Collaborative Autonomous Vehicles

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ABSTRACT

There are many military operations that can be conducted by intelligent unmanned vehicles. Currently, in most cases, the unmanned vehicles are not cooperative, however. In this paper, we will provide two such examples: a mine countermeasure exploratory operation and a harbour defense operation. Both examples involve unmanned vehicles. From these examples, we propose ideas to explore the use of multiple autonomous unmanned agents in military operations.

1.0 BACKGROUND

The appearance of unmanned vehicles is part of an ongoing transformation of military forces worldwide. Such vehicles are appealing because they are able to perform missions, such as mine hunting, with minimal risk to humans. They may also open a new window of opportunity allowing militaries to do what was not previously feasible e.g. collect critical data covertly. In addition, unmanned vehicles are expected to be less expensive than their manned counterparts.

This paper summarizes a few ideas from a Technology Investment Fund (TIF) project that is awarded to the authors by their home organization, Defence Research Development Canada (DRDC), Ref [1]. A TIF provides resources and funding to the scientists at DRDC to explore high risk and potentially high return projects. This TIF explores the use of unmanned agents (which include unmanned vehicles) in military operations. We will consider two such operations: a mine countermeasure exploratory operation (Refs [2-5]) and harbour defense operation conducted by unmanned vehicles (Refs [6-7]). From these examples, we will provide ideas on how these operations can be more effective in presence of multiple cooperative unmanned vehicles.

Section 2 describes a mine hunting operation. Section 3 describes a harbour defense operation. Section 4 describes the essential elements of our TIF. We conclude in Section 5.

2.0 MINE HUNTING

An example of an unmanned vehicle that can hunt mines is the Dorado developed at DRDC Atlantic (Fig. 1), Refs [2-5]. Since the early 1980s, the DRDC Agency has provided support to the Canadian Forces in the area of mine countermeasures. This work has primarily focused on the use of high resolution side scan sonars to image the sea bottom, and through subsequent analysis techniques, determine the presence of mine like objects. Much of this early work was the foundation for the development and acquisition of the current high performance AN/SQS-511 multi-beam side scan sonar that is currently employed by the Canadian Forces for route survey operations.

Since this early work, DRDC has continued to leverage improvements in sonar technology and developments in computer based detection and classification algorithms to develop a state-of-the-art

Remote Mine hunting System (RMS) that provides a capability that previously could only be provided by a very expensive, dedicated mine hunting vessel. Shown in Fig. 1, this system employs the Dorado semi-submersible vehicle to tow a variable depth tow fish that carries a high performance multi-beam side scan sonar. Using pre-programmed mission plans, this system is able to survey a mine danger area and transmit the images of the sea bottom to a tactical control center located many kilometers outside of the mine danger area.

Fig. 1 – The Dorado.

The effectiveness of the Dorado depends on a number of parameters: the probability of detection as a function of range (Fig. 2a), the probability of detection as a function of angle (Fig. 2b), the type of target, the search pattern (Figs. 3-4) and the scenario.

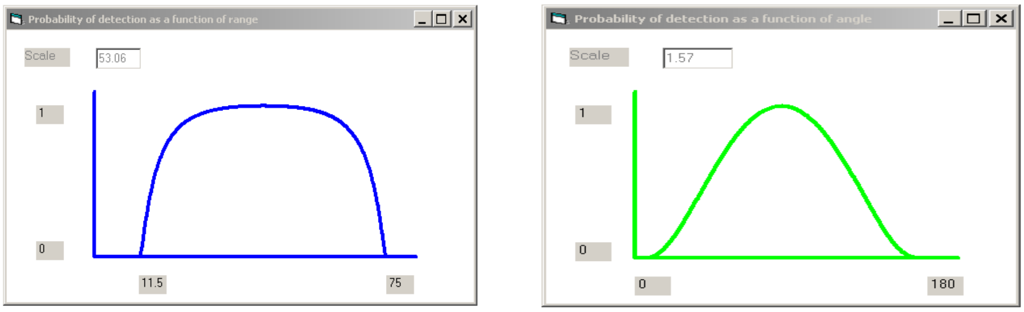

Fig. 2 (a) Probability of detection as a function of range; (b) Probability of detection as a function of aspect angle.

