Protecting Assets within a Civilian Harbour through the Use of a Team of USVs: Interception of Possible Menaces

Enrico Simetti, Alessio Turetta, Giuseppe Casalino, Enrico Storti and Matteo Cresta

Abstract— **The protection of civilian harbours has received an increasing interest after September 11th. One of the areas currently under major investigation is the use of a team of Unmanned Surface Vehicles (USVs), which could be exploited for patrolling purposes and to investigate suspect situations, increasing the effectiveness of the harbor protection system while lowering the number of humans directly exposed to threats. To achieve such aims, the USVs must be properly coordinated by an intelligent Swarm Management Unit (SMU), whose realization is the goal of an on-going research project carried out by the authors' organizations. This paper presents the latest results of the SMU project, i.e. a menace interception system, that off-line optimizes the positioning of the USV team and on-line selects the most suitable USV for intercepting any possible menace.**

I. INTRODUCTION

Maintaining civilian harbours safeguarded against terroristic attacks coming from the "blue border" (i.e. the sea-side) is a problem which has received an increasing interest, especially after September 11th. Indeed, NATO's Defence against Terrorism (DAT) programme has indicated [1] the issue of harbour security as one of the main ten areas of work, where innovative and reliable technologies (like efficient sensor networks, electro-optical detectors and unmanned vehicles) can reveal very helpful.

The idea of using a team of "protecting" Unmanned Surface Vehicles (USVs) can represent a well-promising solution for increasing the effectiveness of the harbour security system and reducing the harbour vulnerability: USVs can perform patrolling of the crucial waterways, acting as mobile sensors; moreover, whenever a possible "menace" (i.e. any unauthorized vessels, or vessels moving too fast or pointing towards restricted areas) is detected, one of the USVs can be used to "intercept" it, i.e. move as fast as possible to its location in order to determine whether the suspect vessel is "hostile" or "friend" without exposing humans directly to threats.

Previous experiments on USVs were mainly performed in open sea or in waterways in the absence of other unknown moving vessels (see [2], [3] for nice surveys on the topic), however the civilian harbours are far different from those scenario, because ship traffic can be intense and the presence of the USVs must not perturb the normal harbour activities, and most importantly, there is a concrete risk of collision with other manned vehicles. These considerations have a clear influence on the requirements of the overall USVs-based security system. USVs need good path following capabilities, to be able to follow reference paths with a certain accuracy; they also need reliable sensory devices to promptly detect any incipient obstacle and reactive obstacle avoidance capabilities, to avoid unforeseen obstacles. Many of these topics have been investigated (see [4], [5], [6], [7]), while for some of them consolidated results are not yet available [3]. However, in this work USVs will be assumed totally compliant with all the above requirements.

However, even under the hypothesis of almost-perfect USVs, the need for an efficient coordination of their operations remains and important issue to be solved in order to achieve an effective and reliable USVs-based harbour security system. To this aim, DIST (University of Genova, Italy) and Selex Sistemi Integrati (a Finmeccanica Company, Italy), one of the international leading players in providing large systems for security and defence, are cooperating within an on-going joint research project, on the realization of the so-called Swarm Management Unit (SMU), a tool conceived for supervising the operations of a team of USVs performing semi-autonomous surveillance activities within civilian harbours. A detailed description of the SMU project and previous works carried out can be found in [8], [9].

The main goal of this work is solving the problem of intercepting a detected menace before it could reach a particular "asset" (i.e. a crucial site to be maintained safeguarded). The solution to such a problem requires two main components. First of all, once a menace has been detected, a prompt reaction is obtained by *on-line* selecting the best USV for the interception, exploiting the knowledge of: position of the menace and its measured (by the harbour radar system) speed and heading, position of all the available "interceptors" USVs and their kinematic characteristics (maximum speeds), current traffic conditions (positions and motions of all the other vessel in the area).

Since the position of the USVs, at the time the menace is detected, plays a major role in the effectiveness of the system, the second main component is the *off-line* optimization of the nominal positioning of all the interceptors, to be found as tradeoff between the need of protecting the asset and the one of guaranteeing a proper area coverage against possible menaces coming from different directions. Note that a menace can in principle "appear" for the first time in any

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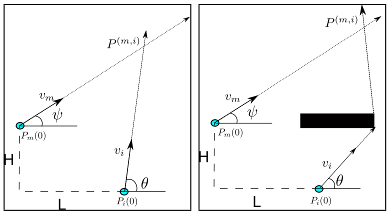


(a) (b)

Fig. 1. The interception problem: **a**) without obstacles (**b**) with an obstacle

point of the considered area, since a vessel is classified by the global security system as a menace in case, at a certain time, it starts exhibiting a suspect behaviour, like if it suddenly starts moving fast towards the asset.

