Synchronous Rendezvous Technique for Multi-Vehicle Mine Countermeasure Operations

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***Abstract*—Advantages of multi-vehicle network over single autonomous underwater vehicle (AUV) platform include extended coverage area, potential cost and time efficiency, and more robust performance. A common issue that slows advancement in the field is the limited available communication between the platforms. The approach we propose is based on assigning a sequence of rendezvous points (RPs) where the vehicles can meet and exchange information. The work we present in this paper applies mainly to mine countermeasure (MCM) and suggests that despite the disadvantage of time to allow for the vehicles to reach the RPs, there are techniques that can minimise the losses and provide advantages such as easier coordination and access point for operator monitoring and system modifications.**

Keywords*—*rendezvous, multi-vehicle, mine countermeasures

I. Introduction

There has been increased interest in using autonomous underwater vehicles (AUV) in a network configuration in the last decade. However, inability to maintain robust communication continuously is a major constraint for the development of such technology. Radio frequency and optical signals do not propagate well underwater and therefore acoustic transmissions are the most common choice for modems. However, there is severe limitation in range and bandwidth of the acoustic communication and the network operation must take this into account [1].

In order to enable cooperation and autonomous decision making between the vehicles, the issue of communication is the main problem that requires resolving. The approach we propose is based on assigning a sequence of rendezvous points (RPs), or a location and time where all agents in the network agree to meet, and the vehicles can exchange information. This way a complete lack of connection can be assumed outside of the RP perimeter and thus provide a means for the system to operate under severe channel conditions. The work we present applies mainly to mine countermeasures (MCM). This paper presents the idea of applying RP to MCM by proposing adaptive RP scheduling.

The remaining of the paper is divided into the following sections: Section II focuses is on relevant work published recently; Section III gives an overview of the RP idea; Section IV explains the methodologies adopted for evaluating the RP method and analysing the suitable conditions for application; Section V shows simulation results. The last section concludes the work and suggests future directions.

II. Related work

Efforts to improve underwater sensor network (UWSN) performance are commonly aimed at modems and networking protocols [2], [3], [4]. When moving platforms are the focus of the network configuration, solutions are driven by ideas adopted by the robotics community. Examples include adapting cooperative multi-robot techniques, such as auction mechanisms [5], [6]. Often such approaches do not take into account the limitations imposed by the communication in the underwater channel. Some efforts of reducing reliance on communication using prediction models are also available [7], however they also rely on anticipated environmental conditions.

The work in this paper was developed with the focus of adapting optimisation techniques to the relevant application constraints. Relevant ideas have been used in a network of surface vehicles to adapt their formation to the water basin borders [8]. The advantage of network reconfigurability has also been recognised when the nodes need to adapt to unexpected conditions or to seek optimal placement [9], [10]. However, such solutions aimed at improving autonomy often discount or neglect the issue of communication.

The idea of synchronous rendezvous has been recognised and adopted in ad hoc mobile network applications [11], however it is not a typical approach for UWSN. Although it provides a means to avoid the communication restriction by allowing all nodes to meet and plan further actions, one major drawback is that part of the resources in the system are sacrificed to allow the nodes to travel to the appointed place. To reduce the lost time, these points can be preplanned in a static sequence to guarantee optimality. This, however, introduces rigidness and lack of adaptability to external events. Therefore, we propose a rendezvous approach that allows dynamic point allocation based on the information gathered by the vehicles and their future goals.

III. Rendezvous point approach

To improve the resource usage in the system, we consider a specific application and scenario to measure the loss and evaluate the significance of parameters for optimising the RP scheduling. This paper looks into applying the RP approach to MCM and the typical operation specifics are presented. Further, the loss mechanism is explained with regards to the selected scenario.

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A. MCM phases and operation for AUVs

A typical mine hunting operation has five phases:

- Search - an area is scanned for mine-like objects (MLO). To secure a consecutive coverage, often the platform is moved in a lawnmower pattern;
- Detection - information from sensors to indicate a contact with a MLO;
- Classification - a decision whether an object is a mine-like or non-mine like. This is done by using autonomous target recognition software or a human operator. However, currently this decision is not trusted to be made autonomously;
- Identification - determines the type of the mine so further neutralisation strategy can employed. Often, there is a long delay between Identify and Neutralise function, due to the system lacking the ability to autonomously Classify and Identify, which means the data have to be recovered and processed first off-board at the end of the mission [12];
- Neutralisation - a mine is considered neutralised once its location is defined and it can be avoided. In case the platform cannot evade it, other measures are adopted. Those can include destroying or disabling the mine's detection or detonation ability.

