Fully Automatic Boom Towing by Unmanned Ships: Experimental Study

Jose M. Giron-Sierra, Alina T. Gheorghita, Juan F. Jiménez
Dep. ACYA, Fac. Físicas
Universidad Complutense de Madrid
28040 Madrid, Spain
e-mail: gironsi@dacya.ucm.es

Abstract*—A commonly used technique for oil spill response is to use two or more ships towing a boom. Our research proposes fully automated operations based on unmanned ships and a computer-based planning system. The system will carry on a complete autonomous operation, requiring only the position of the oil-spill and to push a start button. The paper describes the steps of the research already accomplished, which involves computer modeling and experimental studies. The experiments started with scaled ships and now are based on real scale zodiacs. Boom towing is a peculiar task, which require specific control strategies.. *(Abstract)

***Keywords*—autonomous ships, robot teams, marine vehicles, unmanned surface vehicles, environmental protection, oil spill recovery**

I. Introduction

One of the techniques for oil spill response is to use two or more ships towing a boom. The first steps of our research analyzed with models and simulations how complex this operation is in terms of control and coordination. As suspected, it is not so trivial; in fact people with experience in towing, like fishermen, are usually recruited in emergency cases. Our main idea, according with our experience in marine robotics on sea surface, is to devise a fully automatic system with unmanned ships, only needing the position of the oil spill for going there with a boom, deploy, confine the oil spill, and take it to a designed place (or just collaborate with a skimmer at the end of the boom).

In order to develop this fully automatic system, we initiated a series of experiments with scaled ships. We found specific control problems leading to tug-of-war situations, and solved them with a minimum of information exchange between ships. Note that if you try to tow a boom with two commercial marine surface drones, most probably you will get the same type of difficulties faced in our research.

After intense experimental work, we demonstrated a completely automated oil spill recovery operation with the scaled ships. The system includes an automatic planner that computes the trajectory for approaching the oil spill, and convenient transition points for deployment and then convergence. Once the plan is automatically done, you just push the start button, and the operation is then executed.

Recently our research started to use real scale zodiacs. From the point of view of software and hardware development, the transition from scaled ships to real scale zodiacs required almost no effort, since the on-board control system, and the control software is the same. Actually, the same system can be used for larger boats or ships, with some control constants changes.

This paper focuses on the main peculiar aspects that we observed during the research, which concerns autonomous ship control and parallel formation keeping while towing a boom. In addition, the paper introduces the automatic planning, and presents experimental results.

The paper starts with a short section that specifies our proposed target. Then, next sections of the paper are devoted to the pertinent background, including the research context and the steps of our study along past years. After that, we briefly introduce the experimental system that has been created during our work, and the scenario where experiments took place. Then, the paper tackles the autonomous ship control for coordinated boom towing. Next, the paper considers the operation automatic planning. Finally, experimental results are discussed.

We expect to get complementary experimental results –we have now good weather conditions- in the next months.

II. Target of the Research

Next figure illustrates the kind of operation we want to perform in fully automatic way, using unmanned ships.

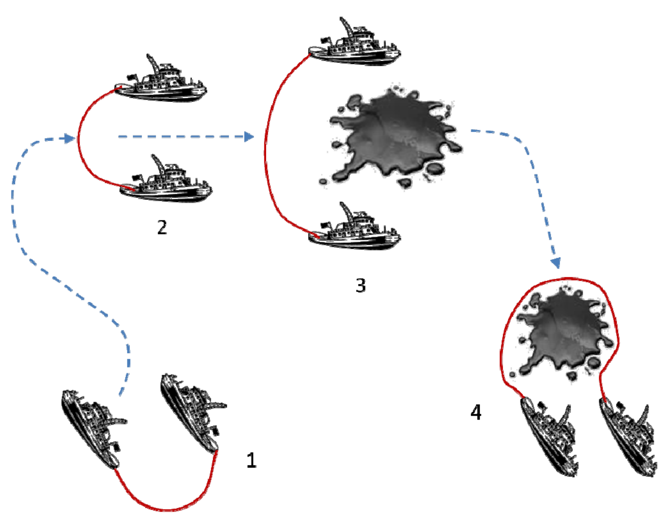

Figure 1. A fully automatic operation with unmanned ships

During the operation the two unmanned ships (unmanned surface vehicles, USVs) use information on the oil spill to establish the motion plan. According with the plan, the USVs execute the following steps:

- The USVs tow the boom towards the objective, trying to minimize the towing effort
- Near the oil-spill target the USVs adopt a suitable angle of attack with respect to the oil-spill, and deploy
- The USVs advance and capture the oil spill
- The USVs converge to a closer mutual distance in order to confine the oil-spill
- Finally, the USVs tow the oil-spill to a suitable place.

Unless necessary, no human intervention would be required during this operation. Via digital radio, an external station (on ground or on a ship) will receive GPS and other pertinent data in order to supervise the mission. The USVs are capable of re-planning during the operation.

III. BACKGROUND

According with [1] during the recent ecological disaster in the Gulf of Mexico, over 700 km of booms were deployed. Professional information on marine spills and remediation, and in particular concerning the use of booms is available from the ITOPF web site and the IOSC repository. These acronyms correspond to the International Tankers Owners Pollution Federation, and the International Oil Spill Conference respectively. Figure 2, from ITOPF, shows a typical boom towing for oil spill recovery.

Figure 2. Photograph of two ships towing a boom for oil-spill recovery

For our research on boom towing, a most interesting advice from ITOPF is that booms should be attached to the towing ships using relatively long lines, like for instance 50 m lines for towing a 300 m boom. Another important recommendation is not to exceed 1 knot speed during towing, otherwise the oil climbs over the boom and get lost. One of the papers from IOSC, [2] recommends a V-shape boom geometry, with a skimmer at the V vertex. More details related to boom towing can be found in [3] and references therein.