In the present work both the above sub-problems are tackled and solutions optimizing given indexes of performances are proposed. The on-line selection of the most suitable interceptor is first described in section II, as it helps introducing concepts and notations used in the following. Then, the off-line optimization of the position of the USVs is detailed in section III. Section IV describes the methods used for solving the off-line optimization problems, while section V shows different simulative results obtained. Finally section VI outlines the next steps of the SMU project.

II. ON-LINE SELECTION OF THE INTERCEPTOR

Once a menace is detected, the key factor for a prompt reaction is time, thus the best USV for the interception is the one with the lowest predicted interception time, which in ideal scenarios without any other vessels, could be trivially solved by means of simple kinematic considerations. However, in harbours things are more difficult, since the presence of fixed or moving obstacles require each USV to find their minimum-time path, which heavily depends on the contingent traffic situation.

The problem of finding the shortest or the minimal-time path connecting two points in the presence of moving obstacles has been a topic of interest in robotics, machine intelligence, and computational geometry for many years (see for instance [10],[11],[12],[13],[14]). Such a fundamental problem has been addressed in a previous phase of the SMU project and has lead to the developing of an real-time motion planner, which takes into account static and moving obstacles, as inspired by theoretical results proposed in [15]. A detailed description of the motion planner has been presented in [8], [9] and is therefore here omitted. Only the basic results, useful for understanding the solution of the problem at hand are here reported for the reader's convenience.

To this aim the simplified problem depicted in Fig. 1 is first considered: given a single USV, say the *i*-th, moving at its maximum speed v_i, find (if any) the USV heading angle θ enabling the interception of a menace m, starting from a generic position $P_m = (-L, H)$ w.r.t. the USV and moving at a constant speed v_m with a constant heading angle ψ.

By defining the motion of the i-th USV and the menace as:

$$P_i(t) \triangleq \begin{bmatrix} v_i cos(\theta)t \\ v_i sin(\theta)t \end{bmatrix}; P_m(t) \triangleq \begin{bmatrix} v_m cos(\psi)t - L \\ v_m sin(\psi)t + H \end{bmatrix}$$

if no obstacles are located between the menace and the USV (Fig. 1.a), the angle θ can be calculated as:

$$\theta = asin\left(\frac{v_m}{v_i} sin\left(\psi + k\right)\right) - k \tag{1}$$

clearly subject to $-1 \leq \frac{v_m}{v_i} sin\left(\psi + k\right) \leq 1$ (where $k \triangleq atan2(-H, -L)$), which is the constraint that determines the existence of a feasible solution. If $v_i > v_m$ there is always a solution; otherwise a solution might exist or not depending on the initial conditions of the problem, i.e. the angle k.

In case solution (1) exists, given the angle θ, the time needed for the interception can be calculated as:

$$t^{(m,i)} = \frac{-L}{v_i cos(\theta) - v_m cos(\psi)}, \quad L \neq 0 \tag{2}$$

while the point of the interception is obtained as:

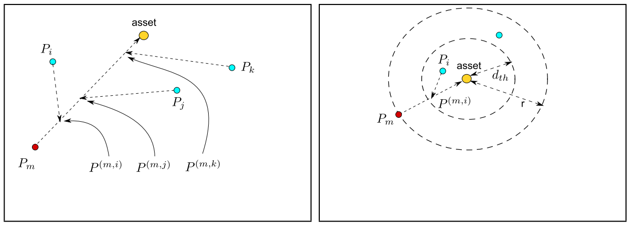
$$P^{(m,i)} \triangleq \begin{bmatrix} P_x^{(m,i)} \\ P_y^{(m,i)} \end{bmatrix} = \begin{bmatrix} v_i cos(\theta)t^{(m,i)} \\ v_i sin(\theta)t^{(m,i)} \end{bmatrix} \tag{3}$$

where the notation $(\cdot)^{(m,i)}$ means that the quantity $(\cdot)$ refers to the i-th vehicle intercepting the menace m.