The work in this paper is concerned with the phases between Search and Identify without taking into account the sensor specifics or the autonomous target recognition restrictions. Instead, it is focusing on optimising the collaboration between multiple platforms to allow following continuouslly the procedure sequence. The Neutralise phase is excluded as often a remotely operated vehicle (ROV), rather than AUV, is used to properly guide a disabling mechanism.

A typical multi-vehicle MCM mission configuration includes two types of sensor packages: Search-Classify-Map (SCM) and Reacquire-Identify (RI) [13]. The SCM relies on a coarse side-scan sonar allowing faster speed during the searching phase. The RI phase makes use of a high-resolution sensor, such as multi-beam sonar, that collects images for final identification and decision making. Often these two tasks are performed by separate vehicles. The SCM or search vehicle follows a lawnmowers pattern, while the RI vehicle relocates the target and further examines it.

B. RP loss in MCM scenario

The limitation of using separate vehicles for distinct tasks in not necessarily due to hardware restrictions. Modern vehicles can have multiple sensors mounted on the same platform. However, reconfigurability of the network is still a big issue underwater. Using RPs throughout the mission enables communication between the AUVs and thus allows for dynamic task reallocation. This can aid higher resource utilisation in the network. On the other hand, there is a trade off with the time spent for the platforms to travel to RP. Evaluating and minimising this time loss is vital for the approach to be applicable.

In order to schedule a RP, all vehicles in the system have to agree on the most convenient time and location to meet. We divide this problem in two stages: 1) select the time and 2) coordinates of the RP. To minimise the time wasted for the vehicles to travel to the RP, we want to minimise the total number of RPs and push the next point as far in time as possible. On the other hand, we want to give the system nodes regular chances to renegotiate future strategy and provide update to the operator. It is useful to define a suitable time interval that satisfies the opposing demands by showing when the resource waste becomes prohibitive for the mission.

The resource loss is defined as the time spent by each platform to travel to the RP instead of doing mission related task. Equation 1 gives this relation by calculating what part of the time window between rendezvous points is spent for reaching the RP:

$$t_{loss} = \frac{x}{n \times s \times t_{RP}} \tag{1}$$

where x is the width of the search area, n is the number of vehicles, s is speed and t_{RP} the time until the next RP. In order to apply this equation, some assumptions are made: the area is searched sequentially, the vehicles are homogeneous and have the same speed. Since the resource loss calculation is very dependent on the geometry of the search area, figure 1, gives a graphical representation of the scenario considered in this paper for evaluating the RP approach. After defining the favourable parameters for minimising the loss, some conclusions can be drawn when this approach might not be applicable due to prohibitive losses.

The mission considered in this paper is demining a strip near the shore. Typically, the width would be much smaller compared to the length of the area. Another assumption is that the vehicles will not be able to cover the whole area before their battery is exhausted so the purpose of the mission is to explore as much of it as possible, while the detected MLOs are revisited.

On Figure 1, x and y are the dimensions of the searched area in the simulated scenario. The red circle on the right side pinpoints the starting position of three available vehicles. They are all equipped with search (side-scan sonar) and RI (multibeam) sensors and can perform both SCM and RI tasks. The first RP is predefined and the speed of the vehicles is known, so this can give a good idea of the location of the next meeting point as well as the area that will be covered by each platform. Since the vehicles are homogeneous, all three search areas will be equal ($area_{veh1} = area_{veh2} = area_{veh3}$).

Normally, the AUVs would search in a lawnmower pattern, as shown in the first vehicle's search box ('veh 1'). At the time of the RP, this will bring the AUV either at the far or close corner of it's search box, which will define the distance, and the subsequent resource loss to the RP. Since the simulation is not optimised to always position the nodes at the near corner, the loss assumed in the calculation is taking the average distance, making a pessimistic loss calculation. As seen in equation 1, the loss would be greater if the width of the search area increases.

