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Experimental Results on Obstacle Avoidance for High Speed Unmanned Surface Vehicles

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***Abstract*—This work presents the first experimental results of the real-time motion planner developed within an on-going research project between DIBRIS, University of Genova and Selex-ES, Italy, one of the leading players for providing large systems aimed at security and surveillance. The ultimate goal of the research project is the development of a complete solution for managing and supervising a team of Unmanned Surface Vehicles (USVs), operating in a (semi-)autonomous manner within a civilian harbour. The proposed obstacle avoidance algorithm exploits the kinematic information of the vessels operating in the harbour in order to compute the optimal path to reach the target position, while at the same time avoiding any moving obstacle. The paper recalls the fundamentals of the proposed approach, introduces the developed USV prototypes and finally presents the adaptation of the motion planner for its use on the real tests. Field trials are presented to show the effectiveness of the approach even at high speeds.**

I. INTRODUCTION

During the past years ISME (with the operative unit of DIBRIS, University of Genova) and Selex-ES, Italy, one of the leading players for providing large systems aimed at security and surveillance, have collaborated on different projects focusing on the critical infrastructure protection (CIP) problem. Among the different scenarios for CIP, one is the harbour protection one, where Selex-ES is very active with its Archimede system [1]. The Archimede reference architecture is designed in order to guarantee flexibility and modularity by means of tactical gateways developed in order to decouple the Command and Control (C2) from sensors and effectors. Gateways are designed to translate in a unique format the proprietary data of the integrated systems in order to comply with every kind and numbers of systems, tailoring each time the specific gateway without modifying the C2 and the other systems. The C2 receives all sensor data (e.g. tracks, video...) and fuses track data in order to have one "system track" for each vessel present in the scenario.

Within this reference architecture, ISME and Selex-ES have collaborated on a joint research project called Swarm Management Unit (SMU) [2]. The ultimate goal of the research project is the development of a complete solution for managing and supervising a team of Unmanned Surface Vehicles (USVs), operating in a (semi-)autonomous manner within a civilian harbour. The main goals and features of the developed architecture are the following ones:

- provide a unique interface to the C2 for the management of the USVs;
- exploit the available tracks information coming from the C2 to provide path planning for the unmanned systems;
- manage the patrolling of the vehicles in the harbour;
- react to incoming suspect vessels providing interception solutions.

The first requirement has been achieved by developing a control station for the USVs and interfacing it with the C2 via a gateway, just as in the Archimede reference architecture. Through the gateway, the C2 provides the information (position, speed, heading) of the vessel operating in the harbour, sends specific missions such as a patrolling mission in a given area or the interception path of a suspect vessel. The base station instead reports the kinematic information and current state of the USVs, the proposed interception mission (since they need to be always validated by a man-in-the-loop) and the planned paths to be displayed on the C2 console.

As instead regards the algorithmic functionalities, the first one to be developed was the path planning and the obstacle avoidance. The developed real time motion planner is based on the three layered architecture presented in [3], [4]. The first layer simply computes the path avoiding the static obstacles employing the well known Dijkstra and the visibility graph algorithms. Once this path is computed, the second layer exploits the kinematic information coming from the C2 to alter the path and make it compatible with the moving vessels operating in the harbour. This path is then sent to the USV, where the third reactive level increases the capability of the system of avoiding incoming obstacles, especially those that could not be seen from the harbour radars.

Work on the patrolling problem has been carried out by the University of Cassino, which is also part of ISME. More specifically, they developed a decentralized coordination strategy for multi robot patrolling missions, adapting the theory of Gaussian Processes to tackle the problem of harbour patrolling. The introduction of a time varying dependency in the probabilistic formulation (thus allowing for the sampled field to be dynamic, i.e., changing in time) makes the proposed solution suitable for the type of mission considered. Moreover, the advantages of Voronoi tessellations are exploited to automatically distribute the vehicles over the environment. The resulting algorithm takes into account several constraints and can be tailored based on the communication and computational capabilities of the robots, thus making it suitable for heterogeneous systems [5], [6].

The last implemented feature regards the interception of suspect vessels. The approach is divided in two separate phases. First, there is an off-line optimization of the positioning that the team of USVs should have in order to maximize the expected performances, measured in terms of both the distance of the intercepted vehicle w.r.t. an asset to protect and of the interception time. Then, on-line, the SMU on the basis of the current vessel traffic and the actual positions of the USVs computes the best interceptor vehicle and its planned interception path [7], [8], [9].

