

(a) Transitions:

$$\alpha = \arctan\frac{(S_y - D_y)}{(S_x - D_x)} \tag{20}$$

First transition point:

$$T1_x = S_x + dt1 \times \cos(\alpha) \tag{21}$$

$$T1_y = S_y + dt1 \times \sin(\alpha) \tag{22}$$

Second transition point:

$$T2_x = S_x - dt2 \times \cos(\alpha) \tag{23}$$

$$T2_y = S_y - dt2 \times \sin(\alpha) \tag{24}$$

(b) Curve:

$$a = (O_x - D_x) \times \sin(-\alpha) + (O_y - D_y) \times \cos(-\alpha) \tag{25}$$

If $a \geq 0$ then $\beta = \arctan(r/d)$; (turn right, around center C1)
If $a < 0$ then $\beta = -\arctan(r/d)$; (turn left, around center C2)
Center of the arc (C1 or C2):

$$C_x = S_x + \sqrt{(d^2 + r^2)} \times \cos(\alpha + \beta) \tag{26}$$

$$C_y = S_y + \sqrt{(d^2 + r^2)} \times \sin(\alpha + \beta) \tag{27}$$

Fig. 24 shows the GPS traces of one of the experiments demonstrating that the automatic planning works correctly.

Fig. 25 presents a display of GPS and ASVs attitude data obtained during the experiment shown in Fig. 24. Filled triangles correspond to real behavior, while empty triangles correspond to previously modeled behavior.

Fig. 24. Experimental confirmation of the automatic operation planning, GPS traces.

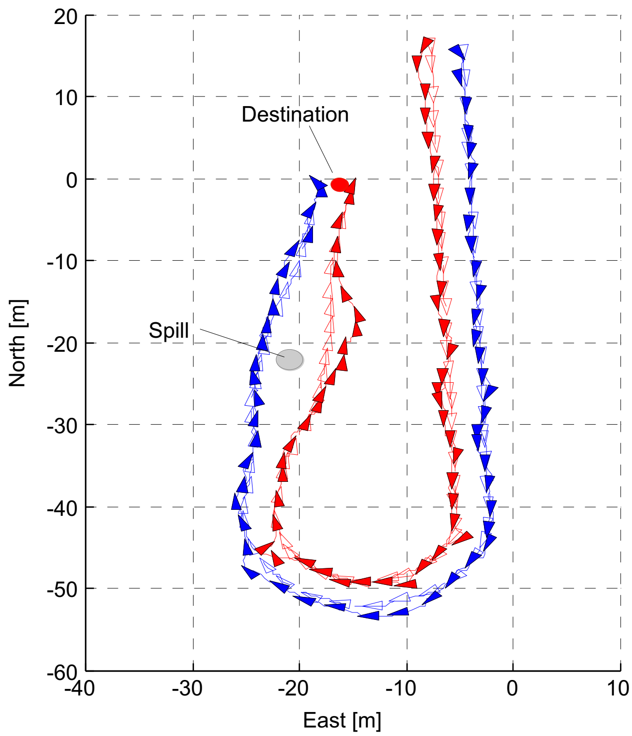

Fig. 25. Experimental confirmation of the automatic operation planning, computer representation.

8. Conclusions

After a step-by-step study, it has been shown that automatic spillover recovery using two ASVs towing a boom is feasible, provided that some specific criteria were satisfied concerning feedback control and geometry. The feedback should focus on mutual distance, and the towing of the boom should take care of the maximum torque the ships can exert.

The study has combined physics and experiments. Since the experimental work was so extensive, scaled ships have been used. That means less cost, faster and easier experimentation tasks, more flexibility. Advantages of scaled ships are that collisions and other problems or difficulties are not so cumbersome, and that direct observation of relevant phenomena is easier.

Part of our work has been to develop the on-board control, so the scaled ships enjoyed autonomous control, ASVs. In parallel, a simulation environment was developed for several purposes: to prepare experiments, and to analyze results after experiments. The simulation embodies the same control code that is on board the ships.

An interesting aspect discovered in the experiments is the tendency of the ships to a final tug-of-war situation. A main objective of the mentioned specific criteria is to preclude this problem.

On the basis of the accomplishments and observations done during the research steps, a first fully automatic recovery operation has been experimentally demonstrated. It seems that other recovery operations involving ASVs could also be afforded.

Apart from environmental applications, there are other maritime activities that were related with coordination, cooperation and physical interaction (like towing), in which the proposed use of ASVs could be of interest.

It is evident that certain facets of our work deserve further studies, related for instance to forces and tensions, motion of the boom, details of formation turning, what to do if critical angle is surpassed, etc. In addition, our plans for the next future include larger scale demonstrations, using 2 to 3 m long boats.

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