We propose the use of unmanned ships for several reasons, one is to keep people out from perhaps dangerous situations (toxic substances, burning, etc.), and another is to promote fast, non expensive spill response systems not needing much training. Figure 3 shows a photograph of a boom confining an oil spill while it burns out.

Figure 3. Photograph of a boom and oil burning

Our project is connected with marine robotics. In particular, we focus on a scenario with a parallel formation of two USVs following a prescribed path. A main reference on the modeling and control of marine vehicles is [4]. The literature uses a variety of names for autonomous boats, like for instance AMVs (autonomous marine vehicles), ASVs (autonomous surface vehicles), etc. With respect to unmanned vehicles, it is convenient to distinguish between remotely operated vehicles, or autonomous vehicles. We deal, in our case, with autonomous vehicles. Relevant papers on the robotic and control aspects of interest are, [5] on trajectory planning and tracking by ASVs, [6] on path tracking by a formation of ASVs, and [7] on ASV formation control.

From some time ago, the research has considered the case of physical interaction between cooperating robots, like for example in the case of two robots pushing a box. In our case there is also physical interaction between our USVs, since they tow a boom together. Some similarities with our problem appear in the scenario considered by [8] and [9], with two ships cooperating in a caging operation.

With respect to our experience , a first autonomous scaled ship was developed and tested in [10]. After that we started to consider the boom towing by autonomous scaled ships. The progress of this research was described in [11, 12]. The present paper corresponds to the transition from scaled boats to real-scale zodiacs.

IV. THE RESEARCH EXPERIMENTAL SYSTEM

The experimental system we created for the research has two USVs and a ground station. More USVs could be added in future research. There is a digital radio link between ground station and the USVs. Normally, the ground station is used for sending waypoints and other behavior specifications to the ships, at the beginning of any operation, and then it remains most of the time in passive mode, just receiving data from the ships.

When desired, the ground station can interrupt the autonomous behavior of the USVs, and then be used for remote control. However, this case is infrequent.

The system is a distributed *autonomous* robotic system, so there is no central computer control, neither humans doing remote control. Each USV, using algorithms, decides its own actions. Therefore, once the mission is setup and initiated, the USVs are able to complete it without any intervention from the ground station.

During the first steps of the research we used scaled ships. Once a good cooperative control for towing was achieved, we started to use real-scale zodiacs.

A. The USVs

Figure 4 shows one of the scaled USVs we used. It is a 1/15 scale Wiking hull zodiac made in Berlin. It measures 0.8 m long and weights 3.9 kg with batteries and on-board electronics. The ship has no rudder, it is propelled with an outboard motor. Maximum speed is about 1.8 m/s.

Figure 4. One of the scaled USVs

Figure 5 shows one of the real-scale USVs we are using now. It measures 2.4 m long and weights 38 kg with batteries and electronics. We use conventional electric outboard motors for propulsion; at present stage of the research the motor we selected has a modest force: 36 lb. We experimentally measured a maximum speed of 2.5 m/s.

Figure 5. One of the real scale USVs

B. The on-board electronics

The on-board electronics is contained in two boxes. One of the boxes includes a printed circuit card we designed for the digital control system, which is based on one micro-controller and surrounding interface electronics. The card is connected to a GPS receiver, a digital compass, and a digital radio link chip. Figure 6 summarizes this part of the on-board electronics.

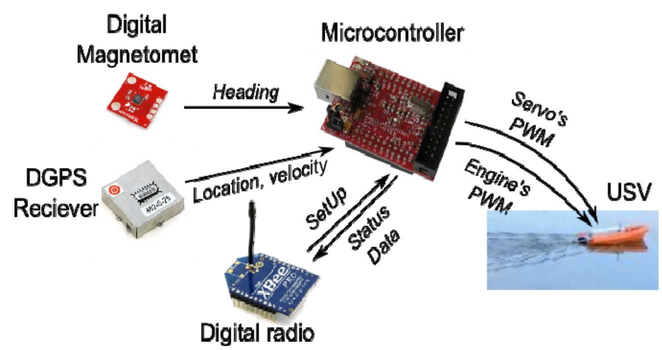

Figure 6. The USV on-board electronics

The other box is devoted to the control of speed and heading. The speed is controlled by a variator (called electronic speed controller, ESC, in the radio-control, RC, community). The heading is governed by a RC servo of suitable torque. Both the variator and the servo are controlled with pulse width modulated, PWM, signals, generated by the micro-controller.

The kind of PWM signals we are using is fairly conventional in RC and industrial applications. Therefore, the control system we designed can be used both in scaled ships and in real-scale ships.

The on-board control software is written in C. It periodically executes a control loop, 10 times per second, for reading incoming information and for computing actuation signals.

The on-board control software computes suitable force and angle of the propulsion, according with the information from sensors. The digital compass gives the current heading, and the GPS gives the location and the velocity.

C. The ground station

The software of the ground station is written in C++. The ground station gives support for the following tasks involved in any experiment on the water:

- Setup of USVs speed and control parameters. Send the oil spill position to the USVs
- Real-time monitoring of the plan execution, gathering data sent by the USVs via digital radio

Our experience is that the development of the ground station software has been of incremental nature. At the beginning of the research the experiments focused on testing the correct individual behavior of the USVs. Further experiments were devoted to path following. Then coordination of two USVs with no towing. And finally, towing by one or by two USVs. Each step of the research required extensions of the initial software. So we can say that this was one of the most time consuming efforts of our project, being so that the main effort has been devoted to the USV on-board software..