Finally ISME, with the operative unit of University of Pisa, has worked on evaluating the performances of the harbour protection developing a GIS-based simulator able to assess the level of underwater security in civilian harbour installations, with the aim of bridging the gaps between system specifications and operative performance of anti-intrusion systems. The integration of a geographical information system (GIS), acoustic and magnetic sensor models, with a dynamic simulator makes it possible to simulate the impact of both new sensors and modification in the sensors placement in the overall harbour protection system. With the proposed approach it is possible to model the harbour environment including geographical and environmental information, to set up the surveillance system with underwater acoustic and magnetic sensors and reacquisition vehicles, and to add several types of intruders to estimate, through dynamic simulations, what security level is obtained by the sensors configuration chosen against the selected intruder [10], [11].

In this paper we present the first experimental trials for real time motion planner described in [3], [4]. The paper will briefly recall the theoretical foundations in Section II, and proceed with the description of the developed USV prototypes in Section III. The adaptation of the algorithms from the simulations to the field tests will be presented in Section IV, along with the experimental trials. Finally, some conclusions and on-going work will be given in Section V.

II. PROPOSED OBSTACLE AVOIDANCE TECHNIQUE

The basic idea of the algorithm proposed in [3], [4] is the exploitation of the kinematic information of the vessels operating in the harbour in order to compute the optimal path to reach the target position, while at the same time avoiding any moving obstacle. To do this, to each obstacle a corresponding *collision bounding box* is associated and the goal is to find the optimal path from the starting position toward the final position while never entering inside any collision bounding boxes. To solve such a problem, the planner computes the interception points between the vehicle (assumed point-wise) and each of the vertexes, exploiting the kinematic information to account for the movement of the obstacle itself (Fig. 1(a)). Each path is then checked for collisions with all the obstacles with simple ray tracing techniques, and if a collision