Fig. 3 (a) Mowing search pattern; (b) Zigzag search pattern.

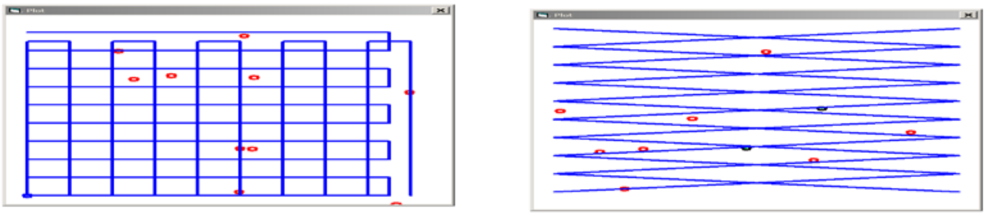

Fig. 4 (a) Two AUVs employing perpendicular mowing search patterns; (b) Two AUVs employing weaving patterns.

A typical path is the lawn-mowing pattern shown in Fig. 3a. It starts from the lower left corner, travels horizontally to the right, and then travels up vertically etc. We also consider the zigzag pattern shown in Fig. 3b. It also starts from the lower left corner, travels to the right with a slant angle wrt the horizontal axis, and then travels to the left with the same slant angle wrt the horizontal axis etc. Note that the small red circles represent the mines.

Fig. 4a displays the search paths of two AUVs each employing the mowing pattern. The first AUV starts from the lower left corner, travels horizontally from left to right, then up, then right to left etc while the second AUV also starts from the lower left corner, then travels up, then left to right then down etc.

Fig. 4b displays the search paths of two AUVs each employing the zigzag pattern. The first AUV starts from the lower left corner, then travels from left to right with a slant angle wrt the horizontal axis, then from right to left with the same slant angle etc while the second AUV starts from the lower right corner, then travels from right to left with the same slant angle wrt the horizontal axis as the first AUV, then from left to right etc.

Fig. 5 compares the probability of detection among different configurations. *P1M* (*P2M*) is the probability of detection based on the employment of one AUV (two AUVs) using a mowing pattern while *P1Z* (*P2Z*) is the probability of detection based on the employment of one AUV (two AUVs) using a zigzag pattern.

As expected, Fig. 5 shows that scenario 2M achieves better probabilities than those of scenario 1M since scenario 2M employs two AUVs while scenario 1M employs only one AUV. Similarly, scenario 2Z achieves better probabilities than those of scenario 1Z.

Fig. 5 shows clearly that *P2M* is the highest probability of detection followed by *P2Z* while *P1M* and *P1Z* have similar values. We can therefore deduce that, in this scenario, the employment of two AUVs in a mowing pattern provides better probability of detection than that of two AUVs in a zigzag pattern. However, there is virtually no difference between the employment of one AUV in a mowing pattern and that of one AUV in a zigzag pattern.

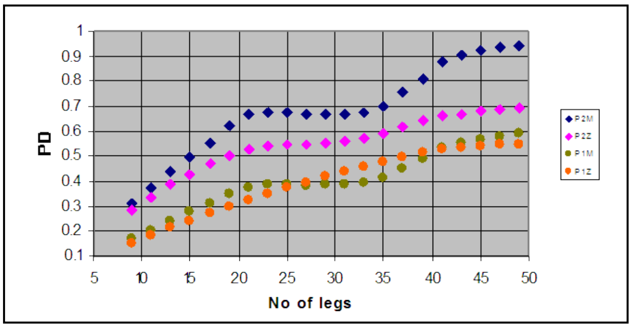

Fig. 5 – Probability of detection (P) for several AUV scenarios as a function of the number of legs.