The ground station hardware is just a simple and small portable computer coupled to a digital radio chip. The computer must work long time on batteries.

Some of the screens shown by the ground station will be included in a next section of this paper.

D. The boom

For the scaled USVs we made a simulated boom using cylindrical floaters. With a length of 15 m the drag of the boom is equivalent, according with the 1/15 scale, to a conventional boom.

Figure 7 shows one experiment with two scaled USVs towing the boom. We added a small RC boat at the middle of the boom, and pointing opposite to the boom motion. This boat is useful for initiating the experiments in a desired position, and for simulating the increment of drag corresponding to oil-spill capturing.

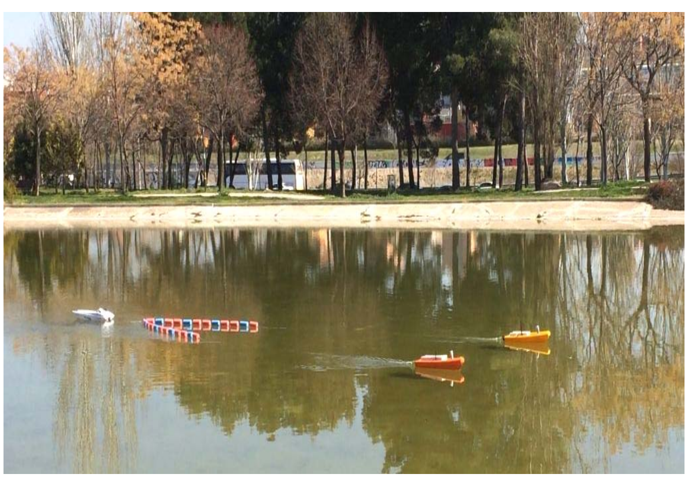

Figure 7. The two USVs towing the boom and a small RC boat.

The boom we made for the real-scale USVs is just a longer version (30 m) of the boom shown in figure 5.

Notice that relatively long ropes were used for connecting the boats and the boom.

E. The data gathering floating platform

In order to obtain more data from experiments, we made a special floating platform conceived as a support of sensors. It is a kind of catamaran, 1 m long. We put on board a light portable computer with a suitable number of USB inputs. The sensors we added are:

- Two force sensors, place near the bow.
- One GPS receiver
- One small camera
- One depth sensor

The boom is divided into two equal segments. Supposing that the boom has a V shape while being towed, the left USV will tow the left boom segment that will be attached to the left force sensor of the floating platform. Similarly with the right branch of the system. The floating platform will be situated at the V vertex, and will be towed by the two USVs.

We are interested in particular with force transients during turning manoeuvres of the USVs pair.

Figure 8 shows a photograph of the floating platform, which has a plastic dome for computer protection

Figure 8. thedata gathering floating platform.

V. CONTROL ASPECTS OF THE RESEARCH

In order to achieve our boom towing system, a series of control issues had to be solved, with experimental confirmation. The first step is to devise the ship autonomous navigation. Then, a ship formation control has to be developed. Next, as one attaches the boom to the ships, one has to face new control problems. We will summarize in this section what has been done. More details are given in [3]

A. The individual USV navigation control

A typical solution for the specification of paths is to use a list of waypoints. However, for several reasons, we prefer to use Dubins paths, which are composed of lines and circular arcs; a path is specified by a series of centers and radii. Figure 9 shows an example of Dubins path.

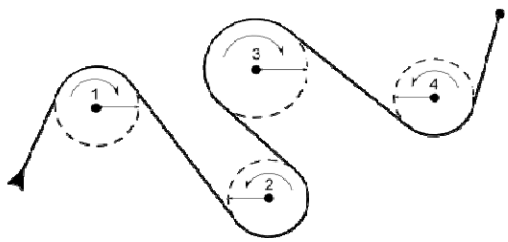

Figure 9. Dubins path

Having in mind that parallel formations will be used, the heading control of the unmanned ship is based on a lateral error and a heading error. The lateral error is measured with respect to the path. Figure 10 depicts the situation.

When the ship follows a curved path, sway force appears and the lateral error of the ship tends to increase. The heading angle has to be adjusted by the on-board ship control in order to counteract this effect.

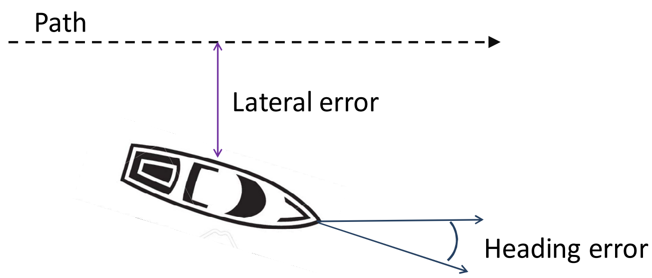

Figure 10. Lateral error and heading error.

B. *Parallel formation*

The two USVs must keep a parallel formation while towing the boom. A leader-follower strategy has been selected. Also, a central path has been considered. The leader USV keeps a constant velocity, and a constant lateral distance to the path. The follower also keeps a lateral distance to the path. Figure 11 depicts the concept. A longitudinal error along the central path is considered. The longitudinal error should be zero for a parallel formation; the follower USV must adjust its speed for this purpose..