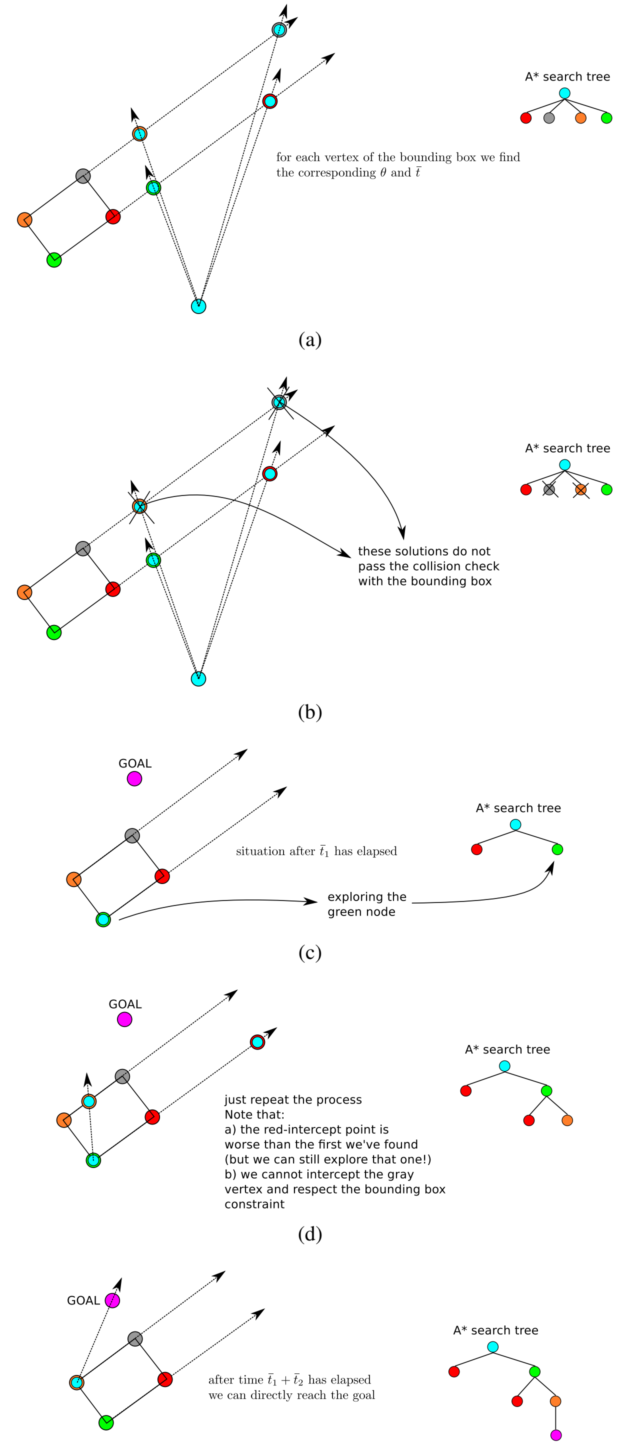

Fig. 1. Simulation of the algorithm: (**a**) interception points with all the bounding box vertexes are found (**b**) some of the nodes built are removed for collision (**c**) the most promising node is selected (**d**) vehicle is at the box's vertex ($t = \bar{t}$) and the algorithm is executed once again (**e**) goal can be reached.

is detected it is discarded (Fig. 1(b)). All the remaining interception points are saved, along with the corresponding time to reach them, as nodes of an A* graph. The successive node to explore is selected as the one having the lowest total estimated cost, i.e. the actual cost to reach it plus the estimate cost to the target (a straight line, Fig. 1(c)). The same steps outlined before are performed, but this time from the A* node as initial position (Fig. 1(d)). The search is terminated whenever the goal position can be reached without collisions (Fig. 1(e)). With the assumption that the USV is faster than the obstacle, the search will yield the time optimal path [12]. The algorithm is easily extended to cope with any number of moving obstacles, without having to make any assumptions on the order of avoidance of the obstacles.

The computation of the interception point between the USV and the vertexes of each bounding box is done in the following way. Consider the following movement equations for the USV:

$$\begin{cases} x_1(t) &= v_1 \cos(\theta) t \\ y_1(t) &= v_1 \sin(\theta) t \end{cases} . \tag{1}$$

Let us consider one vertex of the bounding box. It also will move with fixed speed and a given heading, with an initial position w.r.t. the USV assumed equal to $(-L, H)$

$$\begin{cases} x_2(t) &= v_2 \cos(\psi) t - L \\ y_2(t) &= v_2 \sin(\psi) t + H \end{cases} . \tag{2}$$

The interception problem is finding an angle θ such that, for a certain $\bar{t}$, the USV is coincident with the vertex position, i.e. the following equalities hold

$$\begin{aligned} x_1(\bar{t}) &= x_2(\bar{t}); \\ y_1(\bar{t}) &= y_2(\bar{t}). \end{aligned} \tag{3}$$

By posing $x_1(t) = x_2(t)$ and solving for t, the time $\bar{t}$ of intercept can be found as:

$$\bar{t} = \frac{-L}{v_1 \cos(\theta) - v_2 \cos(\psi)}, \quad L \neq 0, \tag{4}$$

or equivalently, if $L = 0$

$$\bar{t} = \frac{H}{v_1 \sin(\theta) - v_2 \sin(\psi)}, \quad H \neq 0. \tag{5}$$

By putting $y_1(\bar{t}) = y_2(\bar{t})$ the final condition for the intercept is met leading to

$$-Lv_1 \sin(\theta) - Hv_1 \cos(\theta) = -Lv_2 \sin(\psi) - Hv_2 \cos(\psi). \tag{6}$$

The previous equation in the unknown θ can be solved recalling the following trigonometric property

$$a \sin(\phi) + b \cos(\phi) = \sqrt{a^2 + b^2} \sin(\phi + \alpha), \tag{7}$$

where $\alpha = \tan(b/a)$. Exploiting (7) to solve (6), then θ can be easily calculated as follows:

$$\theta = \arcsin\left(\frac{v_2}{v_1} \sin(\psi + k)\right) - k \tag{8}$$

subject to

$$-1 \leq \frac{v_2}{v_1} \sin(\psi + k) \leq 1, \tag{9}$$

Fig. 2. The USV prototype used during field tests.

