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► **To cite this version:**

Antoine Milot, Estelle Chauveau, Simon Lacroix, Charles Lesire, Loïc Tacher. Autonomous and responsive multi-robot system for minehunting. OCEANS Conference & Exposition (OCEANS 2022), Feb 2022, Chennai, India. 10.1109/OCEANSSChennai45887.2022.9775467 . hal-03514510

HAL Id: hal-03514510

<https://hal.science/hal-03514510>

Submitted on 6 Jan 2022

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Autonomous and responsive multi-robot system for minehunting

Antoine Milot^{1,2,3}, Estelle Chauveau², Simon Lacroix¹, Charles Lesire³ and Loïc Tacher

This paper presents an approach to handle a minehunting mission with a decentralized multirobot system. To efficiently take decisions, the described framework merges auctions to allocate tasks with hierarchical planning. The approach is responsive and robust to the occurrence of events thanks to supervision and repair processes. Simulation results illustrate how the proposed decisional architecture operates.

INTRODUCTION

Since 1945, naval mines damaged more US navy vessels than all other weapons combined [1]. They are extremely effective as psychological weapons. As most countries put a zero-casualty doctrine into practice, the simple suspicion of mines is sufficient to deny access to an area and slow down enemy progression. Their threat are more tangible than ever in modern conflicts [2], and effective Mine Counter Measures (MCM) are needed in both peace and war times.

Minehunting is one of the possible countermeasures to clear a minefield. It consists in detecting and identifying mines with sensors, and then in neutralizing them.

The underwater world is however not conducive to human exploration and the possible presence of explosives makes it even more hostile: hunting mines is a difficult and dangerous mission. To accomplish it, most countries rely on minehunter vessels. These vessels have a crew of around fifty members and directly explore the minefield with hull-mounted and high-frequencies sonars. Once a suspicious object is found, divers are dispatched to identify and neutralize the mine. The crew is put at high risk during the whole mission, and lethal accidents still occurs despite the use of safety measures [3], [4]. These measures, such as the reduction of the magnetic signature of the hull, make minehunters very expensive ships [5].

Consequently, most navies are relying on robotic assets to reduce the human risk. For example, during the Persian Gulf War divers were often replaced by Remotely Operated Vehicles (ROVs) to identify and neutralize bottom mines [6]. While the use of ROVs was proven largely effective, the search for suspicious objects and the remote control of the vehicles still requires the presence of minehunters with human operators onboard.

In 2019, a major joint program estimated at 2 billions dollars between France, Belgium and the Netherlands was

announced for the construction of 12 minehunters integrating around 100 robots [7]. In 2020, the Royal Navy announced a £184 million investment to fully replace their expensive and aging minehunters with a Multi-Robot System (MRS) composed of ROVs, Unmanned Surface Vehicles (USVs) and Autonomous Underwater Vehicles (AUVs). Besides efficiency, one of the main advantages of MRS is their reliability thanks to the redundancy of units. This replacement has to be effective by the end of the decade [8], [9]. While the mentioned robotic units will still be mainly remotely operated, these announcements foster the development of researches on MRS.

Accomplishing a minehunting mission with classic MCM vessels is long expensive, and requires significant human resources and equipment. There is however a lot to gain in terms of cost and safety by using robots and more automated systems. Navies are currently adopting hybrid strategies, integrating robotic units which still need to be remotely operated from classic MCM motherships. In line with the logical evolution of these systems, we propose to push forward and use an autonomous MRS to achieve a minehunting mission.

The next section summarizes the characteristics of the minehunting operational context. We then present an overview of the proposed approach, and illustrate how it handles a survey mission with a simulation example. The key concepts of the approach, its advantages and limitations are then discussed.

OPERATIONAL CONTEXT

Considering the high-pressures and absence of light, robotic units are more adapted to the underwater environment than humans. A lot of work on MRS has been carried out for several decades for applications such as maritime archaeology, ocean survey, anti-submarine warfare or minehunting [10].

A minehunting mission consists in three main objectives: 1) Detection 2) Identification 3) Neutralization. The mission is first a coverage problem because one cannot predict the presence and number of mines in the area. However during the mission it is necessary to react to various events, and in particular to the discovery of a suspicious object. These events continually challenge the system which has to adapt its operations in order to take them into account. The mission therefore brings a strong need for *responsiveness* and *adaptability*.

A minehunting swath quality is dependent on the bottom types (sand, rocks...) and the underwater current. Some useful information on these parameters are either already

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know or obtained through a Rapid Environmental Assessment (REA). Nevertheless, these information are incomplete and uncertain.