In case at least one (static or moving) obstacle prevents the USV from using the straight line (see Fig. 1b), the motion planner solves the interception problem between the USV and all the vertices v_k of the obstacle, obtaining the corresponding predicted interception points $\{P^{(v_k,i)}\}$ and related interception times $\{t^{(v_k,i)}\}$. Then from any of the resulting point the planner checks if a collision free straight line can reach the menace; if that is the case, the resulting menace interception point and related time are computed, otherwise the procedure is re-iterated from the considered point $P^{(v_k,i)}$, by solving the set of interception problems with the remaining vertices of the obstacle. While doing so, a tree of the possible alternative collision-free paths is built-up and explored by using the A^* method. At the end, the minimum-time path is always obtained (even in the presence of many obstacles), together with the resulting optimal $P^{(m,i)}$ and $t^{(m,i)}$.

By now moving back the attention to the original problem of on-line selecting the better interceptor, consider Fig. 2a, representing a situation where a menace is discovered at point P_m and is moving towards an asset, located at point $P_a = (x_a, y_a)$. A given number of vehicles $i = 1, \cdots, N$ are located in their respective positions P_i. No obstacles are sketched in the figure for clarity, but an arbitrary number of other vessels can be thought to be present in the area.

As soon as the menace is detected, for every USV, the predicted point of interception $P^{(m,i)}$ and related instant of interception $t^{(m,i)}$ is first of all calculated by the motion planner, as explained before. The problem of selecting the



(a) (b)

Fig. 2. (**a**) Schema of the intercept problem (**b**) with a minimum distance of interception required

most suitable vehicle can then be simply stated as the following minimization problem:

$$\arg\min_i t^{(m,i)} \tag{4}$$

which can be easily on-line solved, given the availability of all the $t^{(m,i)}$ terms. As a result, other than indicating the better USV for the interception, the SMU outputs also the list of waypoints it has to follow for moving among the obstacles, along the minimum-time path to the menace.

III. OFF-LINE POSITIONING OPTIMIZATION

Some preliminary considerations have to be drawn before considering the problem of USVs' positioning.

First of all, considering that a menace can appear for the first time *anywhere* in the considered area makes the problem of asset protection intractable, since the menace could theoretically appear when it is already on the asset. Thus, it is hereafter assumed that if a menace exists, it it always detected before a certain distance r from the asset, an assumption which is not so unreasonable, as the navigation in the proximity of the asset could be totally forbidden.

Further, even if the actual interception time is dependent on traffic conditions, in the off-line optimization problem no other vessels are assumed in the area, since their presence cannot be a-priori predicted reliably. Finally, menaces are assumed to move with a given upper-bound velocity.

Even with these assumptions, the problem of off-line deciding the "best" nominal USVs positioning is not as straightforward as the on-line part of the interception problem, always admitting the optimal solution (4). Indeed, in the considered harbour security scenario an unique optimal criterion driving the optimization process is hard to identify; several *reasonable* alternative strategies can be adopted, in response to the specific index of performances one wish to optimize.

Moving from the above considerations, the proposed solution is based on the following two criteria. The first one requires that, for *any* possible menace, there is *always* at least one among the team of USVs in the condition of intercepting the menace before it can reach a certain security distance from the asset. As shown in the following, the adoption of such a primary criterion, other than reducing the chances of the menace to harm the asset, provides, as a by-product, an indication on the minimum number of "asset-protector" USVs. The eventually extra USVs can be employed for the secondary criterion, that aims to reduce the maximum interception time.

A. Primary Criterion: Preventing Menaces from Getting Too Close to the Asset

The problem of guaranteeing that *any* menace can be *always* intercepted, before it gets too close to the asset, can be translated into a worst-case-scenario optimization problem. Indeed it has to be granted that, even if the menace is detected in the closest possible position to the asset (i.e. at a distance r), the USVs are always in the condition of intercepting it on time (i.e. before the menace reaches a given security distance $d_{th} < r$, see Fig. 2b).

In order to properly approach the formulation of the above optimization problem, let $P \triangleq \{P_1, \cdots, P_N\}$ denote the set of initial positions of a team of N USVs, while be P_m the initial position of a detected menace m. For any given set of initial conditions (P_m, P), the distance between the interception point related to the i-th USV and the asset can be easily computed as $d_i\left(P_m, P\right) \triangleq \|P^{(m,i)} - P_a\|$.