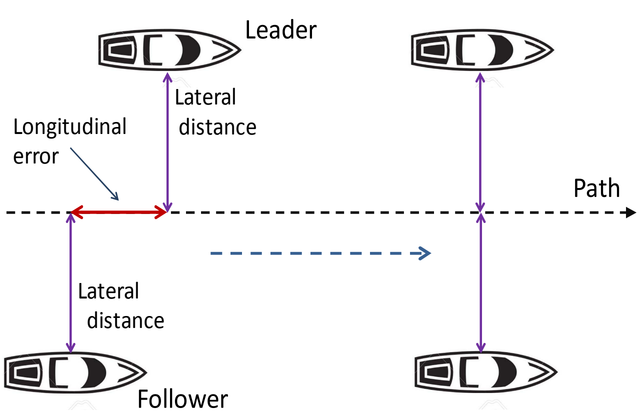

Figure 11. Longitudinal error and parallel formation.

During turning manoeuvres, the external ship must move faster than the internal ship. Since at low speeds the heading control of ships loose authority, and since the ships can only reach a certain maximum speed, there are constraints to be taken into account concerning the mutual separation of ships and the manoeuvre turning radius.

C. *Towing a boom*

In a scenario where a V-shaped boom is towed by two ships, each USV need to counteract a perpendicular force F_P (Figure 12):

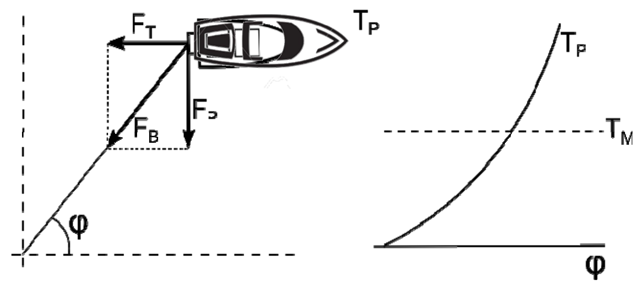

Figure 12. Forces when towing the boom.

In figure 12, the angle φ is half of the boom V angle.

The torque that the USV can exert to counteract the turning torque caused by the boom, will have a maximum value T_M. Depending on the USV characteristics, it may happen that for a certain value of the angle φ (that we call the '*critical angle*'), the torque T_P caused by the boom becomes $T_P > T_M$. In such case, the system rapidly evolves to a tug-of-war situation, as depicted in figure 13.

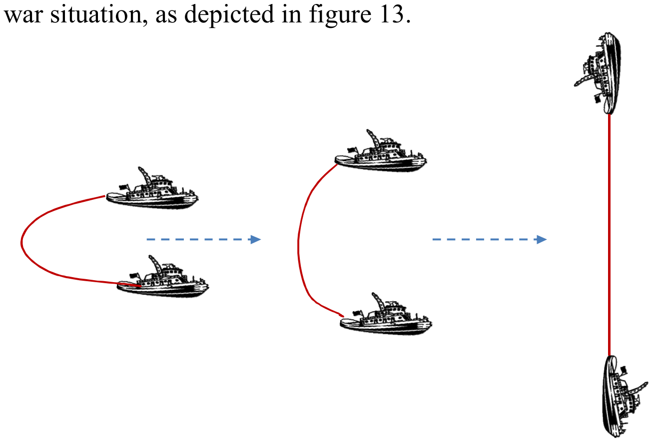
Figure 13. The system may evolve to a tug-of-war.

Supposing that one gets two conventional USVs, which are designed for individual control, and put them on the boom towing task, our experimental observation is that both USVs will increasingly separate along time. An extra control effort should be added to the individual motion control, in order to govern by feedback the mutual distance between the USVs. Otherwise, after some time of more and more separation, the system would reach the critical angle, and fast march to a tug of war is next.

In our case, to avoid the mentioned problems, the control of the lateral error was reinforced, with good experimental results.

VI. AUTOMATIC PLANNING

In general, the oil-spill recovery operation will include three phases: approaching the spill, capture of the spill, and tow the spill to a prescribed place. Let us focus now on the capture, and then on the complete operation.

A. *Confinement of the oil spill*

The confinement manoeuvre consists in two formation transitions, figure 14.

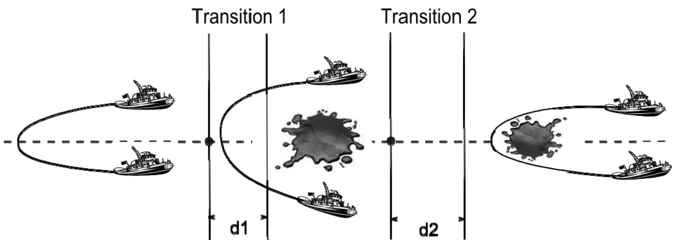

Figure 14. Confinement manoeuvre

The first transition starts when approaching to the oil spill position at a certain distance *d1*, so the two USV must open the boom. The new, larger separation has an upper limit depending of the boom length, to avoid reaching the critical angle. Once the oil spill has been trapped, there is a second transition for the ships to get closer. The width of the transitions must allow a smooth deployment of the boom.

B. *Complete operation planning*

The planning only needs where are the start point, the oil-spill, and the final destination.

As in dynamic programming, the planning proceeds from end to beginning. For the final segment of the plan, a simple straight path of the formation towards the destination is devised. The confinement manoeuvre takes place along this path.

A Dubins waypoint is placed at a prudent distance from the beginning of the confinement manoeuvre. Once this waypoint is established, the first part of the plan is easy: a straight path from the start point to the Dubins circle.

Figure 15 shows a sketch of the planning.

