Deliberative path planning for an autonomous unmanned surface vehicle performing MCM operations

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Abstract — Path planning for a maritime autonomous unmanned surface vehicle (USV) has its own particular set of constraints that are not applicable to land based mobile robots. This is especially true when the application area is mine counter measures (MCM) where the USV's motion may be constrained because it is equipped with a towed sonar. A sonar towed behind a USV constrains the USV in speed, acceleration, deceleration, and turn rate. This paper describes an approach to deliberative path planning that allows the USV to autonomously plan during the mission, reducing or removing the need for watch-keeper interaction. The deliberative path planner conceptually sits above a behaviour based control layer and determines the best path for the USV to follow given the motion constraints of the USV and its towed sonar, taking onto account obstacles and the ocean current as sensed in real-time on the USV. The algorithm has been implemented and integrated with our existing behaviour-based USV control architecture.

1 Introduction

Maritime mine counter measures (MCM) have traditionally employed large manned vessels but advances in artificial intelligence have enabled an evolution towards the use of smaller autonomous unmanned vessels allowing personnel to be kept clear of dangerous areas.

This paper describes the use of a path planning algorithm for an unmanned surface vessel as seen in Figure 1.

Figure 1 Unmanned Surface Vessel

The USV is fitted with numerous sensors for situational awareness, e.g. radar and AIS as well as daylight and infra-red cameras. It communicates with and may be controlled by a shore-side watch-keeper using radio communications. For MCM operations the USV is able to deploy a towed synthetic aperture sonar, a forward looking obstacle avoidance sonar as well as a tethered remotely operated vehicle. The correct operation of these payloads depends on the USV operating with strict constraints on its motion.

The autonomy software on the USV is based on a 3rd party, open source autonomy toolkit. This uses a behaviour-based robotics paradigm [1] where a collection of independent behaviours contribute to the overall autonomous behaviour of the USV.

Although the toolkit provides behaviours specific to the maritime domain such as waypoint achievement and obstacle and collision avoidance it does not provide all the behaviours required for MCM operations, e.g. when the USV is towing a sonar. These behaviours have been developed by Thales to supplement the standard behaviours. These include behaviours to keep the USV's speed through the water within the limits required by the towed sonar.

2 The Problem

Figure 2 shows a typical USV MCM mission. The USV first autonomously deploys its towed sonar and then performs a "lawnmower" pattern sonar survey given only start and end track waypoints.

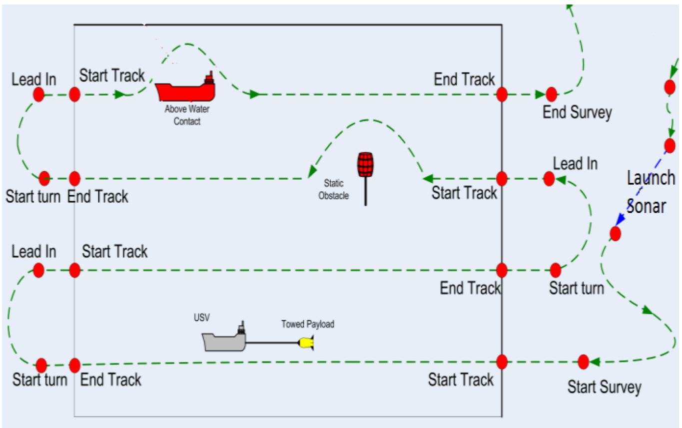

Figure 2 - Typical USV MCM Mission

The deliberative path planner determines the following manoeuvres as the mission progresses.

(i) Performing a turn at the end of a survey track given only the pre-planned end of track waypoint and the next start of track waypoint. This turn must take into account the ocean current sensed by the USV at the time the turn begins since the towed sonar constrains the through the water minimum turn radius rather than the over the ground turn radius. Depending on the track spacing and the minimum turn radius the required turn may be a simple circular turn or a more complex Boutakoff turn.

(ii) Performing manoeuvres for towed sonar launch and recovery. When the towed sonar is being deployed from the back of the USV, the USV must travel in a straight line from the deployment point into the direction of the ocean swell. This means that the positions and poses to be achieved are computed during the mission and depend on the prevailing swell direction sensed by the USV at the time of the manoeuvre.

(iii) Performing manoeuvres to resume a mission when the watch-keeper re-engages autonomous control after a period of direct operator control.