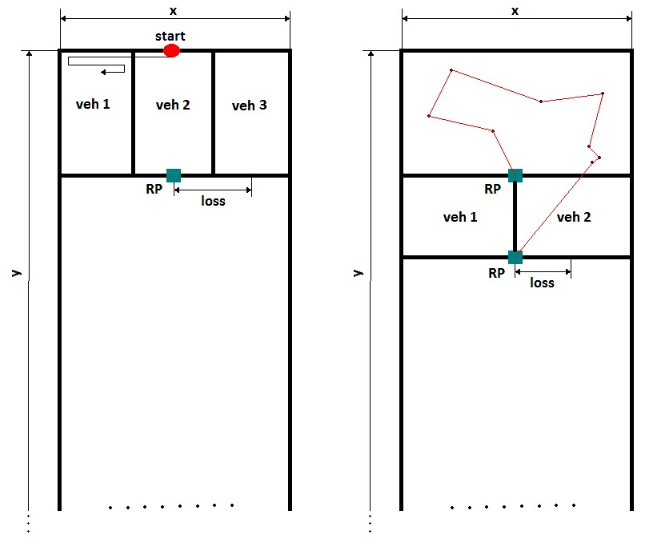

Fig. 1. Rendezvous point approach: Left - starting point to first RP, Right - example scenario between two RP

The time loss also depends on the number of vehicles - as seen on the figure, if three vehicles are involved, the average distance they need to travel is smaller compared to the 2 vehicles configuration on the left. The other parameter is the speed of the platforms - the faster they are, the less time is wasted to travel to the RP. And lastly, the time for the next RP defines what fraction of the total time will be used for task related purposes and what part will be travelling to the meeting point.

It is obvious that the longer the time between the rendezvous, the smaller fraction of the time will be wasted for travelling there. On the other hand, there is a limitation on this time depending on how often the operator would need an update from the network. To evaluate when the loss becomes prohibitive, or to define the minimum time for RP, we have parametrized equation 1 and the result is shown on Figures 2 and 3. The graphs present the loss for a network of two and three vehicles, respectively, for variable speed and width and $RP = 1\ hour$. Then, in Figure 4, we have selected favourable, but realistic, conditions - 3 vehicles, speed of 2 m/s and width of 2500 m. The plot shows what percentage of the total time is wasted if we vary the time of the RP. This can be used as a rule of thumb guidance of the minimum time limit of the next RP.

In the scenario we have selected in Figure 4, RP between 1 and 2 hours gives a loss between 5 and 12 % of the total time. If this is considered unacceptable by the operator, the time window can be moved further in time. The calculations in the next sections adopt the parameters used in Figure 4 and define an RP interval of 1 hour in case there is no other parameter to base the decision on.

IV. Rendezvous point scheduling and analysis

Defining the lower boundary for scheduling RP is useful when there is no other information available. However, the main advantage of the RP approach comes from the ability

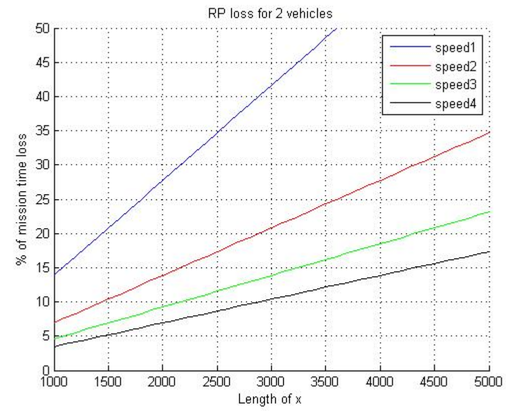

Fig. 2. Loss calculation for two vehicles, variable speed and width of search area, fixed RP time

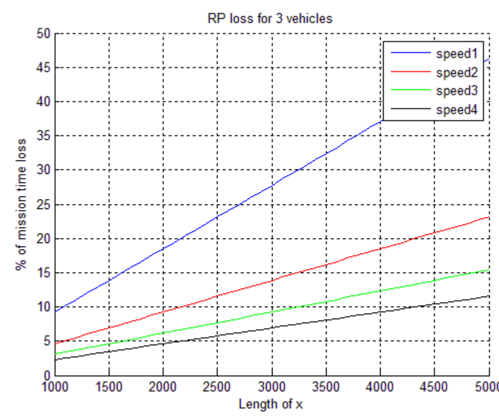

Fig. 3. Loss calculation for three vehicles, variable speed and width of search area, fixed RP time