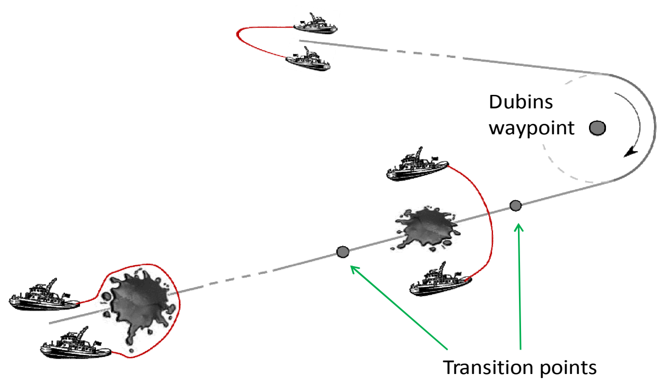

Figure 15. Operation planning

As said before, the planning is made on-board each USV.

VII. EXPERIMENTAL RESULTS

The first experiments with the scaled USV took place on a pond of moderate size. Figure 16 shows a picture from satellite; there are three ponds in cascade, the selected pond is the central one. The pond has an approximate elliptic shape.

Figure 16. The experimental scenario for our first studies

One of the advantages of this pond is that it is relatively easy to do rescue tasks in case of experimental problems.

When it was decided to jump to real scale, based on conventional zodiacs, another pond was chosen. It is a larger pond, with some difficulties in case of rescue. Figure 17 shows a satellite picture, from the same eye distance than in figure 16. There is a kind of peninsula that complicates our practical experimental space. We place our ground station on the lower right corner, where a kind of beach was devised for kayaks.

Figure 17. The experimental scenario for real scale studies

The main screen of the ground station, which is shown in figure 18, includes on the left-hand side the visualization of the following aspects:

- The GPS traces of the USVs motion during current experiment
- The paths specified by the operation planning
- Graphic representation of motion errors compared with desired trajectories
- Data from USVs sensors and control decisions

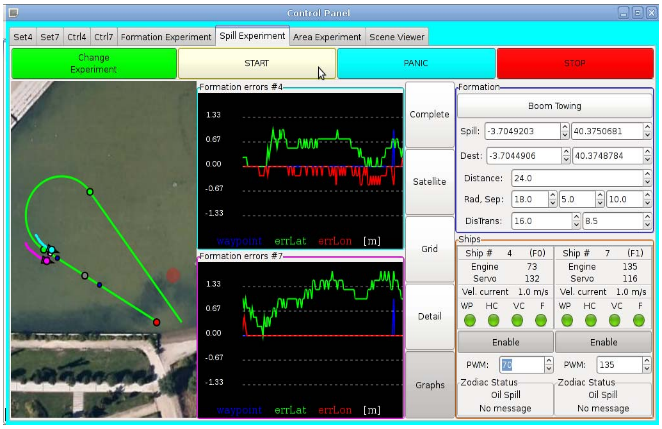

Figure 18. Main screen of the ground station

Using the graphical interface provided on the right-hand side of the screen, the operator can specify the parameters of the mission and the planning.

The parameters of the mission are the coordinates of the oil-spill and the coordinates of the final destination.

The parameters required for the planning are the radius of the Dubins curve, the desired distance between the Dubins curve and the oil-spill, and the desired separation between transition points and the oil-spill. These parameters need only to be changed when using different ships or boom length.

A. Individual control

Our first experiments were devoted to test the autonomous control of one ship. This study focuses on the establishment of proportional-integral-derivative (PID) control of heading, and on path following.

A closed path was specified using just two Dubins waypoints. Figure 19 shows the GPS trace of one of the experiments with a scaled USV on the first pond. The results were quite satisfactory, the path followed was close to the desired path.

Figure 19. Experimental confirmation of individual USV control

Notice in the middle of the picture a white point. This corresponds to a fountain that the USVs should avoid.

In the winter the pond has a solid ice surface. In other periods of the year, there is a lot of algae so propellers get stuck. We have to adapt our type of work, software, simulation, control design, and experiments, to the circumstances.

Individual control experiments have been also done with the real scale USVs on the larger pond, with similar good results.

B. Parallel formations and boom towing

The second series of experiments were devoted to make a parallel formation with two USVs. Here the focus is put on the control of lateral distances with respect to the central path, and on PID control of the follower USV speed.

During turning manoeuvres, the USV more apart from the turning centre is chosen to be the leader. This implies role exchanging in case of bow-tie paths.

Once a correct parallel formation was experimentally confirmed, the boom was attached to the USVs. After reaching several times tug-of-war situations, it was clear that a stronger lateral control authority was required. The corresponding PID constants were adjusted, and a satisfactory behaviour of the system (2 USVs and the boom) was obtained [3].

Figure 20 shows the GPS traces of one experiment with two scaled USVs towing the boom. There was a noticeable wind, but the boats sustained it quite well.

Figure 20. Experimental confirmation of boom towing with a parallel formation of USVs

It is convenient to make a distinction between path and trajectory. The trajectory includes information on where is the ship at every time. In order to analyze the results of our experiments, we post-process the experimental results with MATLAB, and represent the USVs heading and GPS position every 5 seconds, to see how good was the parallel formation. Figure 21 shows the results of the experiment depicted in figure 20, with a visualization that compares the desired trajectory of each USV and its actual experimental behavior.

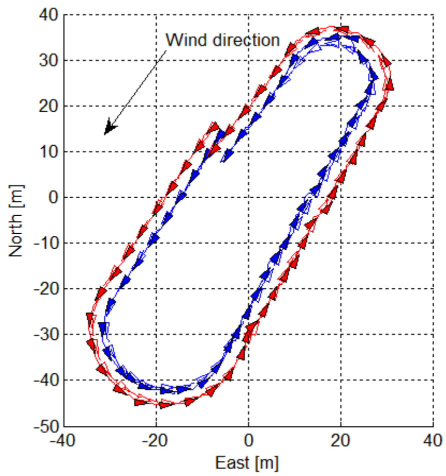

Figure 21. Analysis of the previous experiment using MATLAB

From figure 21 one can see that differences between prescribed trajectories and actual experimental trajectories are small.