Due to their limited payload, the robots have heterogeneous capacities and must cooperate to accomplish the mission. Depending on their capabilities and the current situation, each robot in the MRS can perform differently a given objective: a key point in the deployment of a MRS is the Multi-Robot Task Allocation (MRTA) problem, which optimizes the distribution among the fleet of the tasks to perform, according to the current situation.

Finally, communications take a major role to deploy a MRS underwater. The usual way to communicate underwater is through acoustic waves: despite providing great ranges, sound does not allow to communicate at high bit-rate. Moreover, sound speed in water depends on environmental parameters such as the salinity and temperature, leading to message losses and delays. Underwater communications are a real challenge for MRS, and they must be taken into account in the system design [11]. They are in particular essential to supervise the system operations, which requires regular reports to the remote operators. Depending on the mission parameters, the system must satisfy this constraint.

APPROACH OVERVIEW

Each minehunting objective requires different capacities. A robot capacity is defined by its payload, so we must resort to a team of heterogeneous agents to fulfill the mission. We consider a MRS composed of:

- *Explorers*: AUVs with high-frequencies sonars, in charge of the *detection* objective;
- *Identifiers*: AUVs with chemical, optical or electromagnetic sensors for suspicious objects *identification*;
- *Neutralizers*: AUVs with explosive charges for *neutralization*;
- *Helpers*: USVs which deploy and recharge AUVs while acting as a communication link between the underwater robots and operators.

We propose a decentralized architecture relying on allocation with auctions and hierarchical planning [12]. An overview of this decision scheme is shown in Fig. 1.

When allocating tasks through auctions, the involved robots compete with each other in order to buy parts of the mission [13]. There are four essential steps to allocate a task through an auction: 1) **Announcement**: an auctioneer opens an auction by broadcasting the information on the task for sale; 2) **Bids estimation**: each bidder estimates its cost to accomplish the task and sends its bid to the auctioneer; 3) **Winner Determination**: once the auctioneer received all bids, or a deadline is reached, it resolves the Winner Determination Problem (WDP) to find an allocation; 4) **Reward**: if a winner has been found at the previous step, the auctioneer sends it a reward message.

In order to efficiently solve the bid estimation and WDP we rely on Hierarchical Task Network (HTN) planning [14]. A HTN integrates expert knowledge by decomposing a complex task into simpler ones. This allows to reduce the

complexity of the problem thanks to the mission specification.

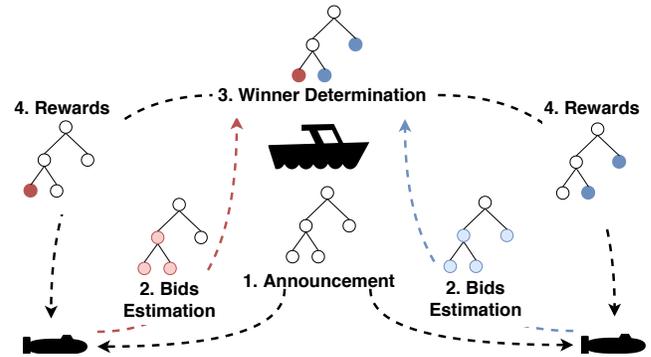


Fig. 1: Overview of the decision scheme. The mission objectives decomposed as a HTN are auctioned. Each robot bids on the sub-tasks, a winner determination process allocates the tasks and sends them to the robots (“rewards”).

EXAMPLE

To illustrate our approach, we consider a *Home Port Survey* in the harbor of Brest in France. The goal is to cover the harbor in order to ensure with a certain level of confidence that no mines are present (or that they have all been found). As it is a survey mission, there are no time or discretion constraints.

In order to accomplish this survey we consider a MRS composed of:

- Three *explorers* called *AUVe1*, *AUVe2* and *AUVe3*;
- One *identifier* called *AUVi1*.

These two kind of robots are respectively responsible of *cover* and *identify* tasks. The initial mission is an exploration problem composed only of *cover* tasks.

The inputs of the system are:

- A HTN describing the mission objectives (also called multirobot tasks);
- A HTN local to each bidder and describing its capacities (i.e. how the bidder can handle a multirobot task).

In our framework, this information is defined using a modeling language called Hierarchical Domain Definition Language (HDDL) [15].

Our approach is implemented using the ROS2 framework and involves independent nodes working in parallel. We use the LCP solver¹ to solve both the bid estimation and the WDP [16].

In order to visualize the mission progress, we use an interface showing various information (the robot position, the area division, the position of detected suspicious objects...). Fig. 4 is a sequence of screenshots of this interface over the mission progress that show the most relevant steps.

