Performance Assessment of MCM Toolbox

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Abstract — The use of autonomous systems in mine hunting operations is a relatively new concept. Nowadays, expert navies in the field of mine warfare are currently replacing their mine hunters with toolboxes containing autonomous drones (UxVs) such as Unmanned Surface Vehicles (USV), Unmanned Underwater Vehicles (UUV), Unmanned Aerial Vehicles (UAV), Sweeps and Mine Intervention and Disposal Systems (MIDS). However, there is no standard method to evaluate the performance of the toolbox as systems of systems. Therefore, customers have the tendency to assess each asset and each sensor individually and express one criterion on the toolbox overall. This paper presents an in-depth discussion of the whole mine hunting toolbox composition with particular focus on sonar performance, the sequencing between different autonomous assets and the impact of communications on standoff distances. Some trade-offs are illustrated by comparing toolbox performance with different toolbox compositions for different mine types in varied environmental conditions.

1 Introduction

Sea mines are a permanent asymmetric threat that makes traditional navies vulnerable. In order to tackle that issue, navies need a dedicated Mine Counter Measure (MCM) fleet. Mine hunters were the traditional platform for MCM missions. Recently, expert navies in the field of mine warfare have started to replace their legacy mine hunter by acquiring UxVs toolbox. For instance, the Maritime Mine Counter Measure (MMCM) program is a bilateral program between France and the UK which will deliver two toolboxes to test drones at sea before renewing their entire MCM fleet (Figure 1). The MMCM concept is based on mothership placed outside of the minefield (stand-off concept) able to deploy unmanned solutions (off-board capability).

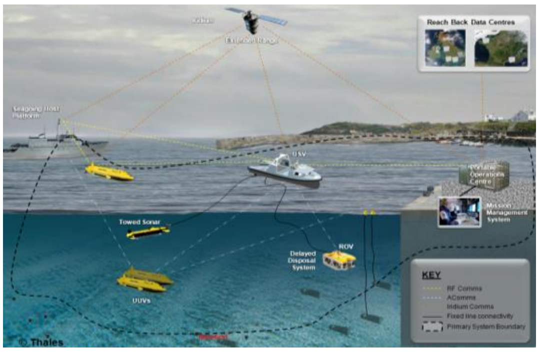

Figure 1: MMCM Toolbox [1]

In this paper, only UxVs are studied; mothership capabilities are not investigated. To assess the performance of one MCM toolbox as a system of systems, an assessment framework needs to be established. This paper can also be applied with a hybrid approach where the mothership is a combatant ship able to proceed in the mine field equipped with onboard capability (hull mounted sonar, propelled variable depth sonar …).

2 Approach

Three parameters are of paramount importance to assess MCM toolbox performance: the global area coverage rate, the standoff distance from the MCM mothership and time to perform the mission (impacted by assets sequencing and post mission analysis).

2.1 Global area coverage rate

2.1.1 Definition

Global area coverage rate is the **sum of all the area coverage rate of each assets able to address a given mine threat in a given depth range** (Figure 2) **for a given environment** (Figure 3). It is a generic key performance indicator (KPI) that aggregates all the relevant assets and sensor characteristics.

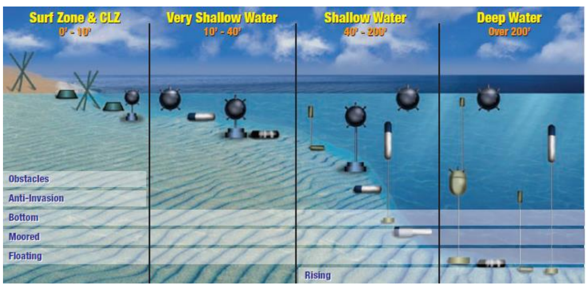

Figure 2: Different threats and different depth ranges [2]

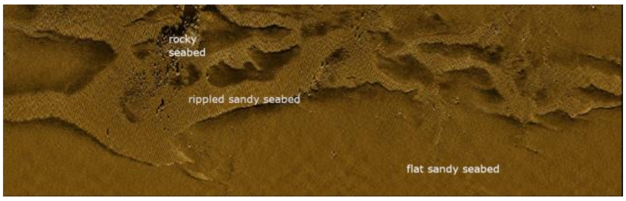

Figure 3: Different environments on a sonar image.