(iv) Performing manoeuvres after a behaviour based collision avoidance manoeuvre where the USV needs to compute a path back to resume its mission.

3 The Approach

The deliberative path planner uses rapidly exploring random trees (RRT) [2] to explore the space from the required start position to the required end position taking into account static obstacles in the area. The position of each node in the tree is determined in a semi-random manner and is then connected to the closest existing node. The tree is built-up from the start position with additional nodes added until there is a node in direct line of sight of the end position. The edges of the tree must not pass through an obstacle.

Figure 3 shows an example RRT from a start position and pose to an end position and pose where the start and end positions are separated by obstacles.

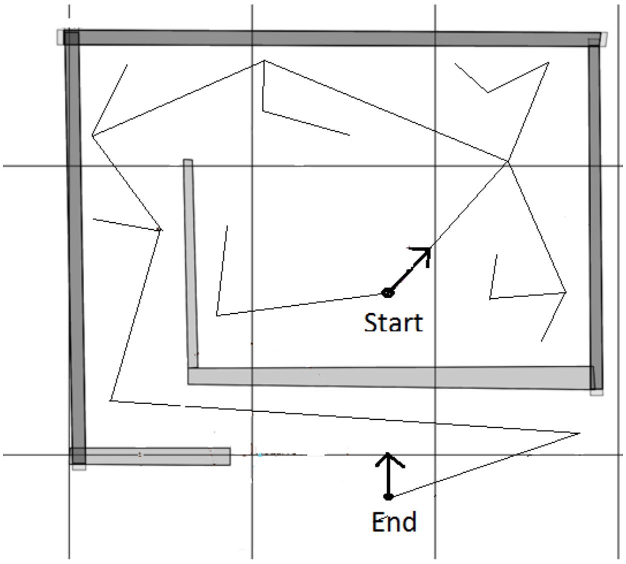

Figure 3 – State space graph

After the initial RRT tree is computed it is searched for the shortest path from the start to end position. The shortest path is then processed to optimise its geometry. Nodes that are in direct line of sight of each other are directly connected cutting out any intermediate nodes and edges are shortened to reduce the overall path length. This may be seen in Figure 4.

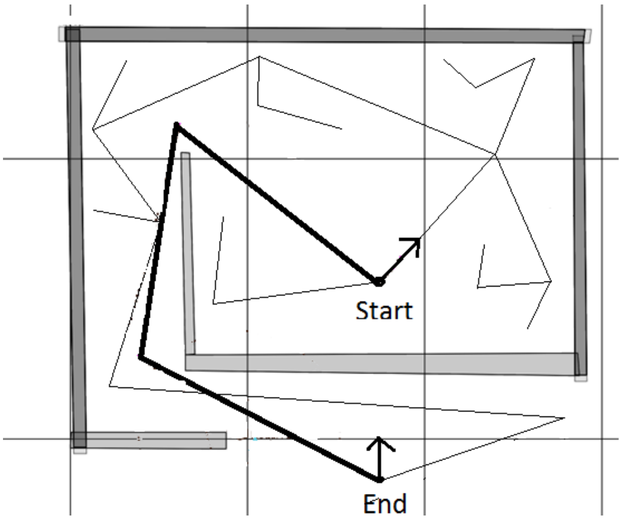

Figure 4 Optimised RRT path

When towing a sonar, the USV is a non-holonomic vehicle with constrained manoeuvrability. In this case the USV has strict navigation constraints, e.g. a minimum through the water turn radius and a requirement to always move forward within strict speed through the water limits. Because of this the optimised RRT path has Dubin’s curves [3] overlaid on top of it. As may be seen from Figure 5, and described by Dubins, any manoeuvre from a start position and pose to an end position and pose for a non-holonomic vehicle is defined by either a left or right-hand turn followed by a straight line and then either another left or right-hand turn.

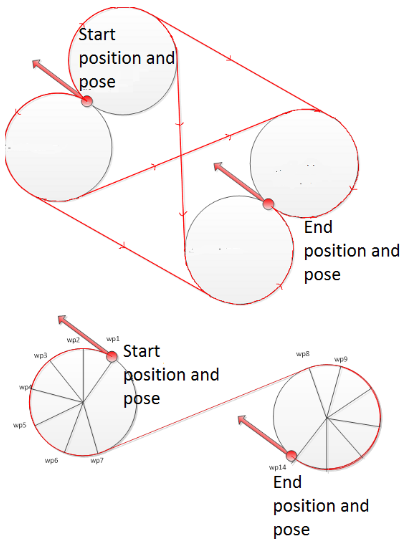

Figure 5 - Dubin's Curves

The specific combination of left or right turns that give the shortest overall path is selected in sequence for each required position and pose along the optimised RRT path. This final path is then broken down into a series of over the ground waypoints.