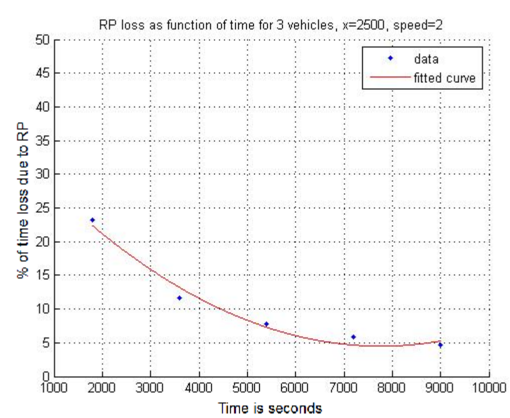

Fig. 4. Loss of time resource vs total time between RP

to reallocate vehicle tasks based on the information they have gathered during the search.

For example, if we assume the scenario from Figure 1, but without scheduling any RP - at the start of the mission 2 vehicles will be performing search task and they will send the locations of the detected MLOs to the third vehicle that is tasked with RI. However, if there is no prior information what number of targets to expect, the mission can be completed with few detected MLOs or with a very large number. In the former case, the RI vehicle will be idle most of the time, in the latter, the mission will be incomplete with targets observed only with low resolution sensor.

On the other hand, a higher amount of system resource can be utilised if at the RP a decision is made whether there is a need for an RI vehicle in the next time window and also, how many platforms are required. Therefore, the number of detected targets, or the time it takes for the RI vehicle to revisit them, is the main parameter that decides how to utilise the available vehicles, as well as how to schedule the RP:

$$t_{RP} = f(t_{RI} + t_{reacquire}), [min, max] \tag{2}$$

where t_{RI} is a calculation of the time required for a single vehicle to travel in an optimal path and visit all detected MLOs to identify them. Additional time for reacquiring the target location once the AUV is at the reported coordinates and collecting high-resolution sensory information was added by the $t_{reacquire}$ term. For more realistic calculation, this parameter needs to be adjusted depending on the mission conditions and the platform sensors. The [min, max] interval is derived by using Equation 1 and Figure 4.

The second stage of scheduling the RP is the position estimation. It is based on predicted vehicles position at the next t_{RP}, or the area coverage of the search AUVs:

$$Area_{search} = s \times sw \times t_{RP} \times loss \times n \tag{3}$$

where s is speed of all vehicles, sw is swath range of the vehicle's sensor, t_{RP} is time until next RP, $loss$ is the resource waste for travelling to RP using Equation 1, n is number of AUVs. However, since all platforms are assumed homogeneous, at time t_{RP}, all nodes will be aligned at the same y coordinate in the search space. Therefore, the location of the RP is the middle of the width of the search area at this y coordinate, as seen in Figure 1.

These relations were used to explore the gains of network reconfigurability by applying the RP approach. The steps used in our simulation are summarised in the pseudo code in Algorithm 1, as well as the rule based decision making for how many platforms to employ search and RI tasks.

At line 3, the first RP is predefined. It is assumed that no prior information is available at the start of the mission hence the RP time is solely driven by the loss calculation, or given the minimum value from Equation 2. The simulation runs while the mission time, or the sum of the RP time windows, exceeds a predefined threshold. This threshold was selected as a percentage of typical battery life of an AUV - 70 % of 10 hours (line 5). Depending on the selected parameters, the

Algorithm 1 Dynamic allocation of vehicle tasks and RP scheduling

```
1:  procedure SCHEDULE RPs
2:      min ← min loss limit from Graph 4
3:      t_RP = min ← assign time for first RP
4:      n ← number search vehicles
5:      while Mission time < threshold do
6:          Calculate loss using Equation 1
7:          Calculate search area using Equation 3
8:          targets ← generate detected targets for RI
9:          t_RI ← calculate RI time (Nearest Neighbor)
10:         if t_RI ∈ [min; min * 2] then
11:             t_RP = t_RI
12:             n = n − 1
13:             targets = 0
14:         else
15:             if t_RI ∈ [min * 2; min * 3] then
16:                 t_RP = t_RI/2
17:                 n = n − 2
18:                 targets = 0
19:             else
20:                 t_RP = min
21:                 targets
22:             end if
23:         end if
24:     end while
```

average resource loss and search area are calculated (lines 6 and 7). Once all platforms reach the first RP, they will share information about the detected targets. Communication at RP is assumed available. The MLOs are simulated by generating random number of targets with locations constrained within the area that have been searched in the time window (line 8), and calculate the shortest path to revisit them (line 9).