¹<https://github.com/plaans/aries>

Initial Planning

The first problem to solve is a coverage one. The robots are initially idle, at the positions shown Fig. 4a, and each sub-part of the whole area to explore has to be allocated to the robots.

The first auctioneer, either a member of the robotic team or a central computer, initializes an auction by putting for sale the initial mission objectives. The corresponding item for sale is a HTN composed only of *cover* tasks and is based on a partition of the mission area, shown Fig. 2. Each colored area corresponds to a leaf *cover* task in the HTN, i.e. a *cover* task that cannot be decomposed into others *cover* tasks. The initial HTN used for the first auction is shown in Fig. 3.

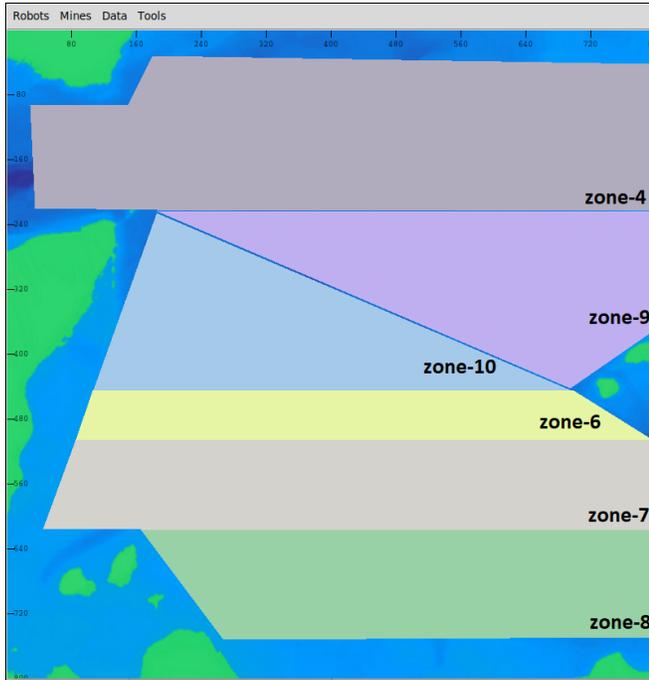


Fig. 2: The partition of the whole mission area.

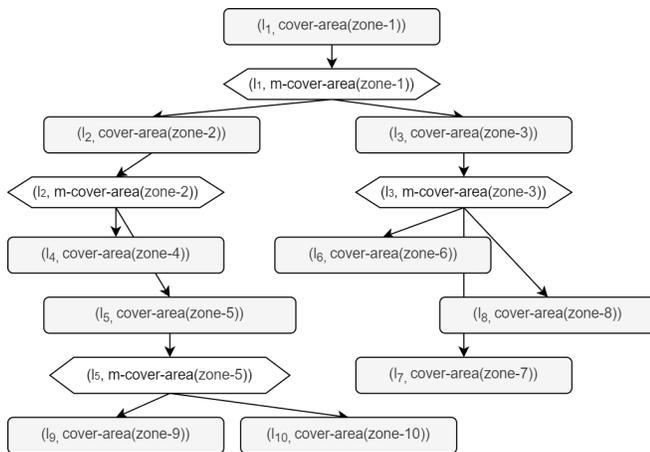


Fig. 3: HTN used for the first auction. Rounded rectangles are labeled tasks, hexagons are labeled methods. A method allows to decompose a task in sub-tasks.

As the *identifier* cannot accomplish *cover* tasks it does not participate to this auction. Each *explorer* acts as a bidder and computes a bid for every task in the HTN. The received bids are integrated by the auctioneer into a hierarchical planning problem corresponding to the WDP, which is then solved by calling a hierarchical solver. The results is the allocation for this auction round. If some tasks remain not allocated at the end of the auction round, the auctioneer builds a new item for sale with them and starts a new round.

In this example case, three rounds are needed to fulfill the allocation problem. The resulting allocations are shown for each round in Tab. I.

Robots	Round 1	Round 2	Round 3
AUVe1	l_4		
AUVe2		l_5	
AUVe3	l_7	l_6	l_8

TABLE I: Allocations of the first auction. Task labels correspond to those in Fig. 3.

Execution of the plans

During the bid estimation process, each bidder computes a local plan to accomplish its allocations. The local plan is a sequence of actions proper to the bidder, such as *GoTo*, *UseSonar*. . . This local plan comes out of the multirobot plan that the bidder committed to execute during the auction. For example, the resulting multirobot plan of the AUVe3 at the end of the first auction is the sequence l_6, l_7, l_8 .

Fig. 4b shows the robots starting to execute their plans.