Based on this good predictability, a simulation environment was established were we specify in advance the experiments, to see if they fit into the available space offered by the pond.

C. *Confinement*

The next experimental step was to test oil-spill confinement manoeuvres, with the corresponding transitions.

Figure 22 shows experimental results with the scaled USVs. This manoeuvre was inserted in one of the straight segments of the closed path. As a result of widening the distance between USVs, the drag of the boom increases and the risk of tug-of-war evolution also grows up. It is necessary to take this into account to establish for the lateral distance a greater control authority.

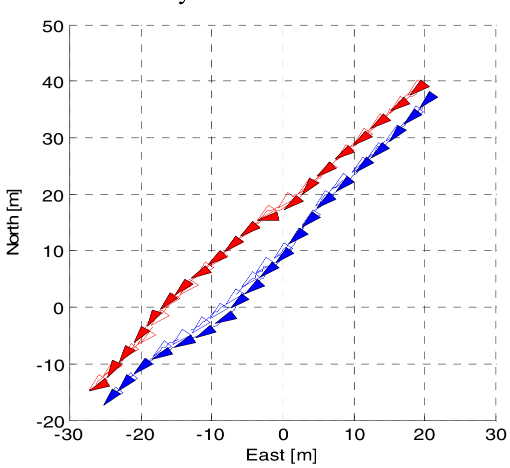

Figure 22. An oil-spill confinement manoeuvre with the scaled USVs

The confinement manoeuvre was also repeated with the real scale USVs on the lager pond. Figure 23 shows the experimental result, with the desired trajectories being represented with dashed curves.

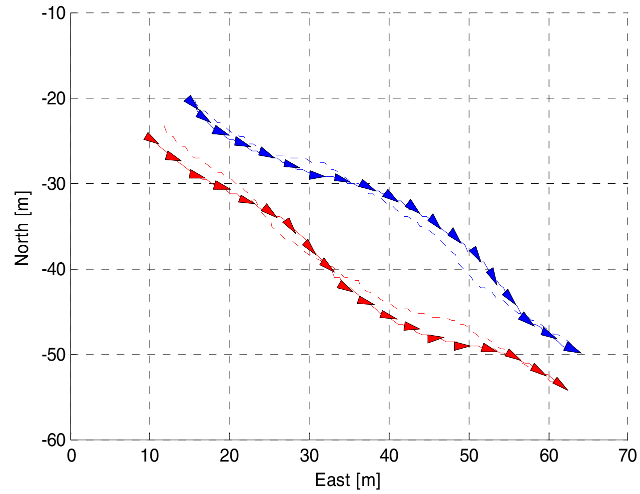

Figure 23. The oil-spill confinement manoeuvre with the real scale USVs

D. *Complete operations*

Complete operations were studied first in simulation, and then with experiments on the large pond. A main target of these experiments is to test the USVs on-board planning of the operation.

For comparison purposes, the first complete operation experiments were done with the scaled USVs.

Figure 24 shows the trajectories of the USVs during the complete operation. The figure includes the two points that were specified to the boats: the oil-spill coordinates and the final destination coordinates. Once this information was given to the boats, the boats took the responsibility of operation planning.

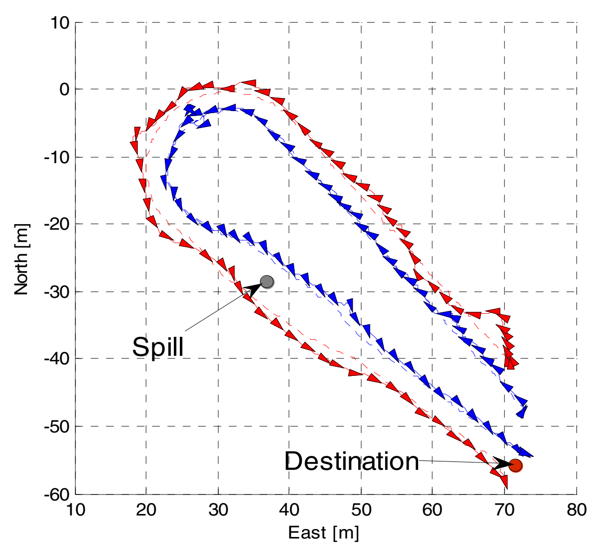

Figure 24. Complete operation with the scaled USVs towing a boom

The mutual separation of the two USVs was 3m during most of the operation. This distance increased to 6m for boom widening during oil-spill confinement. The radius of the Dubins curve was 10m.

Figure 25 shows the GPS traces of the scaled USVs during this experiment.

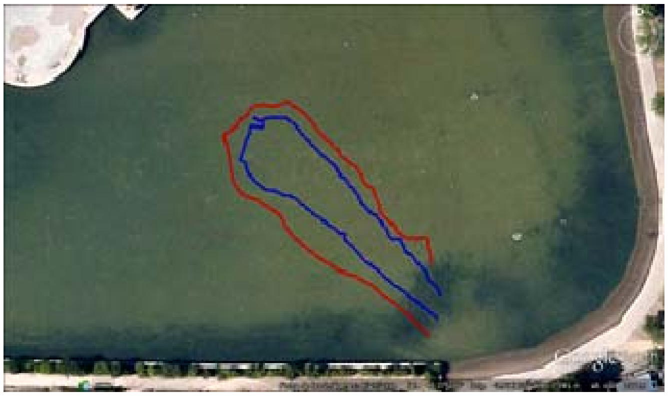

Figure 25. GPS traces of the scaled USVs

A video of the experiment is available at:

https://youtu.be/xZCa2ylfmaI

We used for the first time the data gathering floating platform, for measuring the tensions of the left and the right branches of the boom during the complete operation. Figure 26 shows the results. The red color corresponds to the branch towed by the leader.