The decision making of when to schedule the next RP and how many vehicles to send is given between lines 10 and 23. Simple rule-based logic is used. If the RI time falls in the interval between min and $2 * min$ (line 10), the time for the next RP is selected as the time it will take an RI vehicle to check all targets, the search vehicles are reduced by one and the targets in the searched area are considered identified. In case the time for RI exceeds the $2 * min$ limit - line 15, (due to too many targets), then two vehicles are tasked to perform RI and the time for the next RP is half of the RI time. The number of searched vehicles is reduced by 2 and also all targets are considered identified. In the case when the RI time is below the min threshold, it is better to leave the targets unidentified until the next RP cycle. The advantage is that all vehicles will perform search rather than one vehicle tasked with RI and then being idle for portion of the time. The disadvantage is that on the next cycle, when there are enough targets to identify, the path to travel will be longer. In the next section this trade off is explored further.

V. RESULTS

The function from Algorithm 1 was used to evaluate the performance the RP approach when variable number of MLOs were detected. The aim was to show how the system adapts when there is a different need of retasking the vehicles. The benchmark scenario to compare a system with scheduled RP was a mission where vehicles had designated search and RI functions.

Figure 5 shows three graphs representing simulations with different number detected targets. The top left is a scenario with low number of targets (0 to 5 generated targets per RP window), top right is average number of targets (0 to 10 per RP) and bottom is large number (0 to 20 per RP). Each graph shows results for 100 repetitions of Algorithm 1 where the randomisation of number and location of MLOs accounts for variable losses and gains in the system.

The $x-y$ space shows amount of searched area (x) given the available mission time (y). The scattered black dots are simulations with the RP approach, while the red dots are simulations with designated vehicles tasks. It is seen that is all cases, the red dots follow a liner relationship - the more mission time available, the larger area is searched. On the other hand, the black dots are scattered below and above this red line, showing lower resource utilisation if they are below the red line and higher if they are above.

As expected, in the example of fewer targets, most of the simulations show better performance for the RP approach compared to predefined tasks for the AUVs. The reason is that the RI vehicle from the benchmark mission is performing a search function during most of the RP windows as there were not enough targets found to justify such task. It is seen that with increasing the number of targets, the advantage of the RP is lost due to multiple vehicles tasked with RI throughout the mission. However, the remaining target count that has not been identified at the end of the mission was not recorded for the benchmark simulation, which might make both approaches equally inefficient to perform MCM operation.

Figure 6 shows the average distribution of search vehicles per simulation. The dotted black line at $y = 2$ is the constant number of search vehicles in the benchmark example. When RP is applied, the search platforms change their number at every RP depending on the available MLOs. This result can be correlated with the graphs on Figure 5 explaining the higher search area covered in the case when less vehicles are tasked with RI and thus the average search platform number is much higher. The bottom graph in Figure 6, where the network had to adapt to a large number of targets, shows that in multiple simulations less than 2 vehicles on average were available for the whole mission. This can explain the majority of black scattered dots moving towards the bottom right corner in the third graph of Figure 5. This is the undesirable situation when more time spent at the MCM mission yields less area searched.