2.1.2 Mine Threats

Six types of mine threats exist nowadays: drifting mines, obstacles and anti-invasion mines, moored mines, bottom mines, stealthy bottom mines and buried mines. **Threats are defining sensors and assets to use** (Figure 4).

Mine Type	Sensor – Asset Capacities
Drifting	LIDAR VTOL & EO Camera on USV
Obstacles & Anti Invasion	Portable Man AUV, VSW Diver Team
Moored	MOAS on USV, VSS on AUV, SAS on AUV
Bottom	SAS on USV – AUV
Stealthy	SAS on USV – AUV
Buried	LF-SAS on USV - AUV & SWEEP

Figure 4: Sensor selection based on mine threats

2.1.3 Environment

A lot of environmental parameters have influence on underwater sensor performances. Six main parameters are kept: bathymetry, soil type, clutter, burial, underwater visibility and current. For the sake of simplicity, **three types of environments are defined: easy, medium or difficult** with the following conditions (Figure 5):

Environment	Easy	Medium	Difficult
Bottom Profile	Smooth	Moderate	Rough
Soil Type	Sand	Thick Mud, sand, rock	Soft mud, sand, heavy rock
Clutter	Low	Medium	High
Burial	None	Moderate	High
UW Visibility	High	Medium	Low
Current	<1 kts	1-2 kts	>2kts

Figure 5: Environmental conditions

2.1.4 Asset selection

Depth ranges and mine threats define what kind of assets to use for mine hunting. For very shallow waters and deep sea, UUV must be used. For the remaining water depths, it is preferable to use an USV for its higher area coverage rate. However, tow cable length is the limiting parameter defining USV- towed sonar depth range use.

2.1.5 Asset ACR computation

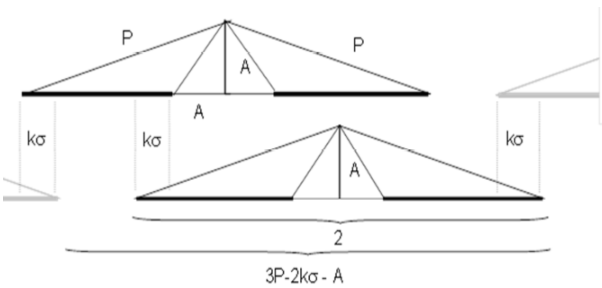

Figure 6: ACR Formula on easy environment

Asset area coverage rate is computed with the given formula:

$$ACR = (3P - A - 2\sigma) * V/2$$

with P the sonar slant range, A the sonar altitude, σ the navigation error and V the carrier speed over ground. This formula is sufficient to cover the nadir gap with identical sonar performances all over.

Concerning ACR performances, **the key limiting factor is the sonar receiver antenna length L** since Synthetic Aperture Sonar SAS speed limit is theoretically limited to V = 0.5*L/T and T the pulse repetition interval defined hereafter by :

$$T = 2 * P/c + \tau + \lambda$$

with P the sonar slant range, c the minimum sound celerity, τ the pulse duration and λ a time margin designed by the sonar manufacturer.

Stability of the vehicle is the main parameter for sonar image quality, and therefore it is recommended to have a sonar altitude constant. Navigation error may also affect the system performance by reducing the sonar coverage and the positioning quality. Some sensors can help reduce positioning error; such as Doppler Velocity Loch (DVL) and GPS for UUVs and Acoustic Positioning System (APS) for towed sonars. Mission planning must carefully pay attention of these two issues.

On a medium or complex environment, it is necessary to either pass over an area several times with a mono-aspect sonar (Figure 7) or use a multi-view in a single path sonar (Figure 8) to increase the probability of classification to 95% according to Johnson's criteria [3] at a given pixel resolution of roughly 2 inch per 2 inch [4][7] for a given threat and threat size.