We assume an area of 3 km by 3km, an AUV speed of 9 knots and an endurance of 30 hours. For the range probability curve (angular probability curve): $\alpha_1 = 0$, $\alpha_2 = 0.75$, $x_1 = 11.5\,\text{m}$ and $x_2 = 75\,\text{m}$ ($\alpha_1 = 0$, $\alpha_2 = 1.25$, $x_1 = 0$ and $x_2 = \pi$). $\alpha_1(\alpha_2)$ controls the symmetry (shape) of the probability curves. These probability curves are modeled using the Johnson distribution, Ref [8] as it is fairly versatile in the sense that we can make it unimodal or bimodal, skewed to the left, symmetric, or skewed to the right as well as controlling how narrow each peak is. The scale (λ) shown on each curve is a factor compounded to Johnson's distribution such that the maximal value of each curve is equal to 1. This is required as we use these curves as probabilities and not as a density whose integration over the variable range must be equal to 1 as is the case in Ref [8].

3.0 HARBOUR PROTECTION

Refs [6-7] consider harbour X. Fig. 6 shows the harbour layout. The harbour area modeled is shown in the white polygon; the operational value of the system effectiveness is calculated at each discrete location within the polygon. The black arrow indicates the threat direction. The dashed line represents the interceptor. The modeling assumes that the initial threat location can be anywhere within the harbour area.

Fig. 7 shows the logic of the defensive systems against an underwater threat. Five modules are delineated: detection and tracking, target interception, engagement, and entanglement by an underwater barrier.

The defense consists of an active sonar system, an intercepting platform (hereafter called the interceptor), and a physical underwater barrier with trip-wire sensors. The active sonar includes a detection and tracking system. The interceptor aims at neutralizing the threat before it damages the High Value Unit (HVU); it achieves this task by engaging the threat with weapons, and then conducting a threat assessment and repeating the process if necessary. The modelling of the defence system is organized into three groups: interceptor, sonar and underwater barrier. We assume there is an unobstructed line-of-sight between the sonar and the threat.

The study assumes an Unmanned Underwater Vehicle (UUV) carrying a payload of conventional explosives targeting a stationary HVU in a harbour. The maximum amount of explosive an UUV can carry depends on the size of the UUV.

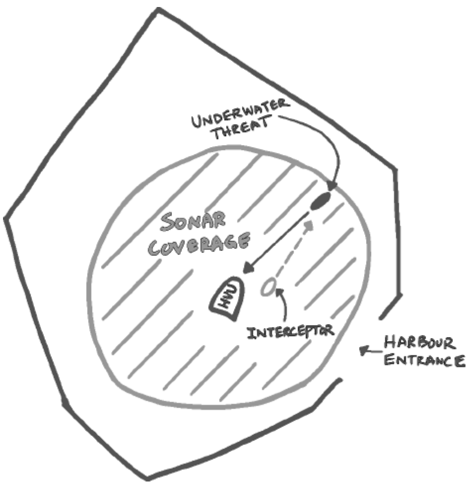

Fig. 6 – A sketch of harbour X.

The Probability of Integrated System Effectiveness (PISE) measures the operational value of the defense system. It depends on the probability of detection and the probability of tracking of the threat by the sensor. It also depends on the interceptor probability of neutralizing the threat and the location of the HVU as well as the size of the harbour.