Repair - Creation and allocation of a new objective

During the execution of l_5 , AUVe2 finds a suspicious object to identify (Fig. 4c). Due to this event, the robot takes the auctioneer role, creates a new HTN composed of an *identify* task and puts it for sale.

During this new auction, AUVe1 buys the task. It starts to join the position of the suspicious object (Fig. 4d), and once arrived, it identifies the object as a mine (Fig. 4e).

Repair - Reallocation of a task

At the beginning of its execution of l_8 , AUVe3 has a sensor breakdown and stops to move (Fig. 4f). As this breakdown jeopardized its accomplishment of l_8 , a repair is needed. In order to do this it starts a new auction as an auctioneer with a HTN for sale corresponding to task l_8 .

At the end of this auction, AUVe2 buys the task and starts to join the area to accomplish its new cover task (Fig. 4g).

Mission end and debriefing

Finally, Fig. 4h shows the final state of the system. All robots accomplished their multirobot tasks and the mission ends.

Before starting the mission, the robots were able to solve the MRTA problem by running a first auction on an initial HTN describing the mission objectives. During the execution of the mission they encountered two events.

At first, the discovery of a suspicious object to identify led to the integration of a new objective. Then, an objective was reallocated to another teammate due to a breakdown. Both of these hazards were overcome thanks to supervision and repair processes. This simple example illustrates how the proposed approach brings *robustness* and *responsiveness* to the system.

In order to accomplish the whole mission, three auctions were held for a total of 5 rounds. Tab. II shows a summary of the exchanged messages for these rounds. Because they contain a lot of information on the MRTA problem, announcement messages are the heaviest to send. The bid messages are much lighter, but they are numerous: their burden on the bandwidth should not be underestimated. The number and size of exchanged messages are however largely matching the underwater acoustic communication means capacities [17].

Message type	Nb. messages	size (B)		
		Average	Min	Max
<i>Announcement</i>	5	8018	2124	12948
<i>Bid</i>	54	439	172	588
<i>Result</i>	5	103	80	144

TABLE II: Summary of the exchanged messages during all the auctions.

Tab. III shows a summary of the solving time for the bid estimation and WDP². While the bid estimation problems were solved efficiently, the WDP is more complex. In our example, the longer round to solve was the first one, with a WDP duration of 20.84s. This auction round contained 11 tasks for sale for a total of 33 received bids. In the later rounds the time complexity dropped-off considerably (less than 1s in average). This difference is due both to the number of bids to consider and the degree of freedom of the multirobot plan at the mission beginning. This maximum WDP solving time is however still acceptable for the considered mission.

Auctions	average estimation time per bid (s)	WDP solving time (s)
First auction	0.14	8.11
Second auction	0.07	0.53
Third auction	0.06	0.65

TABLE III: Summary of the solving time for the bids estimation problem and the WDP.

APPROACH DESCRIPTION

Relying on both auctions and hierarchical planning paradigm brings numerous advantages, which are discussed here.

Allocating tasks with auctions

Auctions are a decentralized and flexible way to allocate tasks. As any robot can put tasks for sale, new tasks can

²measured on an intel® core™ i7-9750h CPU @ at 2.60GHz and 16 GB of RAM.

easily be added to the current mission, as we have seen after the detection of a suspicious object during the *cover* task. The robot has spawn a new *identification* task, and put it for sale among the robots it can communicate with. This ability is a perfect way to bring responsiveness into the system. It does not require full communication connectivity: in case of a lost message the process can still go on with the remaining connected robots.

By using auctions, the robots are encouraged to cooperate locally. Due to the geographical distribution of tasks in a minehunting mission, this local cooperation makes sense at the mission definition level. Finally the scalability is eased by the decentralized design of the system.

Auctioning HTN

While the items for sale in auctions are usually single tasks, we use HTNs instead. This choice is encouraged by the reduced complexity of hierarchical planning problems [18].

There are other benefits in auctioning HTNs. By selling HTNs one can easily allocate entire parts of the mission. When bidding on the nodes of a HTN for sale, the bidders have the possibility to directly buy a branch of the HTN. This process allows to interleave allocation and decomposition, a key element to get better performances while solving a complex MRTA problem.