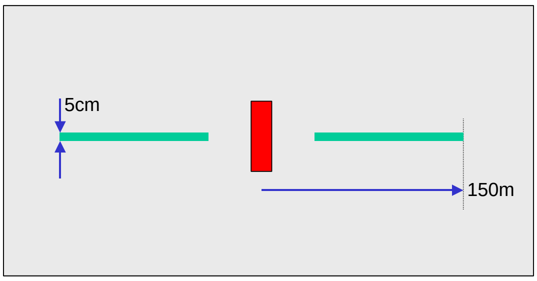

Figure 7 : Mono-aspect sonar

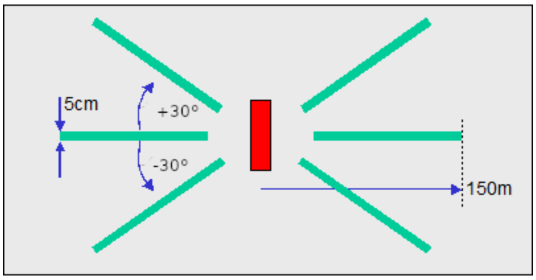

Figure 8 : Multi view in a single path sonar with 30 ° difference in aspect angles.

Improving resolution to 1 inch per 1 inch does not necessarily mean better probability of classification. For instance, MCM operators would classify each object MILCO (MIne Like COntact, that is to say: possible Mine Target), in Figure 9 and Figure 10.

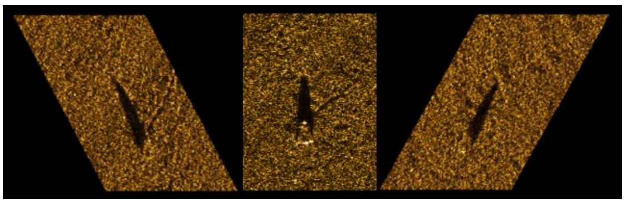

Figure 9: Multi-aspect imaging of a wedge target on an easy environment. Approximately 2*2 inch resolution

Figure 10 High Resolution imaging of a wedge target on an easy environment. Approximately 1*1 inch resolution. Note that the point of view of the object is here relevant for classification. It may not be the case all the time when objects can be deployed at any orientation over 360 degrees. There are some object significant points of view that operators should not miss to obtain good classification performances.

Moreover, MCM operators spend more time dealing with false alarms with rocks or manmade objects (Figure 11) .

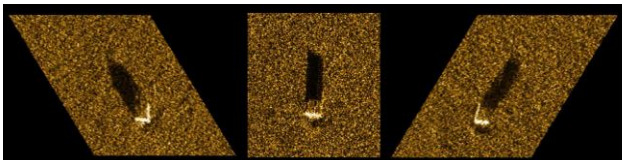

Figure 11: Multi-aspect image of a NO MILCO. Note that the object in the central view can be confused with a MILCO cylindrical object while its shape appears by comparing several points of views.

They must declare rocks without doubts NOMILCO while they would have to classify it MILCO if they are hesitant. On easy environment, one image may be enough and adding one more MILCO to proceed may not be a trouble for successive operations such as Identification and Neutralization. However, when environment becomes more complex and when time is critical in the operational context, it is of absolute need to get more images to give MCM operators confidence in reducing the list of MILCO to be investigated. Shape of the object is one of the criteria brought by crisscrossing the points of view.

On medium or complex environments, ACR is thus divided by the number of passes as defined in the Figure 12 below:

Sonar Type	Mono-aspect sonar			Multi-aspect sonar		
	Nb of passes	Nb of images	Nb of independent images	Nb of passes	Nb of images	Nb of independent images
Easy	1	1	1	1	1	1
Medium	2	2	2	1	3	2
Difficult	4	4	4	2	6	4

Figure 12: Number of passes with regards to environment and sonar type.

For a multi-aspect sonar, on an easy environment, the sonar mode is only broadside while being multi-aspect on medium and difficult environments. An independent image is an image separate from another with a 45° difference in aspect angles. This rule of thumb for pass number gives the same number of independent images for each sonar type.

2.2 Standoff distance

Operationally speaking, standoff distance is key for keeping human operators safe and being able to operate covertly**. It depends heavily on the mothership design and the toolbox composition. This distance is linked to communications and asset endurance regarding the MCM toolbox**

2.2.1 Communication

Three kinds of communication exist in a MCM toolbox: acoustics underwater, radiofrequency above water, and satellite communications. Communication needs are generally expressed in terms of range, bandwidth, number of MCM toolboxes being able to interoperate, encryption, and link to operational center (toolbox, ship or MCM data center).

2.2.2 Asset Endurance

Asset endurance for UxVs is linked to energy and power consumption of sensors.