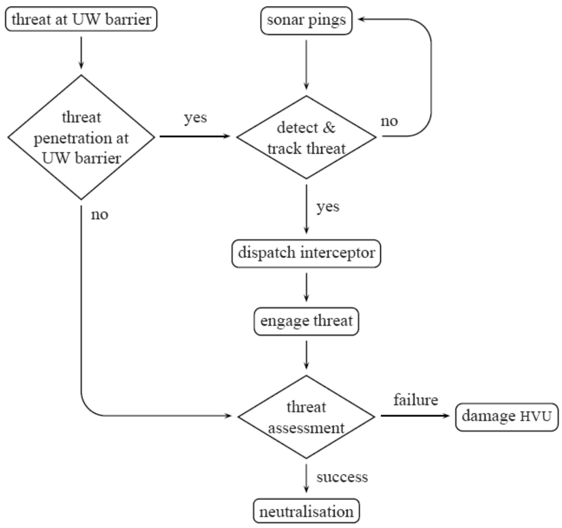

Fig. 7 – Defense logic.

The underwater detection sensor is an active sonar. It emits a ping (sound-wave) at each specific time -interval. In the presence of a target, there will be an echo from the ping allowing the operator to determine whether he detects a target or not. This process is stochastic in the sense that there is a probability associated to a detection event called the probability of detection. The value of the probability of detection depends on the target strength, range between the sonar and the target, and the characteristics of the sonar.

To declare a target as a threat, the tracking algorithm uses a n out of m rule. This rule says that if n out of m consecutive pings lead to detection events then a track of a threat is initiated. Ref [7] shows the process of evaluating the probability of a track is Markovian.

Once the defense declares a track hostile, it dispatches an interceptor to engage the threat. There is a time delay called reaction-time measured from the moment a track has been initiated to the moment the interceptor is launched. The interceptor carries a weapon. The model assumes the worst-case in which any threat will detonate its explosive at the intercept position (successful neutralization). An unsuccessful neutralization results in the threat reaching the HVU and actuating its explosive payload.

Additionally, the defense may also include an underwater barrier. There are two possible interactions between a threat and an underwater barrier. A threat can be entangled in the underwater barrier or it can penetrate through the underwater barrier. If it is entangled then the trip-wire sensors on the underwater barrier will alert the interceptor so that it conducts a threat assessment. The interceptor will neutralize the threat if it is still hostile. However, if the threat penetrates through the underwater barrier the interceptor will be dispatched to engage the threat after the sonar confirms there is a track or the sensors of the underwater barrier system informs the defense that a target has penetrated the barrier.

The survivability of the HVU is estimated by the safe stand-off distance. This safety distance is a function of size and type of the threat's payload, seabed hardness as well as the HVU hull shape and material.

The safety zone is defined to be an area around the HVU where surveillance is kept at a high alert level such that any threat within this zone is engaged and neutralized with effectiveness virtually equal to 1. Its purpose is to improve the protection of the HVU against underwater threats.

System requirements against underwater threats are determined by analyzing the impact of the model parameters on PISE. These model parameters include reaction-time, interceptor speed, underwater barrier length and target-strength as well as the threat’s explosive payload. Table I shows the values of the system parameters. The analysis is based on the results of a simulation written in MathCad version 13, which implements the model and algorithms described in the previous section.

TABLE I. Modeling parameters of the defense system.

Interceptor	
	Reaction Time
	Speed
	Weapon Range
	Weapon Probability of Neutralization
	Initial location
Active Sonar	
	Sonar Ping Interval
	Probability of False Alarm
	Sonar Tracking Rule
	Location
Underwater Barrier	
	Length
	Probability of Entanglement
	Probability of Penetration
	Location

Fig. 8a shows the map of local PISE where the defense system consists of an active sonar and an interceptor. Fig. 8b is the map of local PISE where the defense system includes an underwater barrier. This time, the dark areas of Fig. 8a now become lighter showing an improvement in PISE due to the underwater barrier.