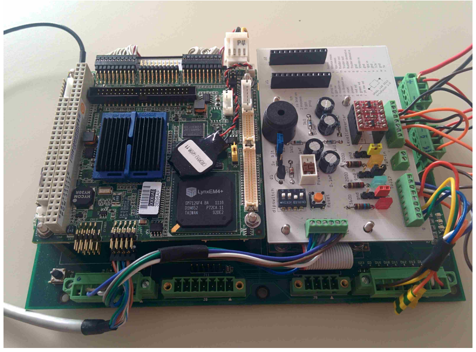

Fig. 3. The developed electronics for the control of the USV.

where $k \triangleq \tan(-H/-L)$. Equation (9) is the constraint that has to be satisfied in order to be able to find an angle. As it can be seen, if $v_1 > v_2$ there will always be a solution, while in the other case there could be one or not depending on the initial conditions of problem, i.e. the angle k.

The position of the intercept point is easily calculated, by substituting $t = \bar{t}$ in (3)

$$\begin{cases} \bar{P}_x &= v_1 \cos(\theta)\bar{t} = v_2 \cos(\psi)\bar{t} \\ \bar{P}_y &= v_1 \sin(\theta)\bar{t} = v_2 \sin(\psi)\bar{t} \end{cases} . \tag{10}$$

It has to be noted that problem (3) could have a second solution

$$\theta_2 = \pi - k - \arcsin\left(\frac{v_2}{v_1} \sin(\psi + k)\right) - k \tag{11}$$

subject to same constraint (9). However, for the majority of cases (always if $v_1 > v_2$), this solution will lead to a $\bar{t} < 0$, thus being an infeasible solution.

III. DEVELOPED PROTOTYPE

In order to test the obstacle avoidance, patrolling and interception algorithms we have developed ten low-cost USV prototypes, shown in Fig. 2. They are based off a 1.3m long commercial hull design used for radio controlled boats. All the control electronics have been customized except for the electronic speed controller (ESC) that powers the electric motor. Given the available space inside the hull, we have chosen to equip the USV with 3 LiPo battery packs in parallel for the motor and 1 pack for the electronics. This setup gives approximately one hour of full use before the discharge of the motor batteries (the electronics autonomy is much longer). The prototype is capable of reaching peak velocities of 14 knots, i.e. around 7m/s or 25km/h.

The main electronic board is shown in Fig. 3. It contains a motherboard PCB which hosts a dsPIC microcontroller, a

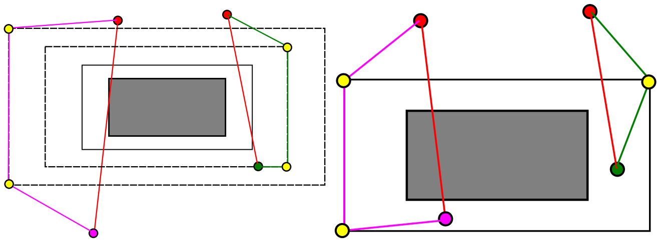
(a) (b)

Fig. 4. Adaptation of the original algorithm: (a) the green and the purple circles are two USVs, whose path to the goal crosses the safety box. A supporting bounding box (the dashed boxes) is constructed enlarging the original one, until a maximum value which is the one used for the purple USV. The generated waypoints are the yellow circles (b) the case when the USVs are inside the safety bounding box. The green vehicle original path crosses the main diagonals and thus is modified with a waypoint coinciding with one of the safety bounding box vertexes.

three axis MEMS gyro, a three axis MEMS magnetometer and a three axis MEMS accelerometer and the DC/DC converters. The motherboard PCB has holes for mounting a 10Hz GPS acquisition board from Novatel, a 2.4GHz RF modem and a PC104+ for doing the main computations.

The software on the PC104+ handles all the communications with the remote base station, exploiting the RF modem. It also implements an extended Kalman filter for the attitude estimation and the position control of the USV.

The dsPIC microcontroller is the one in charge of communicating with the servo controller for the rudder and with the ESC for the propeller motor. It does so by generating the appropriate PWM (pulse width modulated) commands that the two devices need for their operation. To increase the safety and operability of the system, we have maintained the RC channel, which is sampled by the dsPIC. Whenever a good RC signal is received, it overrides the reference commands from the PC104+, guaranteeing that the user can always take control over the automatic control mode. This has been exploited during the tests also for simulating an independent vessel (teleoperated from the shore). During the normal operation, the RC transmitter is turned off and thus the microcontroller just forwards the commands from the PC104+ to the ESC and servo controllers.

IV. FIELD TRIALS

Before presenting the field experiments let us discuss a few changes that proved necessary for the transition from the simulation environment to the actual field tests.