2.2.2.1 UUV

Battery capacity is the source of energy for all sensors and on-board processing. The higher the battery capacity, the more enduring it is. Generally, all power needs are computed for different UUV speeds. Sensor power needs are constant whatever the speed. However, propulsion power, which is the most demanding, is variable with UUV speed.

$$P_{tot}(V) = P_{propulsion}(V) + \Sigma P_{sensors}$$

UUV endurance is then computed by dividing battery capacity per total power needs:

$$Endurance(V) = B / P_{tot}(V)$$

With B the UUV battery capacity (Wh). Sometimes, UUV manufacturers provide endurance curves or some key figures in survey and transit modes.

2.2.2.2 USV

Fuel tank is the main source of energy for USV propulsion and electric power. USVs using additional power sources coming from solar, wind and wave power are not taken into account since they are generally slower. USV endurance is also obviously linked to its speed. Generally, USV speed is computed as a function of engine RPM with maximum fuel and heaviest payload. Thus, USV Endurance is computed with the following formula:

$$Endurance(V) = B / CR(V)$$

with B the fuel tank capacity (l) and CR the consumption rate.

2.2.3 Standoff distance expression

Standoff distance is thus defined:

- for an UUV: by its endurance as it can be translated into a two way distance,
- for a USV: by the minimum between the communication range and a two way distance linked to its endurance.

2.3 Mission Time

2.3.1 Asset Sequencing

Depending on CONOPS, payload choices may be more relevant than others when two USV are available for MCM missions. For instance:

- 1 USV-Towed Sonar and 1 USV-MIDS for fast Detection Classification Localization Identification Neutralization (DCLIN),
- 2 USV-Towed Sonar for fast DCL and in-stride analysis,
- 2 USV-MIDS for intense mine clearing.

It is important to minimize re-rolling at sea since it is a time consuming task.

2.3.2 Sonar Data Analysis Time

MCM operators analyze data coming from UxVs sonar payload looking for mines in two phases:

- **Detection**: spotting every potential mine like object or mine like echo (MILEC)
- **Classification**: deciding if a detected MILEC is a Mine Like Contact (MILCO) or not a Mine Like Contact (NOMILCO)

It could be performed while USV-Towed sonar is surveying with data transfer through communication link: it is called **in-stride** or **post mission** mode when UUV have finished their survey and data are transferred afterwards. The analysis phase is generally time consuming and requires a lot of effort. Key indicators for these two phases are the probability of classification Pc, the probability of false classification Pfc and the time spent on post mission analysis. Pc and Pfc defines a performance status on the ROC curve described on Figure 14.

Classification Decision Matrix		Classification (Decision)	
		MILCO	NOMILCO
Ground Truth	Mine	True positives Pc	False negatives 1-Pc
	Not a Mine	False positives Pfc	True negatives 1-Pfc

Figure 13: Classification decision matrix [7]

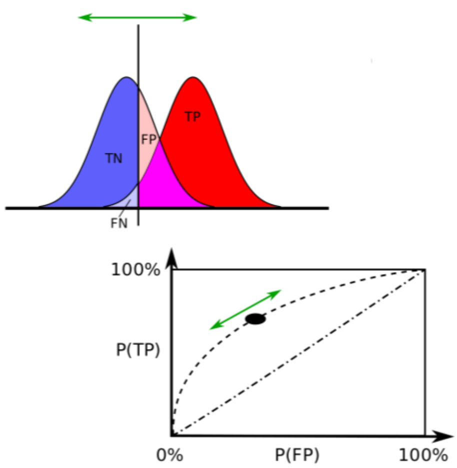

Figure 14: ROC Curve [7]

Another phase, **Localization,** is often associated to the previous two phases. It depends on the geo-referencing capacity of the sonar payload (GPS, APS, INS hybridation…). Every MILCO is then investigated during the **Identification** phase with MIDS and then **Disposal** if necessary.

3 Results and Discussion

According Think Defense [4], two recent mine warfare operations are listed: operation TELIC in Iraq and operation ELLAMY in Libya. Basically, these two operations comprise two operational scenarios:

- **Amphibious operation**: where a naval force needs to select a beach for deploying naval and military assets.

- **Sea port access**: where a naval force needs to access a port for strategic reasons.