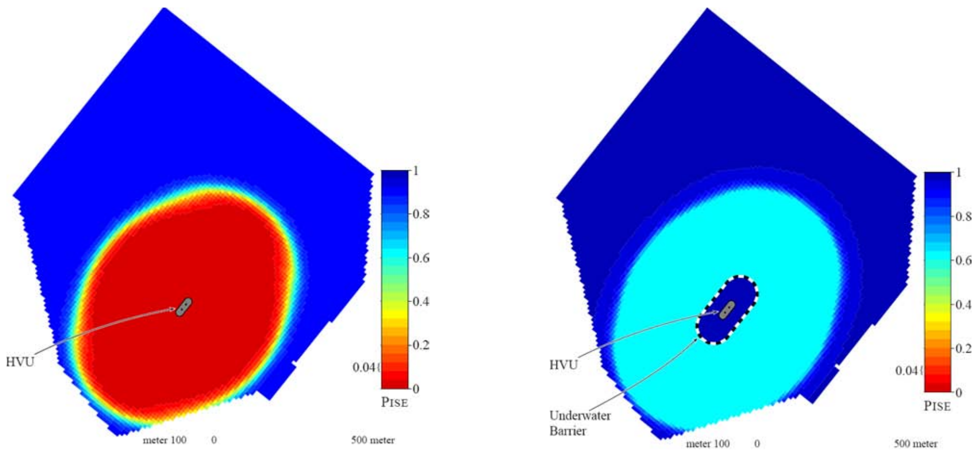

Fig. 8 (a) Map of local PISE without a barrier; (b) Map of local PISE with a barrier.

Fig. 9 illustrates the role of the reaction-time. It shows that PISE decreases when the reaction-time increases. Large reaction-time allows the threat to travel closer to the HVU before engagement by the interceptor. Detonation of its explosive payload is also at positions closer to the HVU, and thus lowers the defense effectiveness.

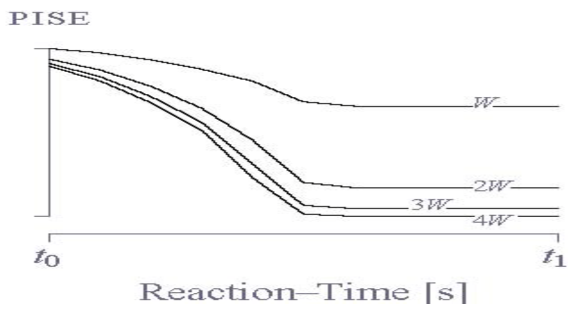

Fig. 9. The impact of reaction-time on the global PISE for a set of explosive payload $\left(W, 2W, 3W, 4W\right)$ on the UUV.

There is a contribution to PISE from each defense system: the underwater barrier alone or the combination of the sonar and interceptor alone. To allow comparison among different combinations and assessment of the value added of a system to the global PISE, Fig. 10 shows PISE as a function of the threat's payload for four distinct system combinations. The first combination consists of an underwater barrier, a sonar and an interceptor with a reaction-time of T. The second combination consists of an underwater barrier and an interceptor. The third combination consists of a sonar and an interceptor with a reaction-time equal to T. The fourth combination is similar to the third combination, but with a reaction-time equal to 2T.

Evidently, the first combination is the best as it includes all components. Comparing PISE of the first combination to that of the second combination shows that the sonar substantially improves the effectiveness against higher payloads. Such a large difference stems from the fact that the sonar can detect the UUV before it reaches the barrier, and hence there are more and earlier opportunities for the interceptor to intercept the UUV.

Comparing the second combination to the third combination shows that at reaction-time equal to T the underwater barrier and interceptor combination is inferior to the sonar and interceptor combination for larger payloads. This can be easily understood as the threat is assumed to always detonate at the underwater barrier in the second combination. And so, since the threat carries a larger payload than the design payload of the barrier, the threat inflicts more damage to the HVU. Note that if the underwater barrier was designed to sustain a different payload, the relative effectiveness of the sonar and barrier would change accordingly.