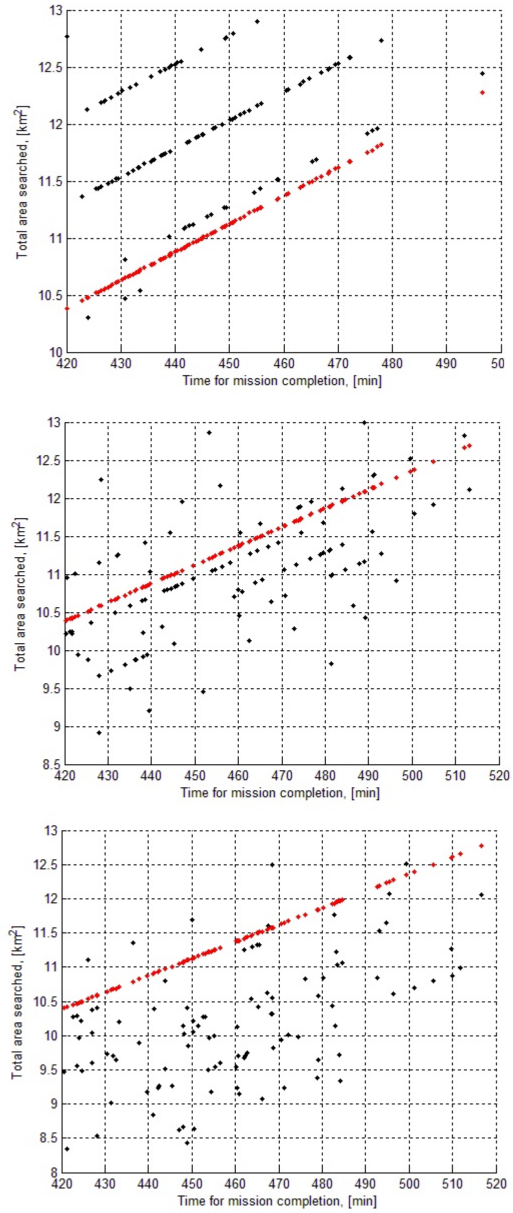

Fig. 5. Searched area gains for RP approach vs benchmark MCM mission example

VI. Conclusion and Future Direction

This paper presents the idea of adaptive scheduling of rendezvous points for MCM application with AUVs. The benefit of using RP is that the vehicles can be utilised at a constant rate independent of the amount of targets detected throughout the mission. In contrast, when relaying on a typical configuration of separating the function of search and ID vehicles from the start of the mission, the overall time to achieve the same result could be significantly increased if there are large number of MLOs, or the ID vehicle could be underutilised if their number is low.

This work can be improved by relaxing or refining some of the assumptions which forced pessimistic calculations such as adjusting the position of the search vehicle when calculating the loss and the time required for reacquiring a target. Another important change would be allowing heterogeneous vehicles with different speed and sensors that will add diversity to the simulation and make it more practical. Finally, relaxing the assumption of sequential search allows for using probabilistic model of selecting which area to be given priority for exploration and which one needs a repeated coverage. This also calls for more sophisticated decision making, such as using Marcov processes.

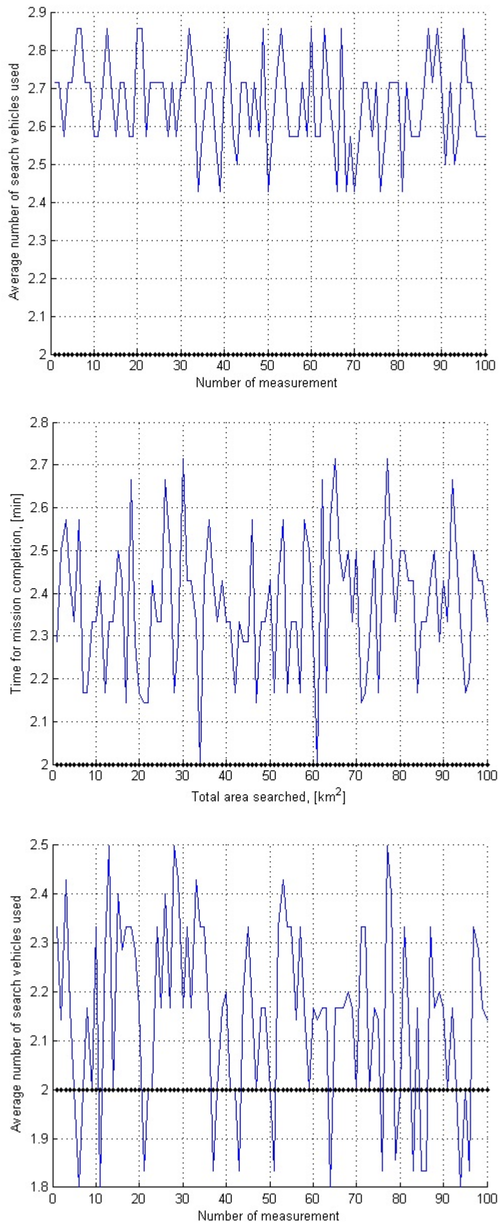

Fig. 6. Average number of search vehicles used per mission

Acknowledgment

This project is funded by Atlas Elektronik UK and EPSRC Doctoral Training Centre no: EP/G037264/1. The authors would like to thank A. Gibbert, A. Charlish and R. Brind for being available and providing early feedback to this work.

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