In the following scenarios, desired operator classification performances correspond to Probability of Classification equal to 95% for a Probability of False Classification of 5%. For example, assume a multi-aspect towed sonar Area Coverage Rate is equal to 0.93 square Nautical Miles per hour (NM²/h) on easy environment, 0.8 NM²/h on medium environment and 0.4NM²/h on complex environment.
For the sake of brevity, only two types of mines are considered in both scenarios: bottom and stealthy mines and sonar data analysis time is assumed to be identical in each configuration.
Note that a hybrid approach (instead of a stand-off concept) impacts the needed endurance parameters on both USV and UUV characteristics.

3.1 Scenario 1: Amphibious operation

Figure 15: Amphibious Operation tactical scene

Navies want to have a sufficient standoff distance for amphibious operations in non-permissive environment in order to be discrete. For instance, 30 Nautical Miles is the standoff distance in [5]. Two available options on the commercial market are available for configuring a MCM toolbox for this amphibious operation:

- a **40 kWh** Medium Autonomous Underwater Vehicle (**MAUV) with a multi-aspect sonar**
- a **10 kWh MAUV with a mono-aspect sonar transportable by a USV.**

In this scenario (Figure 15), water depth is 30m between the mothership and the MAUV survey area (in blue) where MAUV and USV-multi-aspect towed sonar can be both surveying. Moreover, there is 27 NM of transit before a 3 NM long, 0.25 NM wide survey area with a 20 m water depth where only MAUVs can be surveying.

3.1.1 Assets Comparison

Both using a 150m sonar mode, asset area coverage rate is equal to **0.5 square Nautical Miles per hour (NM²/h)** for both multi-aspect and mono-aspect sonar mode for an easy environment. Using the area coverage rate depending on environment formula, Asset Area Coverage Rate is computed according to the different selected environments in the Table below for each asset:

ACR (NM²/h)	10 kWh MAUV & mono-aspect sonar	40 kWh MAUV & multi-aspect sonar
Easy	0.5	0.5
Medium	0.25	0.45
Difficult	0.13	0.23

Figure 16: Asset Area Coverage Rate (NM²/h) with regards to environment

In terms of standoff distance or endurance for UUV, we assumed that 40 kWh MAUV is able to transit at 3 knots for 48 hours or surveying at 5 knots for 20 hours while 10 kWh MAUV is able to transit at 3 knots for 22 hours or surveying at 5 knots for 8 hours. Those values are coherent with typical endurance and operating speed values coming from similar reference UUV datasheets.
A 40 kWh MAUV is longer and heavier due to the additional battery packs. This type of vehicle is more difficult to launch and recover safely by high sea state from an USV of 12 m length approximately. Alternatively, their augmented endurance usually provides sufficient stand-off distances without the need and the complexity of being taxied by USV.

Survey-Mission Times (h) @ standoff distance (NM)	10 kWh MAUV & mono-aspect sonar	40 kWh MAUV & multi-aspect sonar
Easy	1.5-**18.5**@30NM	1.5-**19.5**@30NM
Medium	3-**17**@23NM	1.7-**19.7**@30NM
Difficult	5.75-**14**@9NM	3.3-**21.3**@30NM

Figure 17: Survey and mission time at a given standoff distance for each asset for scenario 1. USV taxi speed 20kts.

Thus, a 10kWh MAUV with mono-aspect sonar cannot transit and survey the final area whatever the environment and needs a USV to transport it at respectively 29, 23 and 9 NM from the beach in easy, medium and difficult environments. In comparison, 40Wh MAUV can be launched and recovered from the mothership. Concerning the time to complete mission at a given standoff distance, mission times are similar for easy and medium environments. On difficult environment, USV taxying a MAUV at 20 knots allows to finish 7h earlier with a reduced standoff distance of 9NM. However, this configuration must only be chosen to have an early sonar preview of an area with such a short standoff distance and its level of maturity is lower since it is a more complex system and provides a greater complexity to handle at sea for the crew.