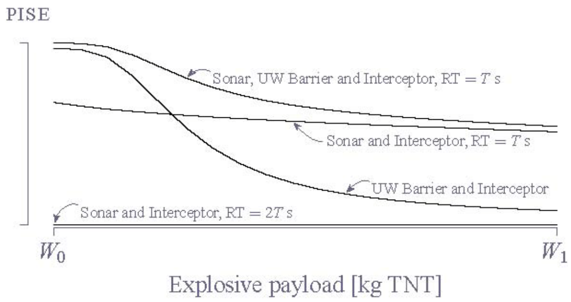

Fig. 10. The impact of the explosive payload on the PISE for 4 cases against an UUV.

The fourth combination represents the worst case. That is, the threat will reach the HVU before any intervention from the interceptor.

4.0 MULTIPLE UNMANNED VEHICLES

Most of the content of the previous sections are obtained from Refs [2-7] and sometimes the text are taken verbatim from these references. We purposely did not detail the analysis as the aim is to provide the reader a flavour on what unmanned vehicles can do in critical military operations.

In both scenarios, mine hunting and harbour protection, we assume that the scenario is deterministic even though the analysis is stochastic. In mine hunting, we assume that there is a mine like object. In harbour protection, we assume there is a threat carrying an explosive device.

The generalization of these scenarios becomes quickly complex and necessitates the use of multiple unmanned vehicles.

In mine defense, if the search area is large, then deploying multiple autonomous underwater vehicles will significantly reduce the search time. Moreover, in a mine countermeasure exploratory operation, the intent is to determine whether there is a mine or there is no mine. As a result, dividing the search area into multiple sub areas, each fathomed by an unmanned vehicle, will further reduce the search time. When unmanned vehicles are cooperative, a vehicle discovering a target can communicate to other vehicles so that these can interrupt the operation. As shown in section 2, there is a high dependence of the probability of detection on the aspect angle. If the unmanned vehicles are intelligent and cooperative, the task of observing the same target at different aspect angles can be performed by multiple unmanned vehicles simultaneously, hence improving the probability of detection and lowering the probability of false alarm.

In essence, multiple unmanned vehicles, when operating in a cooperative way, can improve the effectiveness of a mine hunting mission. They can reduce search time, search area, and fuel. They can also improve the probability of detection and reduce the probability of false alarm.

In harbour protection, the necessity of multiple interceptors becomes essential when there is more than one threat. A feasible scenario is one where the first threat is neutralized but manages to destroy the underwater barrier. The following threats can then leak through the defense and cause damages to the HVU. If the defense consists of an underwater barrier and a single interceptor then it can be easily overwhelmed by multiple threats. In other words, if there are multiple threats, then the use of multiple unmanned vehicles will improve the PISE value.

As an extension to the examples above, the authors propose the use of multiple unmanned agents, which include sensors, unmanned vehicles and operators. Such defensive systems are naturally complex and may operate in highly dynamic and unstructured environments (Ref [9]) especially the underwater environment where sea state fluctuates, and communication among agents are slow and can fail easily. In reality, scenarios change quickly and unexpected events can occur any time. The ability to alter mission planning dynamically becomes essential. Additionally, remote control by a human operator is unpractical in many environments due to the communication range involved and the control time latency, Ref [10]. It is natural to distribute some of the decision process onto the vehicles, Ref [11]. Therefore, introducing uncertainties in the scenarios requires intelligent and autonomous agents.

Various forms and levels of distributed autonomy exist. At one end of the spectrum lies a promising candidate : the emergence of collective intelligence. This distributed autonomy approach is exemplified by termite colonies. Indeed, with no recourse to a master plan by a leader, termites, which by all accounts have very limited individual intelligence, are able to construct large and intricate structures. They achieve this feat not by direct inter-termite communications but rather by synchronizing their behaviours via local interactions with the environment. This is a definite advantage in an underwater or a dense urban environment.

The main objective of our proposal consists of developing concepts of operations based on the emergence of collective intelligence from local interactions of the agents with the environment and their neighbours.

5.0 CONCLUSION

In this paper, we have briefly described the relevance and the promise of autonomous agents. We hope that the ideas herein will generate interests in the community of intelligent autonomous vehicles.

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