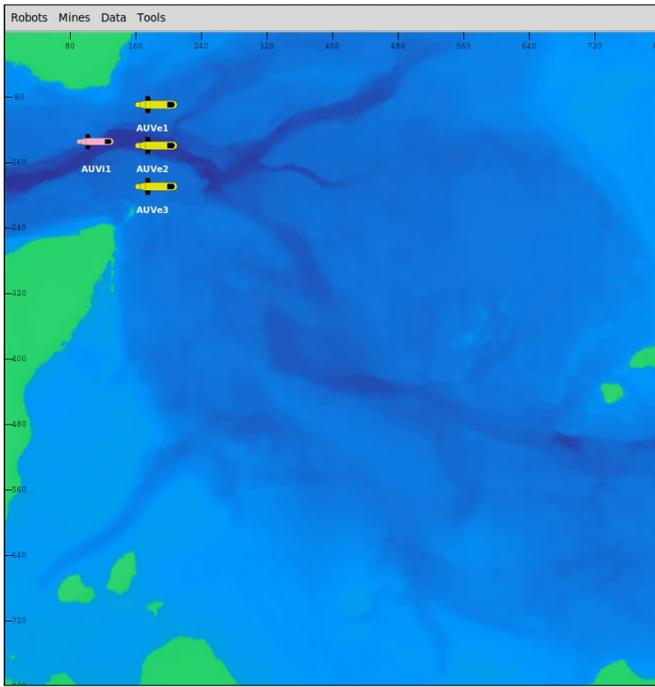
Formulating bids and solving an auction can be difficult problems, especially when considering dependent tasks, e.g. it can be more interesting for a robot to buy a task only if it can also buy another one. HTNs can include hierarchical dependencies between tasks and therefore allow robots to buy a bundle of tasks without increasing too much the complexity.

Some tasks however can be directly linked by mission specific constraints that can not be represented within a classic HTN. For example, depending on the degree of feedback required by the operator, an *identification* task may have to be achieved with live data stream. Then, given communication constraints, the discovery of a suspicious object leads to the creation of two tasks that must be simultaneously executed by two robots: an *identification* task and a *communication relay* task. In this case, both tasks are linked by a synchronization constraint that must be taken into account by the allocation process. Such constraints complicates the MRTA problem, but can however be handled thanks to the HTN formalism, within which specific constraints like this one can be considered.

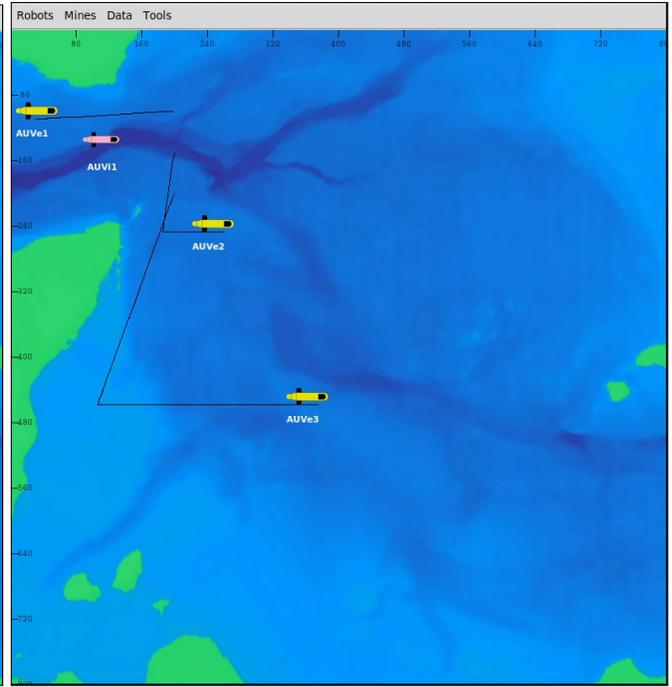
Multirobot vs. local knowledge

An HTN can either be local to a robot and describes its capacities, or it can also be based on mission specification and known to all agents. This duality between the *multirobot level* (tasks to allocate) and the local level (how to accomplish the tasks) is a key point of our framework. The resulting protocol is depicted in Fig. 5.

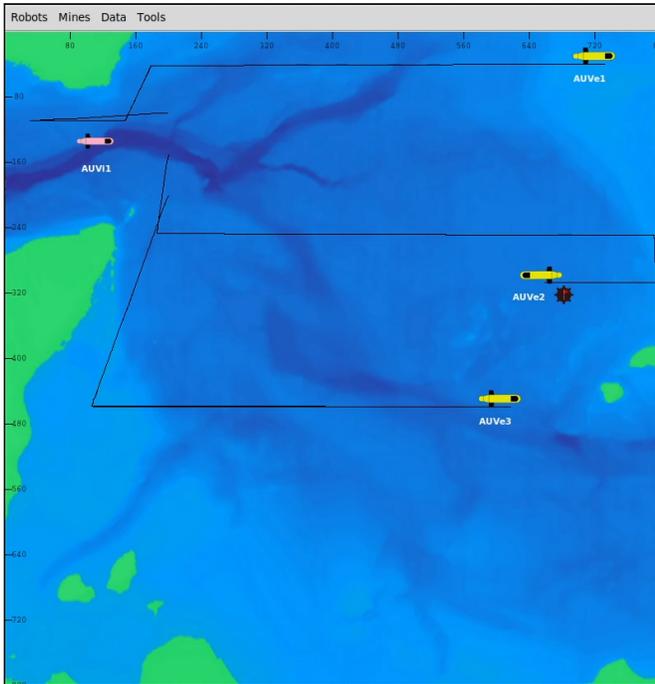
Our system needs as input an initial HTN (the *MultiRobot Graph*) that describes the tasks for sale. At first, the mission is usually an exploration problem consisting in a task *cover*