3.1.2 With MCM Toolbox #1

MCM Toolbox #1 is made of the assets below:

Assets	USV	TSAM	MAUV	MIDS
Number	2	2	1 - 40kWh with multi-aspect sonar	1

Figure 18: MCM Toolbox #1 composition

The toolbox global area coverage rate for this toolbox composition is the following:

Global ACR (NM²/h)	Bottom & stealthy mines
Easy	2.36
Medium	2.05
Difficult	1.03

Figure 19: MCM Toolbox # 1 global ACR

3.1.3 With MCM Toolbox #2

MCM Toolbox #2 is made of the assets below:

Assets	USV	TSAM	MAUV	MIDS
Number	2	2	1-10kWh with mono aspect sonar	1

Figure 20: MCM Toolbox #2 composition

The toolbox global area coverage rate for this toolbox composition is the following; taken into account the fact that one USV is completely dedicated to its USV Taxi function for transporting one 10kWh MAUV:

Global ACR (NM²/h)	Bottom & stealthy mines
Easy	1.43
Medium	1.05
Difficult	0.53

Figure 21: MCM Toolbox #2 global ACR

3.1.4 Discussion

Global ACR (NM²/h) for bottom & stealthy mines	MCM#1	MCM#2
Easy	2.36	1.43
Medium	2.05	1.05
Difficult	1.03	0.53

Figure 22: Benchmark between toolboxes for Amphibious Operation

Looking at the Table above, MCM Toolbox #1 provides 1.5 more global area coverage rate on easy environment and almost twice more global area coverage rate on medium and difficult environments than MCM Toolbox #2. Firstly, MAUV battery capacity is determining the standoff distance. Secondly, sonar payload with a multi-aspect capacity will have higher area coverage on medium and difficult environment providing a more robust solution. Thirdly, as a direct consequence of the first remark, if a MAUV needs a USV taxi capability to be transported, it will be at the expense of the global area coverage rate since a USV-multi-aspect towed sonar provides the best unit area coverage rate of all the assets on top of near-real time transmission of sonar images. Moreover, MCM Toolbox #2 provides full in-stride capability with 2 USV giving earlier access to sonar data. However, an USV taxying a MAUV have an advantage if early access to sonar data is necessary.

Basically, for amphibious operation, standoff distance is of the most importance and it is recommended to use a MAUV with a high battery capacity and a multi-aspect sonar payload if time is critical.

3.2 Scenario 2: Sea Port Access

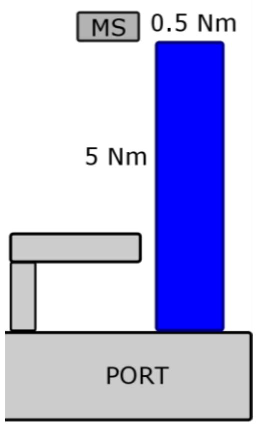

Figure 23: Sea Port Access Tactical scene

Survey area is 5 NM long and 0.5 NM wide with a water depth of 20 m where a USV can tow multi-aspect sonar. MCM tasks are defined as: establishing bottom mapping and clearing mined section of route. The goal is to determine a safe route. The toolbox composition is the following:

Assets	USV	TSAM	MAUV	MIDS
Number	2	2	0	2

Figure 24: Sea Port Access Toolbox composition

Sequencing of assets is important: two choices are available:

- a configuration with 1 USV-multi-aspect towed sonar (DCL) & with 1 USV-MIDS (IN) called **DCLIN**

- a configuration with 2 USV-multi-aspect towed sonar DCL and then 2 USV-MIDS called **DCL then IN**

Global ACR (NM²\h) for bottom & stealthy mines	DCLIN	DCL then IN
Easy	0.93	1.86
Medium	0.8	1.6
Difficult	0.4	0.8

Figure 25: Global ACR Benchmark for 2 configurations

Assuming that a rerolling at sea takes approximately 6 hours and that a USV-MIDS intervention takes 0.5 h per contact, the table below sums up the different times on tasks:

Time for bottom & stealthy mines in surveyed area (h)	Easy	Medium	Difficult
DCLIN survey	2.7	3.1	6.25
DCL then IN survey	1.3	1.6	3
DCL then IN survey then rerolling	7.3	7.6	9
Numbers of already contacts processed in DCLIN configuration	15	16	18

Figure 26: Configuration performances with regards to environmental conditions

Assuming that sonar images are analyzed in near real-time, DCLIN configuration is more efficient as long as the MILCO density is inferior to 8 MILCO per NM². DCLIN configuration is efficient if probability of false classification is low.

4 Future Work

This paper establishes a framework with three key indicators: global area coverage rate, standoff distance and time to complete the MCM mission for given environmental conditions and mine threats on typical MCM CONOPS. Future work includes addressing more environmental situations than just the three listed types. Other classical MCM scenarios should be addressed too. Acoustic and magnetic UxVs signatures are also of prime importance and need to be included in future framework.

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