It then follows that, for any given (P_m, P), the most suitable USV for the interception is selected as:

$$i^o = \arg\max_{i|P_m,P} d_i\left(P_m, P\right) \tag{5}$$

whose corresponding distance between the interception point and the asset is

$$D\left(P_m, P\right) \triangleq \max_{i|P_m,P} d_i\left(P_m, P\right) \tag{6}$$

By now solving the above problem for any possible P_m (while still maintaining fixed the set P), the worst-case-scenario, i.e. the point P_m leading to the closest to the asset interception point, can be calculated as:

$$D_w\left(P\right) \triangleq \min_{P_m|P} D\left(P_m, P\right) \tag{7}$$

By finally letting the optimization variable P vary, the optimal positions of the USVs are obtained as:

$$P^o \triangleq \arg\max_P D_w\left(P\right) \tag{8}$$

whose corresponding distance from the interception point and the asset in the worst-case-scenario is clearly:

$$D^o = \max_P \left\{ \min_{P_m} \left[\max_i \left(\|P^{m,i} - P_a\| \right) \right] \right\} \tag{9}$$

By finally noting that, in case D^o results lower than d_{th}, it means that the considered amount of USVs is not sufficient to always guarantee the fulfillment of the security threshold distance, a simple algorithm is here proposed for determining the minimum number of USVs required for protecting the asset: solve problem (9) for an increasing number of vehicles k (starting from 1) until D^o is made greater than d_{th}. The resulting number k is then the minimum number of required asset-protectors, while the corresponding P^o is the vector of their optimal positioning.

B. Secondary Criterion: Minimizing the Maximum Interception Time

The previous procedure gives the number k of vehicles necessary to meet the required minimum distance of interception from the asset. In case the number of available vehicles N is greater than k, the remaining $N-k$ USVs can be exploited to solve another kind of optimization problem: minimizing the maximum interception time. Indeed it is easy to see that such a criterion allows to spread out the extra vehicles in the area to safeguard, making the team more reactive against menaces detected at any distance from the asset greater than r.

To better approach the problem, it is convenient to split the set of USVs into two subsets: the first k vehicles with a fixed optimal positioning, as determined by the previous problem; and the remaining $N-k$ ones, whose set of positions $\hat{P} \triangleq \{P_{k+1}, \cdots, P_N\}$ is the subject of the here considered secondary optimization problem.

With these premises, for any given initial conditions (P_m, P), the most suitable USV for the interception is now the one with the lowest interception time, that is:

$$i^o \triangleq \arg \min_{i|P_m,P} t^{(m,i)} \tag{10}$$

whose corresponding interception time is

$$T\left(P_m, P\right) \triangleq \min_{i|P_m,P} t^{(m,i)} \tag{11}$$

Then, by again considering the menace in all the allowed positions, the worst-case-scenario can be found as:

$$T_w\left(P\right) \triangleq \max_{P_m|P} T\left(P_m, P\right) \tag{12}$$

Therefore the optimal positions of the extra-USVs can be found by minimizing the time of interception in the worst-case-scenario; that is:

$$\hat{P}^o \triangleq \arg \min_{\hat{P}} T_w\left(P\right) \tag{13}$$

Finally note that, since problem (12) considers all the possible P_m points, the extra USVs are spread out, the farther away from the asset, the bigger the considered area is. The following more convenient formulation of problem (12) can therefore be made, by introducing a proper weighting function $0 \leq W\left(P_m\right) \leq 1$ expressing the "probability of detection" of a menace in any particular point:

$$T_w\left(P\right) \triangleq \max_{P_m|P} W(P_m) T\left(P_m, P\right) \tag{14}$$

In this way the points at the boundaries of the considered area could have a very low weight, as those inside the circle of radius r should have a zero weight.

IV. OFF-LINE OPTIMIZATIONS SOLUTION

Both the off-line optimization problems have been solved using a Monte Carlo approach, coupled with a gradient descent algorithm. During each Monte Carlo run, the team of USVs has been randomly placed in the area, obtaining a particular set P. Then, the area has been discretized using a grid, and for each point the corresponding worst-case-scenario distances (7) or interception times (14) have been calculated. Then, the gradients of the cost indexes D_w and T_w were calculated, by varying one position of the set P at a time, and recalculating the new worst cases. This procedure was iterated until the variation was small enough, or a maximum number of iteration was reached. The final cost values and the relative positioning were saved and the best ones selected by comparing the different results of all the Monte Carlo runs. Naturally, since a numeric method has been used, all the solutions are affected by the discretization process and the numerical precision.