The shape of the turn through the water is then determined by finding the drifted positions of the over the ground waypoints given the speed of the USV and the strength and direction of the ocean current at the time of the turn. This through the water turn shape is then analysed to determine whether it breaks the maximum through the water turn rate required by the towed sonar. The radius of the over the ground turn is increased until the through the water turn rate is within the required limits.

In Figure 6 we have an initial over the ground Boutakoff turn (the solid red line) where the USV proceeds from the right-hand side of the turn to the left- hand side. There is a cross ocean current due west. The dotted red line is the drifted position of the turn waypoints at the end of the turn. The dotted red drifted line is annotated with “P” for the parts of the turn where the turn rate breaks the maximum allowed turn rate. The solid blue line is the smallest radius over the ground turn for which the drifted through the water turn (the dotted blue line) does not break the turn rate constraints.

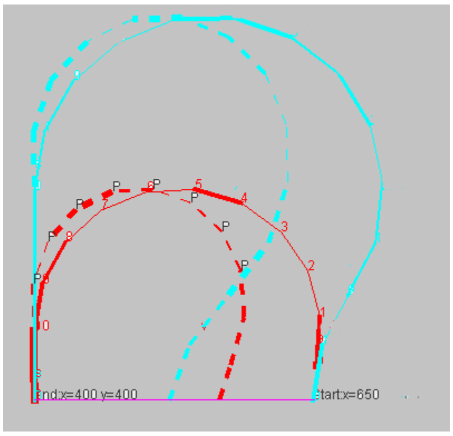

Figure 6 - Drift compensation

The solid blue line is the path that can be followed that respects the USV navigation constraints, i.e. it does not exceed the maximum turn rate through the water.

The drift compensated Dubin’s curves are then over-laid on top of the optimised RRT path. This final path may be seen in Figure 7.

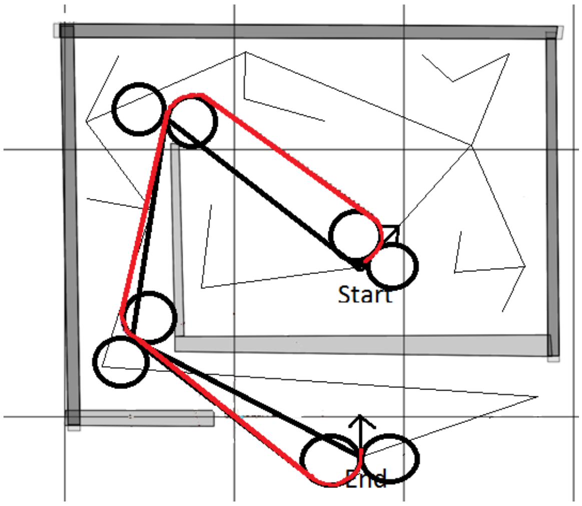

Figure 7 - Final path

The waypoints in the final path are then drip-fed, one by one, in the behaviour based layer and the waypoint behaviour is responsible for achieving each waypoint in turn. The actual path taken by the USV may be seen in Figure 8.

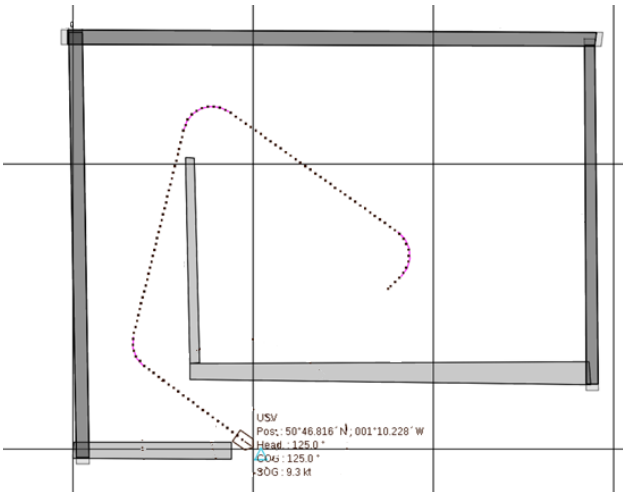

Figure 8 - USV path

It should be noted that the behaviour based autonomy on its own would never find its way past this simple configuration of objects to find a way to the end point, but would become stuck on the “starting side” of the objects.