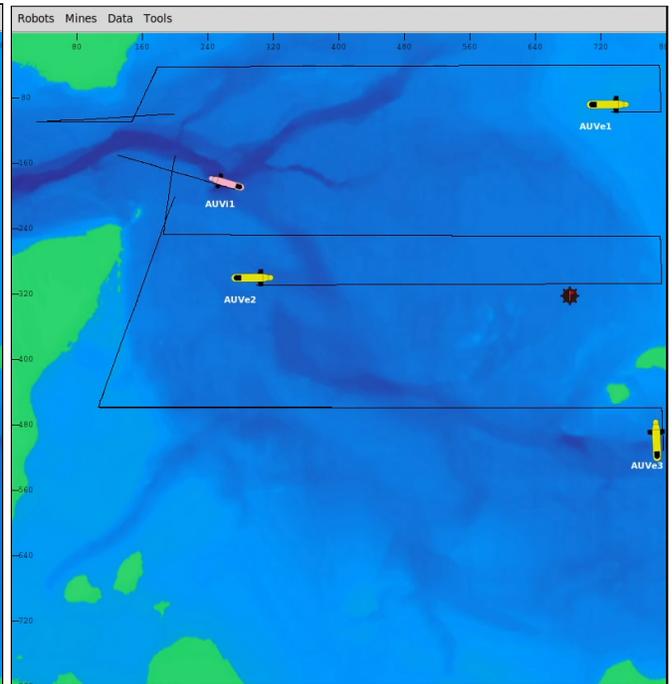
(a)



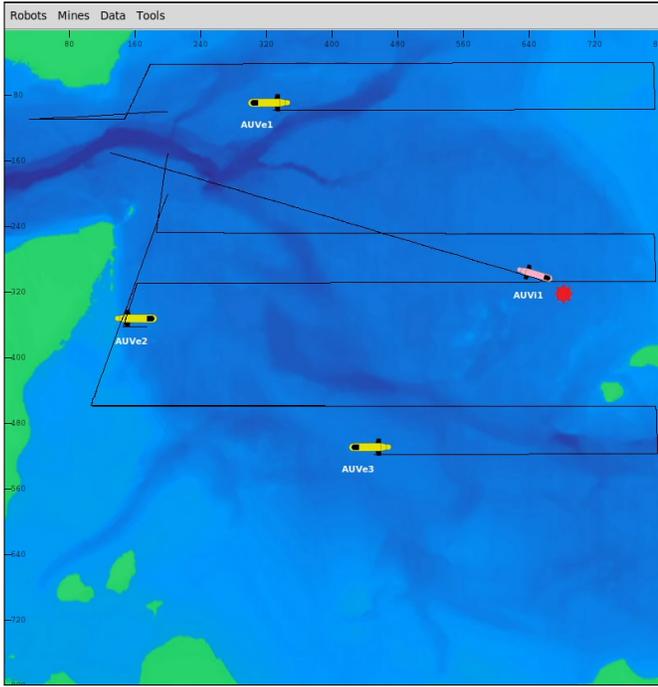
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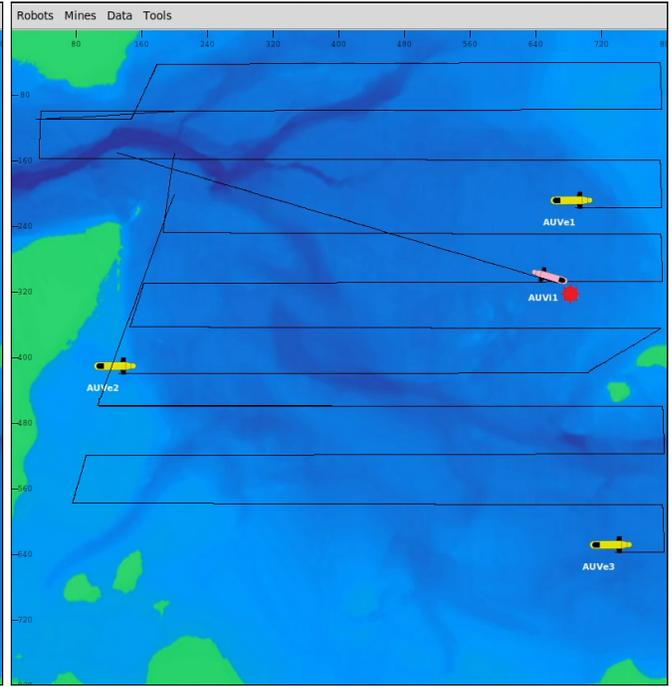
(c)