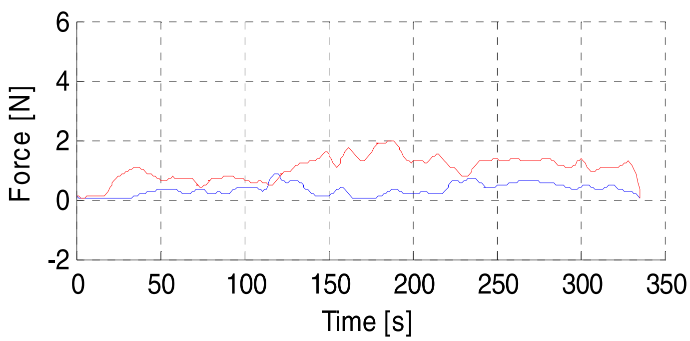

Figure 26. Tensions of the two branches of the boom

Along time, the operation takes the following steps:

- 0..130s, the first straight segment
- 130..210s, the Dubins curve
- 230..280, boom widening and then narrowing
- 280..350s, the last straight segment

Later on, a complete operation experiment was done with the real scale USVs carrying no boom.

It should be noticed that the inflatable zodiacs we are using for real scale, are made for having persons on board. In our case, no pilot means also no weight (our control system includes electronics boards and batteries, with a weight of less than 10 kg). The unmanned zodiacs tend to glide, due to centrifugal forces along curves, or due to wind. At the same time, boom towing requires low speed, and so we have limited navigation control authority.

During this experiment with no boom, the USVs suffered one significant wind gust. Figure 27 shows the recorded trajectories.

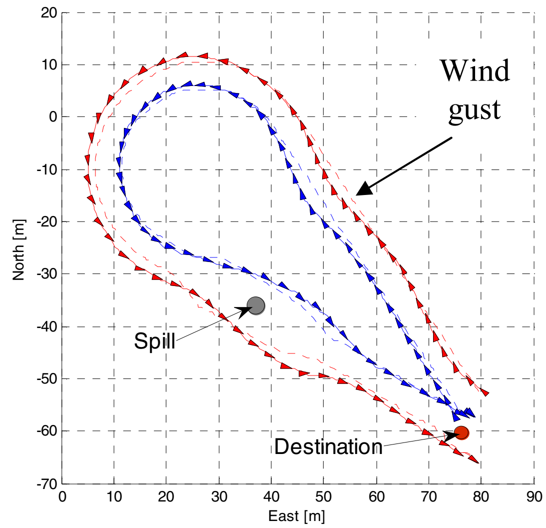

Figure 27. Trajectories with the real scale USVs with no boom

Once it was confirmed that the on-board planning works well, the longer boom was attached to the USVs and we made several times the complete operation with good results. Some of the operations used a clockwise Dubins curve, and others the opposite direction. Figure 28 shows the trajectories obtained with the clockwise turning.

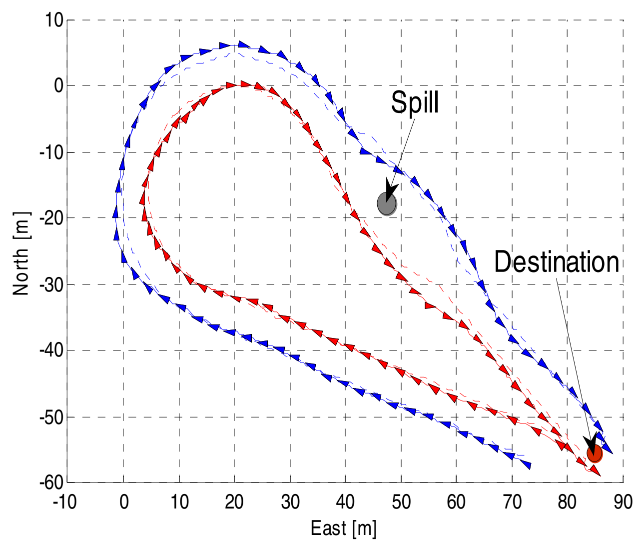

Figure 28. Trajectories with the real scale USVs towing the boom

A video of the experiment is available at:

https://youtu.be/YQ-z-Rv6AO0

Figure 29 shows the GPS traces corresponding to this experiment.

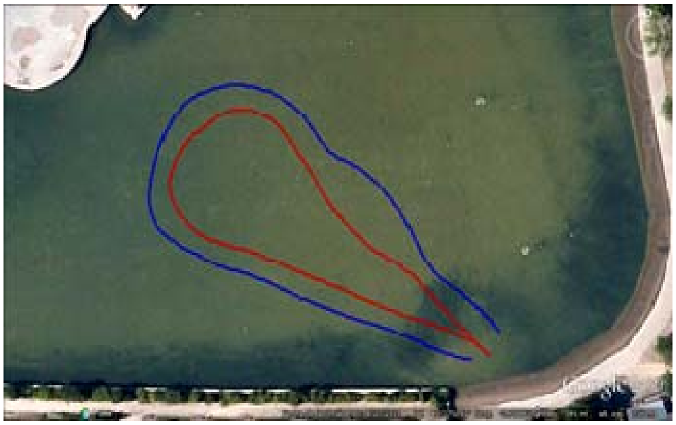

Figure 29. GPS traces of the real scale USVs during the complete operation

The mutual separation of the two USVs was 5m during most of the operation, and increased to 10m during the confinement manoeuvre.. The radius of the Dubins curve was 18m.