A. From Theory to Practice

In the developed theory a few assumption were made. Among those, the one which surely does not hold for the real vehicles is the fact that they can instantly change their heading. The second assumption which generally does not hold is the fact that the USV and the obstacles move with constant speed. These two assumptions allows to find the optimal path, which is constructed using the sides of the obstacle's bounding box. Since such assumptions do not hold for the prototypes, there is the risk of violating the bounding box and thus failing the obstacle avoidance by entering the collision bounding box.

To solve this problem we have adapted the original algorithm in the following way. First of all, a *safety bounding box* around the original collision bounding box is introduced (the solid line of Fig. 4 around the dark-gray rectangle which is the collision bounding box). All the computations for collisions are now performed against this safety bounding box, and its vertexes are used to perform the avoidance. If for some reasons the USV enters the safety bounding box, it must exit it without crossing the main diagonals, ensuring that the vehicle moves away from the collision bounding box (see Fig. 4(b)).

The above procedure allows to proceed with "sliding" along the borders of the safety bounding box, because now it is not anymore the collision one. However, since the obstacle kinematic information is in general subject to estimation uncertainty, this procedure might lead to the vehicle continuously correcting its route unnecessarily. To stabilize the solution, we introduced a further enhancement. Once a path has been computed, the next time instant instead of completely disregarding it and computing a new one, the path (the yellow circles of Fig. 4) is first checked for compliance with the updated information. If no collisions with the safety bounding boxes are found, then it is hold as the reference path, even if a new, more optimal one could be found.

To increase the likelihood that the path is still collision free with the safety bounding box even under estimation uncertainty, instead of exploiting that one for computing the interception points and constructing the final path, we use a *supporting bounding box* whose dimensions depends on the position of the USV. In particular:

- if the USV is inside the safety bounding box, the supporting one coincides with the safety one (see Fig. 4(b));
- if the USV is far away the safety bounding box, the supporting one coincides with a maximum bounding box (see the purple vehicle of Fig. 4(a));
- if the USV is in-between the maximum bounding box and the safety one, the supporting one varies with the distance, shrinking as the USV is closer to the safety one (see the green vehicle of Fig. 4(a)).

In this way, when the USV is far away from the incoming vessel, the computed path will be very robust to changes in speed and heading of the obstacle and its safety bounding box. This allows to reduce the problems connected with the USVs always following the interception points with the obstacles when their kinematic information is affected by estimation uncertainty.

B. Field Experiments

Before presenting the trials, let us comment the graphical interface used to present the results. Fig. 5 shows a snapshot of one of the trials. In particular, we can see two vehicles represented in the picture. The purple one is a regular vessel, moving in the harbour. For such a vessel, the GUI displays its safety bounding box and its maximum-size supporting one. Finally, the GUI also depicts its previous path. For the USV

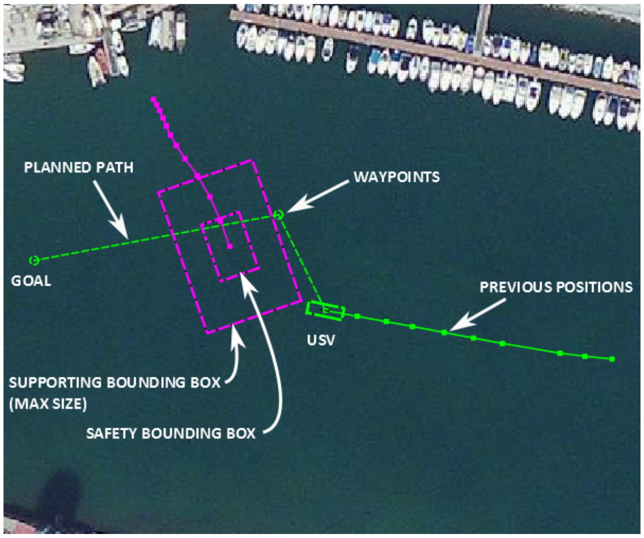

Fig. 5. Control station GUI snapshot: the USV (green vehicle) needs to avoid an incoming vessel (purple). For the incoming vessel, the GUI shows the safety bounding box, its maxumum supporting bounding box and its previous positions. For the USVs, the GUI also shows the planned path with the corresponding waypoints.