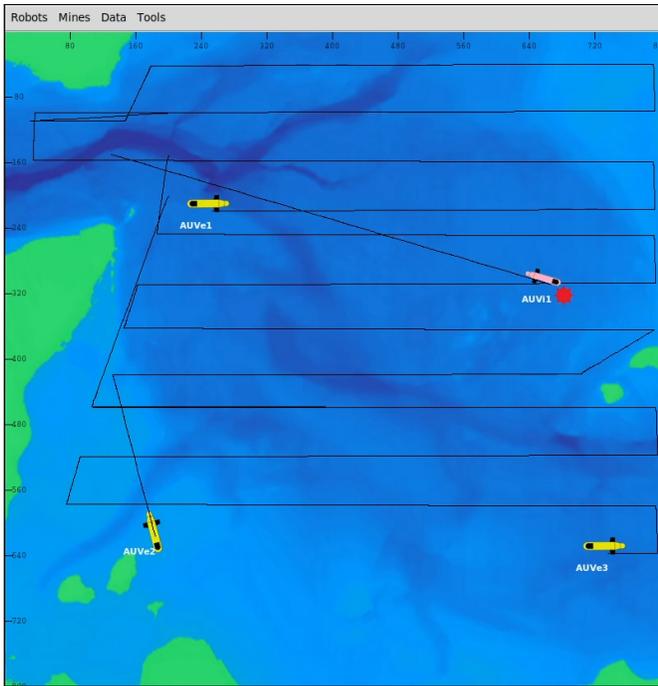
(d)



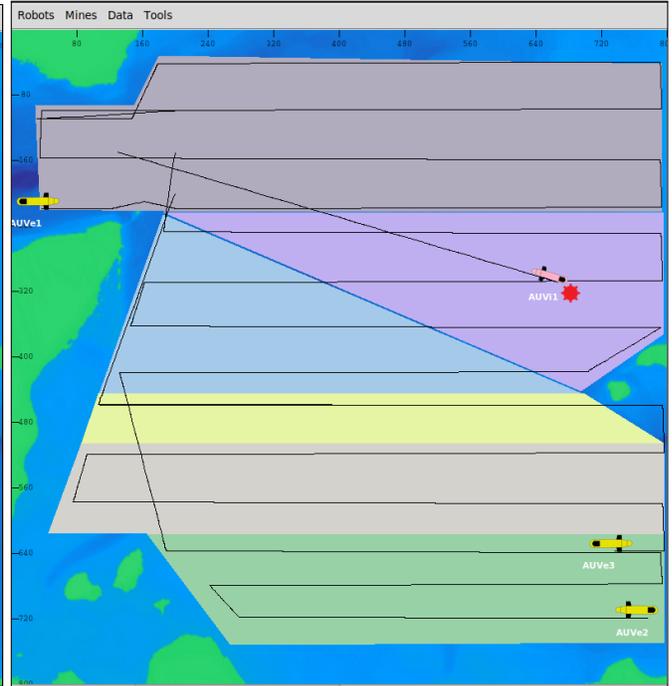
(e)



(f)



(g)



(h)

Fig. 4: Screenshots of the mission progress.

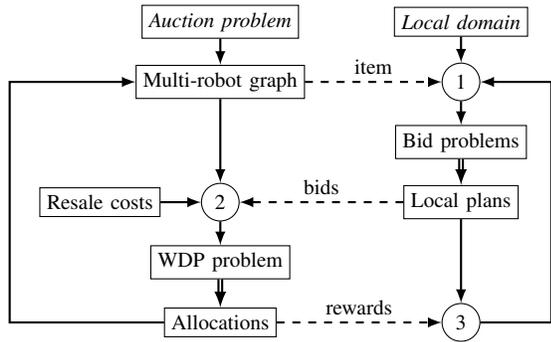


Fig. 5: Protocol description. Rectangles represent information or data structures managed by the agents. Blocks on the left are managed by the auctioneer, blocks on the right by each bidder. Dashed arrows represent data exchanged between the auctioneer and the bidders. Circles indicate processes that aggregate information to build new structures. Double arrows indicate calls to a HTN planner.

the mission area. The mission area can be divided in sub-areas *A* and *B* and so forth. Therefore the exploration of the mission area can be accomplished by exploring *A* and *B*. This information is based on mission specification and encapsulated in the HTN to start the first auction.