The tensions of the two branches of the boom were measured. Figure 30 shows the results.

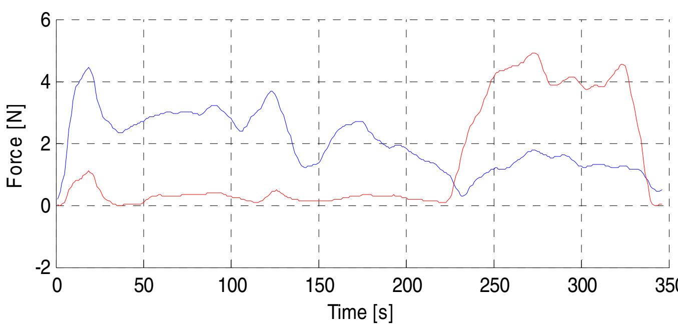

Figure 30. Tensions of the two branches of the boom

Like before, along time the operation takes the following steps:

- 0..100s, the first straight segment
- 100..200s, the Dubins curve
- 220..280, boom widening and then narrowing
- 280..350s, the llast straight segment

During the complete operations, the scaled USVs moved with 0.75m/s speed, and the real scale USVs with 1m/s speed.

It has been observed that when the formation follows the Dubins curve, the leader (which moves faster) tends to take all the boom towing effort. This means that in real life applications, each separate USV should be able of tackling the drag of the complete boom. There seems also that elastic effects happen, expressed as ‘M’ shapes in the tension curves.

VIII. Conclusion

The objective of our research is to develop a system for fully automated oil-spill recovery using two USVs towing a boom. The corresponding development has followed a series of steps with experimental confirmations, which has been described in the paper.

In the present status of our research, we are able to demonstrate complete operations with scaled USVs and real scale USV (conventional zodiacs with our on-board electronic system).

Our immediate efforts will focus on getting more experimental data about forces, and try to get a good model of the boom dynamical behaviour. Another target for the future research is to devise countermeasures when there are symptoms of nearby tug of war situations.

One of the features of our system is that it can perform re-planning in real time. We want to demonstrate this aspect in future experiments.

It would be convenient for the system to be able to detect obstacles, and react in suitable ways. This is also an open issue for the next research.

Since we will need more space for more complex operations, we plan to go to a large reservoir relatively near Madrid, and after that go to the sea.

IX. References

[1] Z. Zhong, and F. You, “Oil spill response planning with consideration of psychochemical evolution of the oil slick: a multiobjective optimization approach,” Comput. Chem. Eng., v.35, n.8, pp. 1614-1630, 2011.

[2] J. Allers, and S. Penay, “Integrated oil containment and recovery systems,” Proceedings of the International Oil Spill Conf., n.1, pp.873-874, American Petroleum Institute, 1995.

[3] J.M. Giron-Sierra, A. T. Gheorghita, G. Angulo, and J.F. Jimenez, “Preparing the automatic spill recovery by two unmanned boats towing a boom: development with scale experiments,” Ocean Eng., v.95, pp. 23-33, 2015.

[4] T.I. Fossen, “Marine Control Systems: Guidance, Navigation and Control of Ships, Rigs and Underwater Vehicles,” Mar. Cybern.

[5] Y.L. Liao, Y.M. Su, and J. Cao, “Trajectory planning and tracking control for underactuated unmanned surface vessels,” J. Central South Univ., v.21, 2014.

[6] X. Liangsheng, and Y. Weisheng, “Formation & path tracking control for multiple unmanned ships,” Proceedings IEEE Second Intl. Conf. Intelligent Control and Information Processing, v.1, pp. 425-428, 2011.

[7] M. Breivik, and V.E. Hovstein, “Formation control for unmanned surface vehicles: theory and prectice,” Proceedings IFAC World Congress, 2008.

[8] F. Arrichielo, H.K. Heidarsson, S. Chiaverini, and G.S. Sukhatme, “Cooperative caging and transport using autonomous aquatic surface vehicles,” Intelligent Service Robotics, vol. 5, n.1, pp73–87, 2012.

[9] S. Bhattacharya, H.K. Heidarsson, G.S. Sukhatme, and V. Kumar, “Cooperative control of autonomous surface vehicles for oil skimming and cleanup,” Proceedings of IEEE Intl. Conference on Robotics and Automation (ICRA), pp 2374-2379, 2011.

[10] J. Recas, J.M. Giron-Sierra, S. Esteban, B. de Andres, J.M. de la Cruz, J.M. Riola, “Autonomous fast ship physical model with actuators for 6DOF motion smoothing experiments,” Proceedings IFAC Intl. Conf. Control Applications in Marine Systems, pp. 185-190, 2004.

[11] F. Pereda, H. Garcia de Marina, J.M. Giron-Sierra, and J.F. Jimenez, “Towards automatic oil spill confinement with autonomous marine surface vehicles,” Proceedings IEEE Oceans 2011, pp 1-6, 2011.

[12] J.M. Giron-Sierra, A. T. Gheorhita, G. Angulo, J.F. Jimenez, “Towing a boom with two USVs for oil spill recovery: scaled experimental development,” Proceedings IEEE Intl. Conf. Control, Automation, Robotics and Vision, 2014.