4 Results and Discussion

The deliberative path planner has been integrated into our USV management system and has been tested extensively in simulation and at the time of writing has begun testing at sea.

Figure 9 shows the planned path when the USV has reached the towed sonar deployment location and plans a path that manoeuvres into the direction of the ocean swell required for towed sonar launch into the sea.

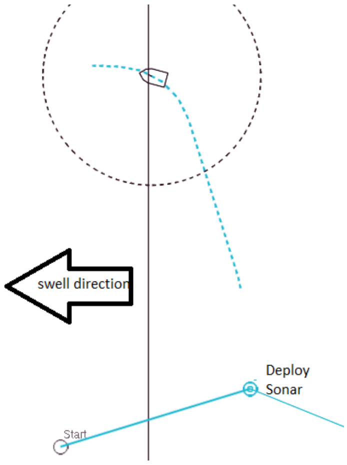

Figure 9 - Manouvre into the swell

Figure 10 shows the planned Boutakoff turn at the end of a track in order to start the next track. It also shows a turn planned after the operator has taken direct control and then resumed autonomy – the planned path allows the USV to resume the survey.

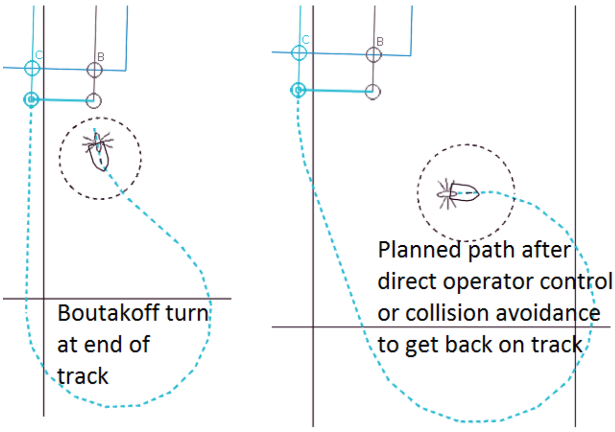

Figure 10 - End of track turn

Table 1 shows the effect on planning duration of adding objects into the path of the USV.

Table 1 - Effect of obstacles on performance

Scenario	Performance
No objects on USV path.	Path planned within a few ms.
Objects not on direct USV path	Path planned within a few ms - not dependent on number of obstacles.
Objects on USV path	Execution time increases linearly with about 0.1s per obstacle

Some tuning of the algorithm performance limits has been required at sea to prevent the more noisy sea environment in higher sea states from causing the deliberative path planner from deciding it was no longer following the planned path and therefore invoking a re-planning of the path.

5 Future Work

The deliberative path planner takes into account non-moving obstacles and plans a path around them. This means that the lower level obstacle avoidance behaviours should in theory never be needed but are retained as a last resort. The deliberative path planner could be extended to take the same approach for moving objects so that it plans paths that avoids moving objects and other vessels in a COLREGs compliant manner.

6 Conclusions

The inclusion of the deliberative path planner into the USV autonomy software has enabled the USV to handle the scenarios defined in Section 2 without watch-keeper intervention. This has raised the general level of autonomy of the USV.

7 References

[1] Brooks, R.A. (1991) Intelligence without Representation. Artificial Intelligence, vol. 47 pp 139–159.

[2] S. LaValle and J. Kuffner, “Rapidly-exploring random trees: Progress and prospects,” in Algorithmic and Computational Robotics: New Directions, (2001), pp. 293–308.

[3] L. Dubins "On curves of minimal length with a constraint on average curvature, and with prescribed initial and terminal positions and tangents." American Journal of mathematics 79.3 (1957): pp 497-516.

8 Author Biography

Ed Rimmer is a software architect at Thales and had developed software for maritime systems for over 20 years. This has included naval sonar systems as well as leading the development of the autonomy software for an MCM USV. Ed holds a Ph.D. in Artificial Intelligence and is an associate lecturer with the Open University in the UK.