In order to build this initial HTN we use the partition of the mission area, which can be established by a human operator relying on the knowledge of the area and the detection sensors.

Once the *MultiRobot Graph* is defined the auctioneer sends it to the bidders. Then bidders use their *local* knowledge to estimate bids. Finally the auctioneer integrates the received bids into a HTN describing the WDP and solves it to find an allocation. When building the WDP, the auctioneer also integrates a resell process. Depending on how this resell process is designed one can control the allocation behavior. For example we can implement preferences on the urgency of selling a task.

In previous work [19], we tested a proof-of-concept decision architecture to solve a single auction and we got promising results in terms of solution quality, duration and control over the allocation.

Framework advantages

As the system evolves in a complex and constrained environment, the need for responsiveness goes beyond the sole capacity to integrate new tasks. Due to uncertainties and unforeseen events, a robot may indeed not be able to accomplish a task that it previously bought. For example, a *cover* task can have been bought for a certain cost (e.g. a duration). But during execution, unforeseen events such as stronger water currents than predicted may impact the actual task cost: the plan committed during the task allocation is no longer valid and a repair action is necessary. The proposed approach, interleaving auction and hierarchical planning, can handle such events, e.g. by allowing the robot to re-sale the task it cannot properly achieve.

By integrating a supervision scheme and specific methods for problem detection and repair, the decision scheme is meant to be used online and endows the system with robustness against unforeseen events.

Moreover, the proposed approach is flexible and generic. The keystone is the mission modeling to generate the necessary inputs. The comprehensive HTN formalism greatly facilitates this modeling step, and allows to easily add new constraints.

We can also benefit from auctions parameters to yield particular behaviors of the system. In our work, we use a cost as our bid value. This is the most basic way to work with auctions but we could use more descriptive information to set the bid value. There is a whole corpus of auctions literature focusing on this value design [13]. For example, we can use *how well the bidder will accomplish the task* to set it.

The resell process is also a convenient way to control the allocation process. Depending on its design one can for example optimize the solution quality or minimize the necessary number of rounds. We refer the reader to [19] for more complete information on how it is accomplished.

Thanks to these advantages the system can be adapted to doctrine evolutions in the field of minehunting. One can even adapt it to very different missions: in [12] we tested our framework on a classic logistic mission consisting in moving packages.

Perspectives and limits

Even though the implemented version of our framework already shows the ability to allocate tasks in a decentralized way and to handle plan repair, it is still work in progress, and there remain some issues to tackle.

The most important one is to improve the existing description of the mission to match a more realistic use case. Currently our framework indeed relies on a sequential execution of the tasks, whereas some tasks need other constraints than precedence or causal constraints. For example the task *communication relay* will have to be executed in a specific time window. In order to implement these new tasks we need to augment the approach with temporal constraints, which we believe can be done with the HTN formalism. This will allow to tackle new tasks to handle communication relays, AUV recharge, mine neutralization and data mule. Another benefit will be to make a better use of robots often idle, such as *identifiers*, to accomplish support tasks (e.g. communication relays).

Our approach comes however with some limits inherent to its design. While guided by the underwater environment constraints, the choice of a decentralized architecture establishes a trade-off between robustness and solution quality. In auctions, the solution quality of the allocation is mainly dependent on the diversity of bidders able to communicate with the auctioneer. As our system is intended for use in harsh communication environments we aim to investigate the impact of communication quality on the mission performance.

Also, the WDP complexity is a usual pitfall of auction schemes. While reduced by the use of HTN planning, we still need to study carefully variables affecting it the most.

CONCLUSION

In this paper, we proposed an approach to accomplish a minehunting mission with an autonomous multirobot system. The approach relies on allocations through auctions and hierarchical planning. We described how the approach encapsulates decision, supervision and repair processes to bring responsiveness and robustness to the system. To illustrate both of these advantages, we used a simulation of a minehunting mission including the occurrence of unforeseen events.

Future work will consist in improving the mission modeling and demonstrating the applicability of the approach on more realistic problems with temporal constraints. We will also study carefully the impact of communication quality over the system performances.

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