(i.e. the green vehicle in the picture), the GUI other than the above information also shows its goal position and its planned path.

a) First trial: in the first experiment the USV is commanded to move along the channel, while the vessel is moving at just 3 knots (Fig. 6(a)). Successively, the vessels maintains its course and increases its speed to 12.5 knots, but the USV path is still safe because it does not intersect the safety bounding box (Fig. 6(b)). The next figure shows that, since the vessel has further increased its speed to 13.35 knots, the USV changes its course to avoid collision, by creating a waypoint on the expected interception position with the supporting bounding box. Fig. 6(d) show that the USV has changed its heading to go toward the new waypoint. The two final figures show the completion of the successful avoidance manoeuvre.

b) Second trial: in the second trial the USV is again commanded to move while the vessel is more or less stationary. In Fig. 7(a), the vessel has started its movement and has reached a velocity of 8.35 knots, thus the USV modifies its path to avoid the incoming obstacle, choosing the front side as it is the time optimal one. However, the vessel continues to increase its speed, up to 12.44 knots. Then the previous path, which avoided the vessel from the front side, is not anymore collision free. Thus the USV changes its path again and decides to pass behind the moving vessel (Fig. 7(b)). Figure 7(c) shows that the USV maintains its computed path, even if a better could be easily found. Figure 7(d) show the completion of the manoeuvre.

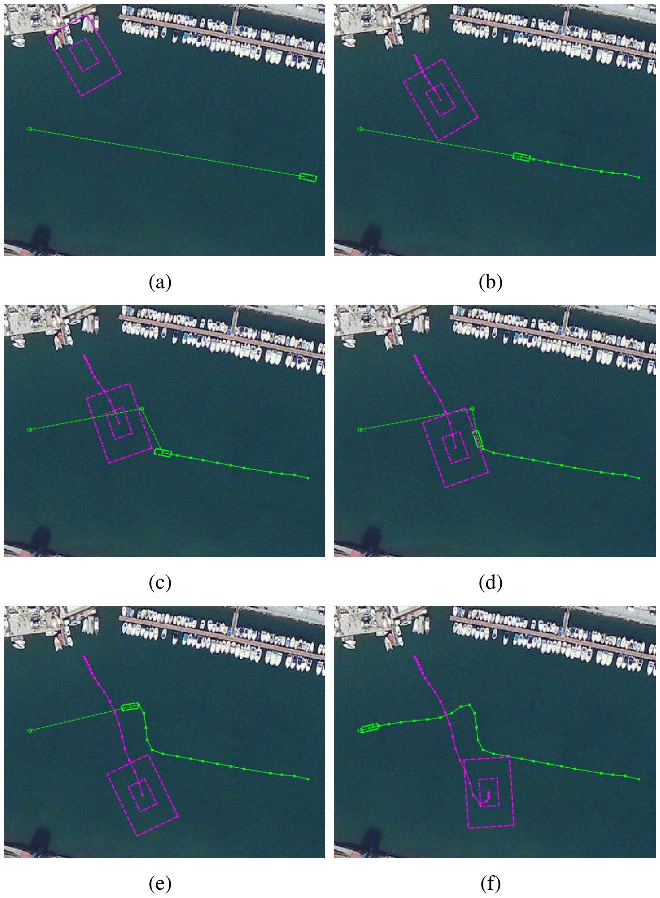
(a) (b)
(c) (d)
(e) (f)

Fig. 6. Field test 1: (a) USV goes straight to the goal (b) the vessel accelerates but the USV can still go straight (c) the incoming vessels accelerates further, thus the USV decides to pass behind it, generating a corresponding waypoint (d) the USV is moving toward the newly generated waypoint (e) the USV has reached the waypoint (f) the vessel has been avoided and the USV proceeds toward the goal.

Figure 7(c) has shown that the USV maintains its previous path if it still collision safe, despite the availability of shorter paths. This enhancement has been introduced to cope with the fact that the kinematic information of the vessels is uncertain and varies between each sampling instant, and thus leads to continuously changing the USV path. The enhancement stabilizes the solution and thus simplifies the operation of the USV, introducing a suboptimality which in many cases is neglectable. In the future, we plan to compare the previous path with the best path available and to operate as follows: if the new path is only slightly shorter than the previous one, the planner will keep the previous to improve the stability of the path; only if the new path is significantly better, the planner will discard the previous and use the new one.