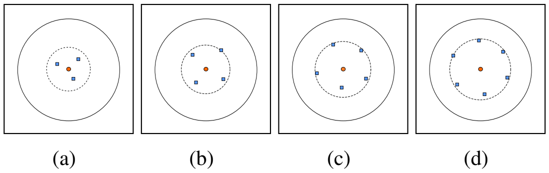


Fig. 3. Different optimized results of the asset protection problem obtained by varying d_{th}: **(a)** $d_{th} = 86m$ **(b)** $d_{th} = 96m$ **(c)** $d_{th} = 110m$ **(d)** $d_{th} = 120m$

V. SIMULATIVE RESULTS

This section presents some simulative results, obtained by considering a simple squared area of $4km^2$ and solving the two off-line optimization problems. Cases with irregular borders, such as coast lines or harbour infrastructures, are not found here because, in this first phase of evaluation, simpler cases are easier to understand and validate, and, since presence of fixed obstacles requires that the menace *somehow* avoids them, a further effort is needed to determine (in a probabilistic way) the expected path of the menace. This last issue is currently under investigation and is a very challenging part of the future works.

In all the following figures the orange circle represents the position of the asset, while the blue squares represent the positions of the USVs, as they result from the considered optimization problem.

Fig. 3 shows simulations performed for the asset protection problem with a given forbidden region $r = 200m$ (solid circle), varying the security threshold d_{th} (dashed circle). Menaces are supposed to move at a speed of $20m/s$, while USVs are considered slower, with a velocity of $15m/s$. As expected, the minimum number of required asset protectors is strictly dependent on the dimension of d_{th}.

All the succeeding simulations tackle the secondary optimization problem, where in all the considered cases, a pointwise asset with a very low d_{th} threshold has been used. It is easy to see that the solution of the first optimization problem leads to a single asset protector located on the asset (and not depicted in figures). In this way the the positioning of the extra-USVs is emphasized.

The first simulation, depicted in Fig. 4a and Fig. 4b, shows the different results obtained with the asset placed in $(0, 1000)$, by varying the velocity of the USV. According to intuition, the slower the USVs are, the closer they need

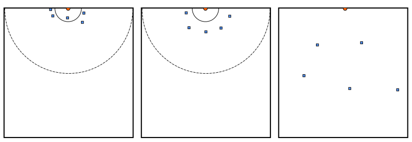

(a) (b) (c)

Fig. 4. (**a**) USV with speed of 5m/s (**b**) speed 15m/s (**c**) with $W(P_m) = 1$

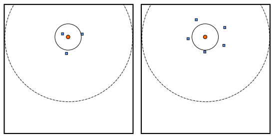

(a) (b)

Fig. 5. (**a**) with 4 USVs (**b**) with 6 USVs

to be to the asset. The following weighting function is used:

$$W(P_m) = \begin{cases} 0 & d < 200; \\ (d-200)/1000 & 200 < d < 600; \\ (1000-d)/1000 & 600 < d < 1000; \\ 0 & d > 1000 \end{cases} \tag{15}$$

where $d = \|P_m - P_a\|$ is the distance of the considered point to the asset. In this and all the following simulations, the dashed circle represents $d = 1000m$ from the asset, so outside it $W(P_m) = 0$. In the second example, shown in Fig. 4b and Fig. 4c, the effects of the weighting function $W(P_m)$ can be seen. While in Fig. 4b the use of the previously defined $W(P_m)$ is shown, in Fig. 4c the results have been obtained by setting $W(P_m) = 1$ for each point. As expected, not weighting the points makes the vehicles spread even more towards the points farthest away from the asset, as they are the ones with the highest possible interception time.

The simulation of Fig. 5 (again performed with the above weighting function and with speeds of $20m/s$, and $15m/s$ for menaces and USVs respectively) shows instead the effects of the number of available USVs.

Fig. 6 instead depicts the results obtained under the same conditions of the previous one by using 6 USVs, and the effects of the position of the asset with respect to the zone of interest. Indeed, if the asset is in an open sea zone, the USVs will be spread all around, while if the asset is on the margin of the zone, or even in one corner, the USVs are positioned in front of it. The last simulation (see Fig. 6d) shows a perfectly symmetric case, where the asset has been placed at the center of the zone and a radial $W(P_m)$ has been used as weighting function. According to common intuition, the procedure places the USVs in a circle all around the asset.