V. CONCLUSIONS

This paper has presented the experimental results on obstacle avoidance performed by high speed unmanned surface vehicles, as part of the current research work carried out by ISME. In particular, the paper has briefly recalled the theoretical work done by ISME on the obstacle avoidance [3], [4] and presented its adaptation for the use with real prototypes. Two field trials have been presented showing the effectiveness of the proposed approach, even when the vehicles move at very high speeds (the peak velocities are of 14knots,

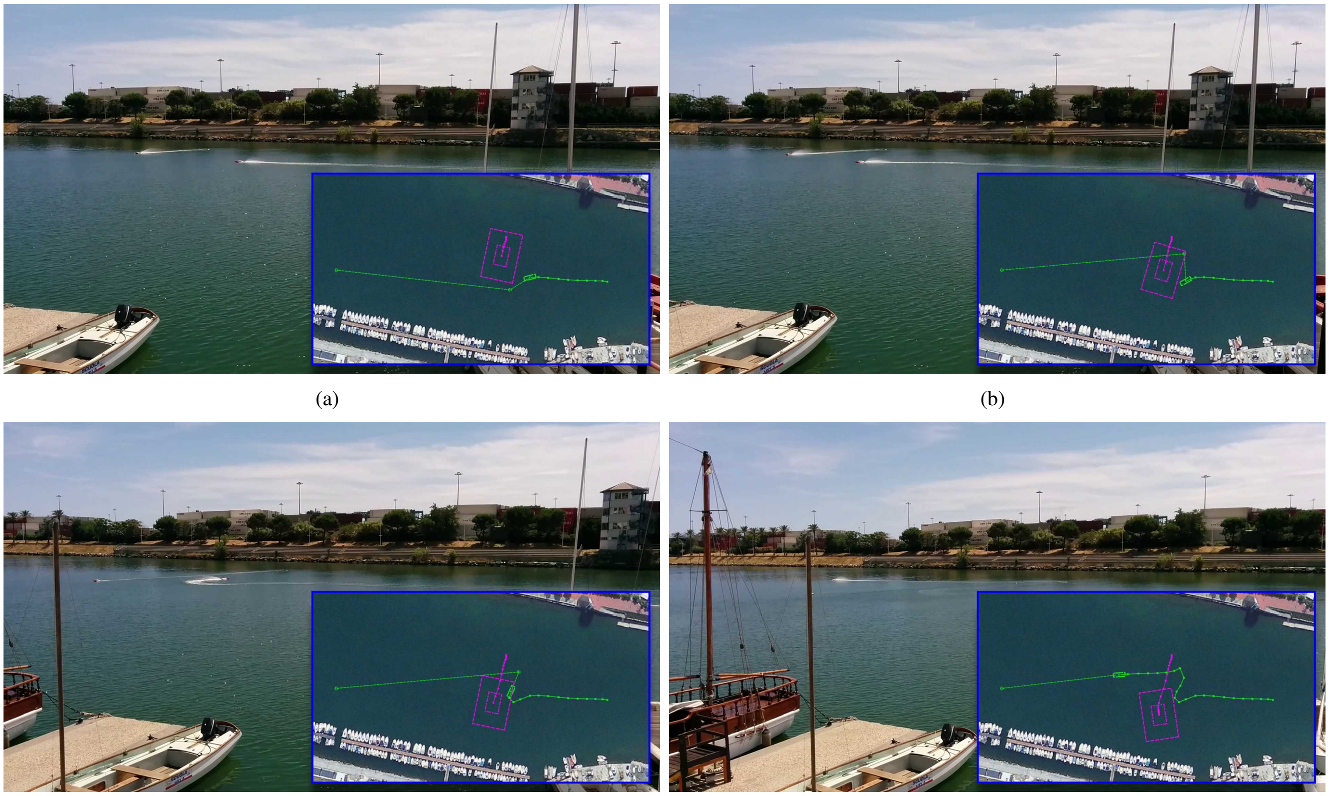
(a)
(b)
(c)
(d)

Fig. 7. Field test 2: (a) the USV avoids the incoming vessel from the front side (b) the vessel has increased its velocity, thus now the USV decided to pass behind it, (c) the USV moves toward its new waypoint, (d) the vessel has been avoided and the USV proceeds to the goal.

i.e. 7m/s or 25km/h). The enhancements used for the transition from the theory to the field experiments have proved to be reasonable and well working even when the moving obstacles suddenly accelerate and create unexpected collision situations.

Future works will concern the inclusion of COLREGS [13] rules to the path planner, as well as the enhancement outlined at the end of the previous section.

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