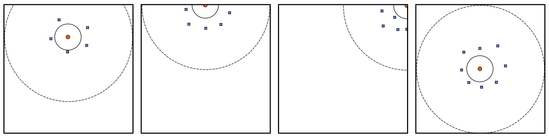

(a) (b) (c) (d)

Fig. 6. (**a**) 6 USVs with asset in $(0, 500)$ (**b**) asset in $(0, 1000)$ (**c**) asset in $(1000, 1000)$ (**d**) 9 USVs with asset in $(0, 0)$

VI. CONCLUSION AND FUTURE WORKS

This paper has shown the latest research results of the Swarm Management Unit project, a tool conceived for the control of the operations of a team of Unmanned Surface Vehicles performing surveillance activities within civilian harbours. In particular, a solution to the problem of intercepting menaces has been proposed here, which is made by two fundamental parts: the first one is run on-line and selects the predicted time-optimal vehicle for interception, while the second one is run off-line and optimizes the USVs' positioning. Current works are focused on the cases with fixed obstacles, while the next steps will tackle the problem of multiple assets and/or multiple menaces. Finally, sea trials to be held in La Spezia's harbour have been planned by Selex Sistemi Integrati for Spring 2010, where the latest version of the SMU will be tested.

REFERENCES

[1] (2004) NATO defence against terrorism (DAT) programme. [Online]. Available: http://www.nato.int/issues/dat/

[2] J. Veers and V. Bertram, "Development of the USV multi-mission surface vehicle III," in *5th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT 2006)*, May 2006.

[3] M. Caccia, "Autonomous surface craft: prototypes and basic research issues," in *Proc. 14th Mediterranean Conference on Control and Automation MED '06*, June 2006, pp. 1–6.

[4] J. Larson, M. Bruch, and J. Ebken, "Autonomous navigation and obstacle avoidance for unmanned surface vehicles," in *Proc. SPIE Unmanned Systems Technology VIII*, April 2006.

[5] A. J. Healey, D. P. Horner, S. P. Kragelund, B. Wring, and A. Monarrez, "Collaborative unmanned systems for maritime and port security," in *Proc. of the 7th IFAC Conference on Control Applications in Marine Systems*, Zagreb, Croatia, 2007.

[6] M. Caccia, M. Bibuli, R. Bono, and G. Bruzzone, "Basic navigation, guidance and control of an unmanned surface vehicle," *Autonomous Robots*, vol. 25, no. 4, pp. 349–365, November 2008.

[7] M. Bibuli, G. Bruzzone, M. Caccia, and L. Lapierre, "Path-following algorithms and experiments for an unmanned surface vehicle," *Journal of Field Robotics*, vol. 26, no. 8, pp. 669–688, June 2009.

[8] G. Casalino, A. Turetta, and E. Simetti, "A three-layered architecture for real time path planning and obstacle avoidance for surveillance USVs operating in harbour fields," in *OCEANS 09*, Bremen, Germany, May 2009.

[9] E. Simetti, A. Turetta, G. Casalino, E. Storti, and M. Cresta, "Towards the use of a team of USVs for civilian harbour protection: Real time path planning with avoidance of multiple moving obstacles," in *IEEE IROS09 3rd Workshop on Planning, Perception and Navigation for Intelligent Vehicles*, St. Louis, MO, US, October 2009.

[10] J. S. B. Mitchell, "Geometric shortest paths and network optimization," in *Handbook of Computational Geometry*. Elsevier Science Publishers B.V. North-Holland, 1998, pp. 633–701.

[11] Y.-H. Liu and S. Arimoto, "Path planning using a tangent graph for mobile robots among polygonal and curved obstacles," *Int. J. Rob. Res.*, vol. 11, no. 4, pp. 376–382, 1992.

[12] B. Donald, P. Xavier, J. Canny, and J. Reif, "Kinodynamic motion planning," *J. ACM*, vol. 40, no. 5, pp. 1048–1066, 1993.

[13] J. A. Storer and J. H. Reif, "Shortest paths in the plane with polygonal obstacles," *J. ACM*, vol. 41, no. 5, pp. 982–1012, 1994.

[14] S. M. LaValle and J. J. Kuffner Jr., "Randomized kinodynamic planning," *Int. J. Rob. Res.*, vol. 20, no. 5, pp. 378–400, 2001.

[15] K. Fujimura and H. Samet, "Planning a time-minimal motion amidst moving obstacles," *Algorithmica*, vol. 10, no. 1, pp. 41–63, 1993.